Industrial Metaverse: A New Spacetime for the Deep Integration and Development of Digital Technology and the Real Economy

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Abstract

In the Metaverse era, digital transformation of manufacturing represents an imperative for reshaping the manufacturing value chain and enhancing industrial competitiveness. The Industrial Metaverse integrates digital technologies with real-world industry, fosters efficient development of physical industry, and constructs a novel manufacturing and service system encompassing the entire industrial chain and value chain, marking a new stage in the digitalization and intelligentization of industry and broader industrial sectors. The Metaverse constitutes a more concrete synthesis of the digital future, representing a new frontier for digital economy innovation and industrial chain expansion. The Industrial Metaverse serves as a work platform that combines real and virtual employees to complete the industrial manufacturing value chain cycle, enabling virtual digital technologies to empower the real world and achieving symbiotic coexistence and integrated development between the physical and digital realms. It replicates and transforms the real world within the digital world, realizing innovative management characterized by intelligence, human-centricity, and crowdsourced innovation. This paper articulates that digital transformation is the inevitable path toward high-quality enterprise development, and the Industrial Metaverse represents a new spacetime for the integrated development of the digital economy and real economy. It briefly introduces the machine vision measurement solutions of Gechuang Dongzhi and the digital twin solutions of Siemens and General Electric, along with their effectiveness.

Full Text

Preamble

Industrial Metaverse: A New Era of Deep Integration and Development of Digital Technology and Real Economy

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Abstract

In the metaverse era, the digital transformation of manufacturing is an inevitable requirement for reshaping the manufacturing value chain and enhancing industrial competitiveness. The industrial metaverse integrates digital technology with real-world industry, promotes the efficient development of physical industry, and constructs a new manufacturing and service system covering the entire industrial chain and value chain, representing a new stage of digital and intelligent development for industry and the broader economy. The metaverse is a more concrete synthesis of the digital future and a new frontier for digital economic innovation and industrial chain expansion.

The industrial metaverse is a work platform that combines real employees with virtual employees to complete the industrial manufacturing value chain cycle, enabling virtual digital technology to empower the real world and achieving the coexistence and integrated development of the physical and digital worlds. By replicating and transforming the real world within the digital realm, it enables intelligent, humanized, and crowdsourced innovative management. This paper elaborates that digital transformation is the necessary path for high-quality enterprise development and that the industrial metaverse represents a new spatiotemporal dimension for the integrated development of the digital economy and the real economy. It briefly introduces the machine vision measurement solutions of Gechuang Dongzhi and the digital twin solutions of Siemens and General Electric, along with their effectiveness.

Keywords: metaverse; virtual reality; augmented reality; industrial metaverse; digital twin
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1. Introduction

"The metaverse can be regarded as a new world integrating the physical and digital worlds, called the third-generation Internet (Web 3.0), which can be subdivided into three-dimensional Internet and value Internet (Fang Jun, 2022)" [**?**]. The metaverse will empower all industries, stimulate new functions in traditional industries, and achieve high-quality industry development.

The industrial metaverse is an industrial ecosystem where new information and communication technologies, represented by XR and digital twins, deeply integrate with the real industrial economy. Through technologies such as XR, AI, IoT, cloud computing, blockchain, and digital twins, it achieves seamless connectivity among people, machines, objects, and systems, combining digital technology with real industry to promote efficient development of physical in-

dustry and build a new manufacturing and service system covering the entire industrial chain and value chain. This represents a new stage of digital and intelligent development for industry and the broader economy. The industrial metaverse continuously expands the spatiotemporal dimensions of technological innovation, providing a solid foundation and space for the implementation of service-oriented manufacturing transformation content such as personalized customization, mass customization, flexible manufacturing, and product lifecycle operations and maintenance. The industrial metaverse is both a new path for the digital and intelligent transformation of manufacturing and a new spatiotemporal dimension for the integrated development of the digital economy and the real economy.

2. Industrial Metaverse: A New Path for Digital Transformation in Manufacturing

2.1 The Concept of the Metaverse

"The metaverse is the conceptual materialization under new technologies such as extended reality (XR), blockchain, cloud computing, and digital twins" [**?**]. In September 2022, the National Committee for Scientific and Technical Terminology held a seminar on metaverse and core terminology concepts. After in-depth discussions, experts reached consensus on the names and definitions of three core concepts including "metaverse" —the English counterpart being "metaverse," defined as "a virtual world constructed by humans using digital technology, which maps or transcends the real world and can interact with the real world" [**?**].

"The metaverse may be the next major cloud computing platform after the World Wide Web and mobile Internet. Meanwhile, 'decentralized' digital financial technology is developing at an explosive pace, which has driven a new round of business model transformation and encourages everyone to play a role in building the metaverse (Raja Koduri, 2021)" [**?**]. The future represented by the metaverse is not about using high-tech devices such as virtual reality headsets to immerse us in virtual images and audio-visual stimuli presented before our eyes, but rather a new digital world that provides people with a better life experience. "If we look more closely, the future new digital world includes three possibilities: an immersive, fully virtual new world; a new world where physical entities merge with digital technology; and a new world where digital technology enhances physical entities (Fang Jun, 2022)" [**?**].

With the manufacturing of increasingly powerful terminal devices (AR/VR), the operation of high-bandwidth networks, and breakthroughs in network computing power, the metaverse vision will gradually become reality. An article titled "The Present and Future of the Metaverse" in the April 2022 issue of *People' s Tribune* argues: "The metaverse is a new type of Internet application and social form that integrates multiple new technologies to create a blend of virtual and real. Based on technologies such as high-speed communication, artificial

intelligence, blockchain, virtual reality, augmented reality, sensors, and brain-computer interfaces, it provides users with immersive experiences by digitally transforming reality, building a special form that integrates economic systems, social systems, and identity systems, is open, and allows each user to produce and edit content" [**?**].

2.2 VR/AR as the Gateway to the Metaverse: VR Promotes Deeper Understanding of Physical Reality

Jaron Lanier (2017), the "father of VR," provides his seventh definition of VR in *Dawn of the New Everything*: "By contrast, crude simulated reality promotes our understanding of the depth of physical reality. As VR progresses in the future, human perception will correspondingly advance, allowing us to learn to explore physical reality more deeply" [**?**]. "The task of a VR system is to elevate the nervous system beyond a threshold, causing the brain to believe in this virtual world rather than the physical world for a period of time. From a cognitive perspective, reality is the brain' s expectation of the next moment. In VR, the brain is persuaded to expect virtual things rather than real things for a period of time" [**?**]. Lanier believes that VR is a medium that allows you to change perspectives, and it is expected to become a pathway to enhance empathy; he hopes VR will be a medium for achieving universal information sharing and collaboration.

VR is a medium that emphasizes interactive biological movement. "VR should be more of a measurement science than a synthesis science"[**?**]. The emergence of VR data gloves enables users to interact with the virtual world and influence it. Through VR gloves, people can touch the virtual world and have a real impact on it with their hands. Lanier also invented an electronic musical instrument called the "Theremin," which can be played by moving hands in the air near an antenna without touching anything. This playing method gives performers a sense of contact with the virtual world—the prototype of today' s "hand tracking." In 1985, Lanier and Tom Zimmerman, who invented the "data glove," co-founded VPL Research. In 2014, Lanier received the German Book Trade Peace Prize.

VR is a universal tool for cognitive enhancement, a media technology that prioritizes stimulating cognitive dynamics to simulate alternative environments, thereby enabling accurate cognition of the world. VR represents "human-centered, experience-based digital technology that is expected to drive the digital economy without neglecting real individuals as sources of value." VPL Research helped Boeing establish cabin design, field maintenance, and production line design simulators; it also helped Ford and other automakers use VR to build design prototypes, a practice now widely adopted in the automotive industry. VPL had similar collaborations with train and ship design companies. "For the past 20 years, every commercial vehicle you have ridden in has used VR prototypes" [**?**]. VR is a future trend that allows people to engage in more endless exchanges and explorations between fantasy and wonderful times. VPL

Research was acquired by Sun Microsystems in 1999 and eventually became part of Oracle Corporation (which acquired Sun Microsystems for $7.4 billion in January 2010).

At the end of August 2021, ByteDance acquired Beijing Xiaoniao Kankan Technology Co., Ltd. (owner of the smart wearable device brand Pico) for 5 billion RMB, officially entering the VR market. Pico' s offline channels have spread across Beijing, Shanghai, Guangzhou, Shenzhen, Chengdu, Chongqing, and other cities. In addition to self-operated stores, sales methods include vending machines, distributors, and operators. ByteDance raised its 2022 VR sales target from 1 million units to approximately 1.8 million units. Pico provides ByteDance with a passport to the metaverse [**?**].

2.3 NVIDIA Demonstrates Ultra-Thin Holographic VR Device Prototype; Apple Launches Apple Vision Pro

2.3.1 NVIDIA Demonstrates Ultra-Thin Holographic VR Device In August 2022, NVIDIA, in collaboration with Stanford University, demonstrated an ultra-thin holographic VR device prototype weighing only 60 grams with a thickness of just 2.5 millimeters. In this design, users do not see two-dimensional planar images displayed on small screens in front of their eyes, but rather three-dimensional images reconstructed from respective holograms, bringing researchers one step closer to true three-dimensional VR displays.

2.3.2 Apple Releases "Apple Vision" In June 2023, Apple released its first MR (mixed reality) headset, "Apple Vision Pro," at its annual developer conference WWDC23. Its immersive audio-visual effects and real-time interactive experience in the metaverse world have attracted global attention, with the industry anticipating that Apple Vision Pro may once again trigger a major transformation in personal consumer electronics. Apple Vision Pro essentially functions as ordinary AR glasses, with 12 cameras and 3D depth sensors (including both structured light and time-of-flight types) installed at different positions on the device' s exterior. It first captures the external scene and then displays it on the screen, allowing users' eyes to clearly see the surrounding environment. Additionally, Apple Vision Pro features an extra EyeSight display on the outside of its main screen, showing virtual human eye images to outsiders, making the device appear somewhat like AR glasses with transparent lenses.

It is understood that "Apple Vision" has an independent battery pack and can be controlled through eyes, hands, and voice. Positioned primarily as an AR device, it can switch between augmented reality and full virtual reality using a dial. The device has no controller but allows operation by looking at application icons in the visionOS operating system; users can also click to select, flick to scroll, and issue voice commands. "Apple Vision"supports Bluetooth accessories, including keyboards and trackpads, allowing users to connect Mac computers for use within the headset.

2.4 Industrial Metaverse: A New Path for Integrating Physical and Digital Worlds

The industrial metaverse is "an industrial ecosystem where new information and communication technologies, represented by XR and digital twins, deeply integrate with the real industrial economy. Through technologies such as XR/AI/IoT/cloud computing/blockchain/digital twins, it achieves seamless connectivity among people, machines, objects, and systems, combines digital technology with real industry to promote efficient development of physical industry, and builds a new manufacturing and service system covering the entire industrial chain and value chain, representing a new stage of digital and intelligent development for industry and the broader economy" [**?**]. The industrial metaverse brings full-scenario and digital-real integration applications, gathers rich digital assets, greatly enhances industrial value creation, and will reconstruct the new ecosystem of digital industrial development.

The metaverse represents a fully immersive three-dimensional digital environment and a more inclusive cyberspace. With technological assistance, the metaverse will eventually become a shared online space spanning all representation dimensions. The manufacturing industry will also achieve deep integration with the metaverse. By organically integrating concepts such as CPS (cyber-physical systems), digital twins, and AR, VR, AI computer vision, and low-latency remote control triggered by 5G according to the metaverse concept, the "industrial metaverse" is constructed. For example, Zhejiang Geely Automobile Company has extensively used CPS in new car design, process development, and trial production verification, greatly shortening the new vehicle development cycle. "The industrial metaverse based on 'dark factories' (a new type of intelligent unmanned factory in intelligent society) and digital twins, CPS, AR, and VR will overturn the current economic and social structure, and different traditional industries will undergo 'butterfly transformation' and rebirth in the industrial metaverse (Le Xiaoli and Wu Zhengbin, 2021)" [**?**].

"Meanwhile, all decisions and results in the virtual and real worlds are recorded through blockchain, which is traceable and tamper-proof, serving as the basis for assessment and audit, creating imaginative space for building new compensation systems. A new generation of 'game-like' work methods with human-machine collaboration is thus born, with various skill competitions and innovation and development competitions becoming the best venues and methods for enterprises to select and employ personnel. The new generation of human resources market will shift from institutions to the metaverse (Le Xiaoli and Wu Zhengbin, 2021)" [**?**]. The industrial metaverse combines digital technology with real industry, representing a new stage of digital and intelligent development for industry and the broader economy, and an important driving force for future manufacturing transformation.

3. Industrial Metaverse Continuously Expands the Spatiotemporal Dimensions of Manufacturing Technology Innovation

In recent years, the continuous development of emerging technologies such as cloud computing, big data, artificial intelligence, and the Internet of Things, along with innovations in various business models in the digital economy era, has shown enterprise managers the tremendous energy of integrating business innovation with technology. The introduction of digital strategies in automotive enterprises will be a digital process running through the entire enterprise operation and product production. Autonomous driving powered by artificial intelligence will overturn the automotive driving method that has existed for over 130 years. The construction of intelligent manufacturing will achieve collaboration between humans and robots without isolation. Technologies such as virtual/augmented reality and 3D printing will also overturn product design, operation management, and personnel training methods. Digital transformation brings enterprises not only further efficiency improvements but also expanded capabilities in design, manufacturing, operation, and maintenance services.

3.1 Industrial Metaverse Continuously Expands the Spatiotemporal Dimensions of Technology Innovation

The industrial metaverse not only empowers manufacturing innovation and transformation in product, service, operation, and human resource fields but also helps expand the spatiotemporal dimensions of manufacturing technology innovation. In 2019, Johns Hopkins University in the United States successfully manufactured a prosthetic limb whose fingers could move with thought. Another project at the university involved creating a complete artificial arm that could be controlled by the brain. Currently, about a dozen types of prosthetic limbs have been put into application, but they also require surgery, with each prosthetic limb currently costing $500,000. However, Robert Armiger, the project manager for amputation research at the university, said: “The long-term goal of all this work is to find ways to control sophisticated robotic devices in a non-invasive manner, without additional surgery, and ‘without additional implants.’ ” If this non-invasive, surgery-free, and implant-free method is realized in the future, enabling direct brain control of sophisticated robotic (prosthetic) devices, it will be a major blessing for humanity.

The U.S. Defense Advanced Research Projects Agency (DARPA) is conducting a project whose program manager says attempts to “open a channel between the human brain and modern electronics”(brain-computer interface) by implanting a device in the human brain that converts brain activity into meaningful electronic signals. The agency will invest $62 million in this work as part of its Neural Engineering System Design program. Moreover, it is by no means the only organization engaged in such projects; several other public and private groups are exploring possible limits [**?**].

Since 2022, official policies across China have increasingly supported frontier technology industries such as virtual reality and the metaverse, with various regions successively introducing action plans to further drive industrial development. In October 2022, the Industrial Metaverse Collaborative Development Organization was formally established in Beijing. This organization will assemble an authoritative expert team, sort out the development path of the industrial metaverse, formulate top-level design and medium- to long-term development plans, and regularly release the *China Industrial Metaverse White Paper*. It will also build a core standard system for the industrial metaverse and gradually develop standards in key areas. On March 1, 2023, Minister of Industry and Information Technology Jin Zhuanglong stated at a press conference themed "Authoritative Departments Discuss the New Journey" held by the State Council Information Office: "We will layout future industries prospectively, research and formulate action plans for future industrial development, and accelerate the layout of frontier fields such as humanoid robots, the metaverse, and quantum technology." The industrial metaverse, integrating multiple digital technology functions, will become a new spatiotemporal dimension and path for manufacturing transformation and rebirth.

3.2 Industrial Metaverse: Machine Vision Virtual Measurement Achieves Quality and Efficiency Improvement

Gechuang Dongzhi Technology Co., Ltd. (referred to as Gechuang Dongzhi, whose "Dongzhi Industrial Application Intelligent Platform" is one of the 28 "dual-cross"industrial Internet platforms confirmed by China's Ministry of Industry and Information Technology in May 2022) is an industrial Internet platform company invested and founded by Guangdong TCL Group in 2018. Relying on TCL Group' s 40 years of manufacturing experience and large-scale group digital transformation practice, the company has accumulated core technical capabilities for multi-scenario manufacturing, mature scenario-based solutions, and built modular, replicable platform systems to promote manufacturing transformation and upgrading from point to surface. Its "Dongzhi Industrial Application Intelligent Platform" can establish industrial algorithm libraries and industrial model libraries based on industry experience and knowledge, packaged in the form of microservices within the industrial platform. aPaaS (application Platform as a Service) can also leverage the platform to form industrial APPs.

The company provides various end-to-end databases, such as the Equipment Health Management System (EHM) applied in digital factories and the machine vision "Dongzhi Tianshu." For example, in semiconductor production, during wafer grinding, inaccurate pressure control can lead to excessive wafer film thickness. Virtual measurement tools can establish relationships between film thickness and other parameters, guiding operators to adjust parameters to achieve ideal results. Virtual measurement tools enable true online measurement, boosting the development of the semiconductor industry. Currently, Gechuang Dongzhi has cooperated with hundreds of large and medium-sized

manufacturing enterprises to build smart manufacturing benchmarks, vertical industry platforms, and digital capability platforms, playing a role in more than 30 industries including semiconductors, electronic information, new energy, petrochemicals, automotive parts, steel, and pharmaceuticals [**?**].

4. Industrial Metaverse: Manufacturing Transformation and Upgrading Through Physical-Digital Integration

4.1 Machine Learning in the Metaverse Era Drives Enterprise Organizational Restructuring and Human Resource Management Innovation

4.1.1 Three Elements and Three Types of Machine Learning In the metaverse era, machine learning is one of the technologies that enable artificial intelligence. Machine learning involves repeated learning by several (dozens or more) supercomputers in the industrial Internet to discover patterns and features from samples. The three elements of machine learning are: information science, computer environment, and big data. "Information science" refers to deep learning algorithms for machine learning; "computer environment" refers to computer resources such as supercomputers or cloud computing technology; and "big data" refers to massive amounts of data prepared for machine learning purposes. Machine learning has multiple classification methods and can be divided into three categories: "supervised learning," "unsupervised learning," and "reinforcement learning." "Supervised learning" is machine learning that requires (standard or exemplary) sample correct answers; "unsupervised learning" is machine learning that does not provide standard answers ("semi-supervised learning" falls between these two); and "reinforcement learning" is a machine learning approach that repeatedly trials and errors on problems with unknown answers to find solutions, representing a form of machine learning close to artificial intelligence. Today' s highly successful digital technology model "neural network" is basically also classified as "supervised learning." The most famous AI technology "deep learning" (or "deep learning") has a hierarchical structure that also belongs to particularly deep levels of neural networks. "Neural network" uses digital technology models to represent neural networks in the human brain [**?**].

4.1.2 Machine Learning Boosts Enterprise Organizational Structure, Process, and Human Resource Management Innovation The application of artificial intelligence technologies such as machine learning in the metaverse era boosts enterprise organizational restructuring, process reengineering, and human resource management innovation, enhancing operational efficiency and competitiveness. Around 2000, Goldman Sachs had 600 traders at its headquarters alone with annual incomes exceeding $1 million. However, by using machine learning to master traders' methods and gradually shifting to computer-automated stock trading, only two traders remained by 2017. Currently, about one-third of Goldman Sachs employees—approximately 9,000 people—are computer engineers [**?**].

In the new era of the digital economy, Sany Group has formed a new organizational vision: achieving a leap in sales revenue from 170 billion yuan in 2021 to 300 billion yuan within five years; significantly adjusting personnel structure by reducing its nearly 30,000-strong industrial worker team at the end of 2020 to 3,000 people, while expanding its research and engineering team from less than 5,000 to 30,000 people; and completely transforming from a labor-intensive enterprise to a knowledge-intensive one. All employees become drivers of organizational change. At the group level, besides the chairman taking personal responsibility, a senior vice president is specifically appointed to directly lead digital strategy execution. An Intelligent Research Institute is established to oversee overall digital research. The status of the BPIT Department (Business Process and IT Department), an important driving force for digital transformation, is elevated in the enterprise, with a significant increase in digital talent. At the departmental level, the previously tightly coupled, centralized digital transformation authority is partially decentralized to business divisions and subsidiaries, allowing professional digital teams to penetrate every corner of the group with loose coupling. Each functional headquarters and business division is required to establish an intelligent headquarters and set up research centers responsible for digital transformation [**?**].

4.1.3 Machine Learning Expands the Instantaneous Space of Human Cognition In the industrial Internet, machine learning is achieved through data exchange among multiple supercomputers, endowing machines with human capabilities of cognition, communication, and learning. Simultaneously, through machine learning, the instantaneous space of human cognition is further expanded, strengthening human cognitive abilities. For example, aircraft engines flying in Europe and those flying in Middle Eastern sandstorms both transmit data to the industrial Internet. This way, an engine that has never been to the Middle East can also learn about the impact of weather on flight, and if it suddenly needs to fly to the Middle East one day, it can learn relevant meteorological and environmental knowledge from the network and adjust its operation accordingly. The more machines connected to the network and the more data stored, the stronger the machine' s learning ability becomes. The entire industrial Internet integrates the three major elements of "intelligent machines," "advanced analytics," and "people at work," systematically improving the manufacturing operation model [**?**].

4.1.4 Digital Employees and Digital Rotating CEOs Virtual digital humans, from a technical perspective, refer to virtual images created through convergent technologies such as computer graphics, speech synthesis, deep learning, brain-like science, and computational science, possessing multiple human characteristics (such as appearance, behavior, and even thoughts or values) [**?**].

Virtual digital humans have three important characteristics: First, they have human-like virtual images that require physical devices for presentation but are not physical objects themselves, which is the core difference from robots; second,

they possess unique character settings with their own personality and behavioral traits; and third, they have interactive capabilities, with future virtual digital humans being able to communicate, act, and express emotions freely. Virtual digital human is a general term, also known as virtual person or digital person, which can be further divided into virtual idols, digital employees, virtual anchors, etc., according to different application scenarios. The commercialization of virtual digital humans has entered the fast lane, and in practice, they can be classified into different types based on technology, application, and presentation methods. From a technical perspective, virtual digital humans can be divided into two major categories: human-driven and intelligent-driven. Human-driven types emphasize "human-machine coupling"and are currently a relatively mature field, while achieving fully intelligent-driven types requires a long-term development process. In terms of character building and operation of virtual digital humans, from comprehensive operation by professional digital human brokerage companies to OpenAI (a U.S. artificial intelligence non-profit organization) using ChatGPT chatbots, from Google' s AI large model Palm2 and Microsoft' s New Bing chat to the large model "Superhero" —XAgent jointly developed by Beijing Mianbi Intelligence Company and Tsinghua University, the business models and application scenarios of digital humans are also rapidly iterating.

At the end of 2022, OpenAI launched ChatGPT, triggering a global craze and accelerating the development of AIGC (Artificial Intelligence Generated Content) technology and applications, marking the entry of artificial intelligence into the popularization and application stage. As an important component of AI technology, AIGC plays an increasingly important role in the business society. Among many AIGC tools, GPT-based applications allow users to quickly generate applications and content through natural language, including low-code, RPA, and other tools that can also automatically generate programs needed by users with the help of GPT. Wang Wenjing, Chairman and CEO of Yonyou Network, believes: "Generative AI based on large models is the latest development trend in AI technology and applications. Large model research and training has become a trend in the global industry" [**?**].

Gartner Group (established in 1979, a U.S. information technology research and analysis company) predicts that by 2024, 40% of AI applications will be generative AI applications; by 2026, more than 100 million people will work with robot colleagues (generative AI) or have an AI assistant; and by 2027, nearly 15% of new applications will be automatically generated by AI without human involvement. The *China Artificial Intelligence Large Model Map Research Report* released by the New Generation AI Development Research Center of China' s Ministry of Science and Technology shows that "the number of large models developed in China ranks second globally, only after the United States, and currently 79 large models with more than 1 billion parameters have been released in China" [**?**].

Appointing Digital Humans as Company Rotating CEOs. NetDragon Websoft Inc. (stock code: 00777.HK on the Hong Kong Stock Exchange, head-

quartered in Fuzhou, Fujian Province) was established in 1999 and has been selected for the "Top 100 Chinese Internet Enterprises" list released by the Ministry of Industry and Information Technology for eight consecutive years. In 2020, NetDragon' s Edmodo was selected for UNESCO' s recommended remote teaching platform list. The 2022 financial report shows that NetDragon' s total operating revenue was 7.866 billion yuan, with a year-on-year growth process.

4.2 Siemens' IoT Operating System Merges Real and Digital Worlds

Siemens' IoT operating system, MindSphere, merges the real physical world with the digital virtual world. Utilizing powerful industrial applications and digital services through open communication standards, equipment, assets, and automation systems provided by other suppliers can also transmit data to MindSphere, ensuring that the same platform can be used by multiple suppliers and customers and enabling the combined application of various data analysis technologies. MindSphere provides a wide range of device and enterprise system connection protocol options, industrial applications, advanced analytics, and an innovative development environment that leverages Siemens' open Platform as a Service (PaaS) capabilities and Alibaba Cloud services.

"Currently, more than 8 billion devices are connected to the Internet worldwide, and this number will reach 1 trillion by 2030 (Lei Wanyun, Yao Jun, 2019)" [**?**]. Siemens' Riligent, dedicated to the transportation industry, is developed for the railway transportation industry to manage railway assets, improve asset availability and efficiency, reduce operational risks and costs, and improve maintainability. It includes functions such as remote monitoring, rapid diagnosis, and fault prediction and prevention for all vehicles and infrastructure. Its applications include: visualization of vehicle health status and location, component (gearbox, bearings, traction motors, doors, transformers, etc.) fault prediction, operational support, condition analysis, fault prediction, and railway network throughput analysis [**?**].

Siemens and HBIS Group established a comprehensive strategic partnership in October 2016, conducting extensive and in-depth cooperation in the digital field and establishing a joint laboratory. In June 2019, HBIS Group became the first steel enterprise in China to access Siemens' MindSphere industrial IoT as-a-service solution. Siemens MindSphere fully integrates with HBIS Digital' s IoT acquisition technology and 3D visualization technology to form an intelligent rolling mill solution, helping HBIS Hengban Company optimize rolling mill operation. With MindSphere, Hengban Company has established a digital twin of its rolling mill in the virtual world, capable of real-time collection of key parameters such as vibration, temperature, tension, and power consumption of bearings, motors, and other equipment during operation, and transmitting them to the MindSphere platform for analysis. Based on analysis results, Hengban Company can guide production with data, formulate better maintenance plans, and even predict potential failures. "Empowered by big data and cloud computing technology, enterprises reduce dependence on worker experience, achieve

scientific maintenance of rolling mills, improve production efficiency, product quality, and yield rate. After project completion, the yield rate exceeded 99%" [**?**].

4.3 Automotive Industry Digital Twin Solutions Help Optimize Design and Product Innovation

Siemens' overall solution for creating digital twins (Digital Twin) in the automotive field can reduce the number of prototypes required during new car development and predict the performance of production units and products themselves. Siemens Simcenter is a new platform developed for R&D digital twins, a flexible, open, and scalable simulation and testing solution portfolio that supports various innovation activities in enterprise digital transformation. Simcenter integrates system simulation, 3D CAE (Computer-Aided Engineering), and testing, helping enterprises predict the performance of all key attributes in the early stages and throughout the product lifecycle, and combines physics-based simulation with insights derived from data analysis to help optimize design and product innovation. The automotive industry digital twin solution ensures flexible production according to customer customization needs.

4.3.1 Three Aspects of Automotive Industry Digital Twins Siemens' digital twin solution in the automotive industry is an accurate virtual model of a vehicle or production facility, including three aspects: First, the product digital twin, which designs and simulates in a completely virtual environment; second, the production digital twin, which plans the entire production process in a fully virtual environment; and third, the "performance" digital twin (including production performance and product performance), where products and production facilities continuously input data, which is then analyzed in-depth in the cloud to achieve continuous optimization of the entire value chain.

4.3.2 Achieving Intelligent Decision-Making Throughout Product and Production Operation Lifecycle For example, at the BMW Group plant in Leipzig, Germany (BMW Group, headquartered in Munich, Germany, with automotive brands BMW, Rolls-Royce, and MINI), digital twins seamlessly integrate Automated Guided Vehicles (AGVs, also known as intelligent transport vehicles) into the BMW i3 production process. Through standardized SIMATIC (Totally Integrated Automation software) and drive components controlled by SIMOVE (Siemens' fully integrated automation programming software based on TIA Portal), production flexibility is maximized. In July 2020, Siemens Ltd., China was awarded the "Zhanlu Award" for industrial Internet—Technology Innovation Award jointly issued by Forbes and the World Artificial Intelligence Conference (WAIC 2020).

5. Industrial Metaverse: Remote Monitoring and Diagnostics in Physical-Digital Interaction

5.1 Remote Monitoring and Diagnostics Help Safe Production and Quality/Efficiency Improvement

One of GE' s main products, gas turbines, has more than 100 physical sensors and over 300 virtual sensors on each unit. Virtual sensors are software-simulated sensors created by algorithms to obtain data from locations in harsh environments where physical sensors cannot be placed. All massive amounts of data collected by these sensors are transmitted to a monitoring and diagnostics center in Atlanta, USA, where more than 50 engineers can analyze 35,000+ alerts annually, including gas turbine thermal performance, combustion chamber exhaust temperature, and rotor vibration amplitude. Currently, GE captures data daily from more than 1,500 gas turbines and generator sets worldwide. Data scientists have developed dozens of algorithms for massive data, currently capable of providing early warnings for more than 150 potential faults. In 2014, GE served power station customers from 58 countries, providing 8,000 amplitude limits and helping customers avoid more than 30 unplanned shutdown inspections. GE' s power station equipment operation and maintenance services are of very high value to customers. The transition from selling equipment to selling services is based on massive data brought by the industrial Internet.

Public data shows that GE has more than 3,500 gas turbines, over 20,000 wind turbines, more than 20,000 oil and gas equipment sets, over 20,000 commercial aircraft engines, more than 20,000 locomotives, and millions of medical devices worldwide, with total assets of approximately $1 trillion. These devices contain 10 million sensors and 50 million data elements [**?**].

5.2 Industrial Cloud Operating System: "Digital Twin" Empowers Efficiency Improvement

"Digital twin is the digital shadow of a physical product. Through integration with external sensors, it reflects all characteristics of an object from micro to macro, demonstrates the evolution process of the product lifecycle, and achieves seamless integration covering product design, production, and operation and maintenance (Sun Yanming et al., 2020)" [**?**]. GE' s Manufacturing Execution System (Proficy MES) can transform customers' manufacturing operations through data integration, industrial IoT (IIoT), machine learning, and predictive analytics insights and intelligence. By merging the digital world with the physical world of manufacturing, it provides overall performance management for connected enterprises. GE' s Operations Performance Management System (Predix OPM) is a complete local control-to-cloud analytics solution designed to manage variable processes and predict and improve product quality. Predix OPM uses machine learning and the latest analytics technologies to continuously improve processes, optimize production line and plant performance, reduce waste and costs, while increasing enterprise output, quality, and

efficiency.

GE can build "digital twins" of its products (such as jet engines) based on collected equipment operation field test data. Engineers can then simulate aircraft conditions when encountering cold weather, hot weather, dust storms, heavy rain, and even bird strikes, and conduct tests based on virtual scenarios. The company also monitors 10,000 wind turbines, whose digital twins help the turbines adapt to real-time environments. Data analysis suggests that it is better to let the front turbines run slower than engineers expected based on wind direction. "When the front turbines absorb less energy, the turbines behind can approach their optimal operating level, thereby increasing overall energy generation. This program shows that digital twin technology can be applied not only to individual products but also to comprehensively optimize the operation of entire wind farms. According to GE data, digital twins can increase wind farm output by 20% and generate $100 million in profit over the 100-megawatt lifecycle of a wind farm (Paul Daugherty, James Wilson, 2018)" [**?**].

6. Industrial Metaverse: A New Spatiotemporal Dimension for Manufacturing Digital-Intelligent Transformation

The industrial metaverse is the mutual integration of industrial physical reality, virtual reality, and augmented reality. It is mainly understood from three levels: First, the industrial material data layer, referring to the fact that industrial metaverse development cannot be separated from material data such as factories, machinery and equipment, raw materials, and energy in industrial production, which is highly related to concrete industrial production; second, the industrial technology layer, where the industrial metaverse continuously meets consumers' physical and psychological needs through ongoing technology R&D and product and service creation based on existing industrial material data, mainly including composite technology layers composed of VR/AR/MR and other extended reality technologies and digital twin technologies, with immersion and interactivity as its notable characteristics; third, the industrial interaction layer, where under the support of industrial material data layers and technology layers, a continuously maturing interaction layer is formed, with enterprise R&D, production, management, and service personnel simultaneously completing a series of social production and service activities in both physical and virtual worlds, and producers and consumers communicating, interacting, and co-creating value in both physical and virtual worlds.

6.1 Five Ministries Release Three-Year Action Plan with Building Industrial Metaverse and Empowering Manufacturing as Main Goals

In early September 2023, China' s Ministry of Industry and Information Technology, Ministry of Education, Ministry of Culture and Tourism, State-owned Assets Supervision and Administration Commission of the State Council, and National Radio and Television Administration jointly issued the *Metaverse In-*

dustry Innovation and Development Three-Year Action Plan (2023-2025) (MIIT Joint Science [2023] No. 49), with building the industrial metaverse and empowering manufacturing as main goals, driven by the integration and innovation of new-generation information technologies. The plan proposes 14 key tasks from five aspects: building advanced metaverse technology and industrial systems, cultivating three-dimensional interactive industrial metaverse, creating immersive digital life applications, building comprehensive industrial support, and building a safe and trustworthy industrial governance system.

6.1.1 Exploring and Promoting Metaverse Transformation of Key Industrial Processes Build industrial metaverse basic general model databases to create high-precision, interactive industrial virtual mapping spaces. Support manufacturing enterprises in building industrial metaverse simulation design and verification platforms, deploy production link applications, and improve design phase effectiveness and production phase efficiency. Actively explore new models of production line operation and maintenance and product inspection based on the metaverse, strengthen predictive maintenance, and improve operation and maintenance inspection efficiency and service quality. Create metaverse-based marketing platforms and virtual training systems to provide immersive sales and training environments.

6.1.2 Accelerating Industrial Metaverse Layout in Key Industries For discrete manufacturing industries such as home appliances, automobiles, ships, major technical equipment, and electronic information manufacturing, accelerate cross-industry collaboration based on the industrial metaverse. Build mechanism model libraries for key industries and develop personalized full lifecycle management systems for different products. For process manufacturing industries such as steel, textiles, and power, promote the application of industrial metaverse in key scenarios such as material formula optimization and process simulation, and strengthen predictive service capabilities such as process scheduling, material calculation, and material tracking.

6.1.3 Exploring Innovative Application Models of Industrial Metaverse Support the construction of industrial metaverse digital identity management platforms and build full-link trusted identification service systems. Accelerate the capitalization of regional industrial data elements, create industrial data asset service platforms, and explore mechanisms for industrial data rights confirmation, pricing, transaction, and circulation. Explore supply chain finance application models and carry out supply chain financial services around asset equipment and order data. Break down data barriers among all links of regional industrial chains and supply chains, and create three-dimensional, virtual-real integrated dynamic monitoring, early warning, operation, and decision-making.

6.2 System Composition and Application Scenarios of Industrial Metaverse

6.2.1 System Composition The industrial metaverse is mainly composed of five major systems, including technology system, standard system, product system, service system, and guarantee system. The technology system of the industrial metaverse is still in a stage of continuous evolution and development, "currently mainly composed of spatiotemporal engines + real-time rendering + large-scale modeling technologies, natural interaction technologies, blockchain technologies, network communication and computing power technologies, artificial intelligence technologies, IoT/sensing technologies, and digital twin technologies. Among them, hot technologies in the industrial metaverse include 5G, computing power networks, virtual reality/augmented reality technologies, digital twin technologies, artificial intelligence technologies, blockchain technologies, industrial metaverse platforms, and advanced computing" [**?**].

6.2.2 Application Scenarios From the perspective of the product full lifecycle, the industrial metaverse has achieved varying degrees of application in industrial R&D, production, management, sales, and training stages. From the perspective of industrial system levels, the industrial metaverse has achieved equipment-level, production line-level, factory-level, and industrial chain-level applications, significantly promoting enterprise quality improvement, cost reduction, and efficiency enhancement, as well as serving industrial chain governance and supply chain optimization.

6.3 Main Objectives of Industrial Metaverse Application

6.3.1 Strengthening Technology Reserves Focusing on the integrated application of new-generation information technologies, systematically sort out the current status of the industrial metaverse industrial chain in hardware facilities, basic software, virtual platforms, content production, and industry applications. Study the long-term development of industrial metaverse scientific and technological innovation, target shortcomings in key breakthroughs and integrated applications, expand existing strengths, formulate and deploy strategic plans for metaverse-related technology 攻关, and implement a number of key projects in a targeted and step-by-step manner.

6.3.2 Accelerating Standard Development "Relying on existing standardization organizations for blockchain, artificial intelligence, AR/VR, brain-computer interfaces, and graphics and images, coordinate domestic standardization forces, accelerate research on industrial metaverse standardization roadmaps, and build standard systems. Focus on standardization needs such as industrial metaverse technical architecture, system integration and interoperability, and data asset exchange, and carry out the development of key standards in basic, technical, and application categories" [**?**]. Simultaneously, track foreign standard dynamics in the metaverse field in real-time and ensure

good communication and connection with foreign standards.

6.3.3 Cultivating Application Scenarios Focus on channels such as R&D design, production assembly, remote collaboration, sales, and training in industry, as well as subdivided fields such as industrial culture digital collections and digital humans, to promote industrial metaverse innovation. Rely on manufacturing transformation and digital China construction to promote the application of industrial metaverse in large-scale scenarios such as industrial manufacturing, metallurgy, agriculture and forestry, ports, mines, aerospace, energy, transportation, and underwater engineering, enhancing the depth of industrial metaverse application. Drive the development of the industrial metaverse through the pull of scenario applications to achieve the goals of digital transformation and quality and efficiency improvement, and promote the realization of China' s manufacturing powerhouse and intelligent manufacturing goals.

6.3.4 Building Industrial Ecology Build an open, competitive, green, innovative, and sustainable industrial metaverse industrial ecology, strengthen the industrial metaverse system operation service industry, and significantly enhance the resilience of industrial chains and supply chains. Establish industrial metaverse enabling innovation centers in key industrial cities to form a number of influential and distinctive industrial metaverse industry clusters.

6.4 Industrial Metaverse: Helping Optimize Industrial Product Design

6.4.1 Industrial Product Virtualization Reaches Manufacturable Levels In the industrial field, the virtualization of industrial products will reach levels that can be actually produced. In reality, enterprises are often divided by function into designers, process engineers, workshop process engineers, workshop production workers, team leaders, and dispatchers. Designers often consider relatively less in terms of process and production, leading to problems during the transition from design to production. In the metaverse era, "the industrial metaverse will create conditions for improving virtualization levels, such as domestic industrial software being more cost-effective, enabling the popularization of three-dimensional design (CAD), computer-aided manufacturing (CAM), and computer-aided engineering (CAE, simulation analysis)" [**?**]. When conducting virtual simulation analysis, it is necessary to consider not only the enterprise' s own level but also the level of world peers and customer needs to establish a leading position. Achieving such a level of virtual industrial products can significantly improve first-time manufacturing success rates, making products more competitive in the market.

6.4.2 Virtual-Real Integrated Industrial Products Industrial products are not just a single piece of equipment but also include spare parts, installation and commissioning, and maintenance services. On the basis of the Internet of

Things, industrial Internet, and 5G mobile networks, industrial products will become more intelligent and smart. Industrial product manuals have evolved from early manuals (including text and two-dimensional diagrams) to three-dimensional disassembly and installation explosion diagrams, then to providing QR codes for viewing disassembly and installation videos, and even to VR and AR-based application and maintenance training. With the arrival of the metaverse era, the capabilities of industrial products will be greatly enhanced, such as industrial machine tool equipment, robotic arms, and robots. Machine tool equipment can introduce visual recognition technology and apply artificial intelligence to quickly achieve part clamping; "rice transplanting robots can automatically plan routes and automatically lift transplanting platforms after setting, automatically bypassing obstacles such as trees and power poles; a plant protection drone spraying pesticides can operate 50-80 acres per hour, with efficiency 40-60 times that of manual labor, while saving 50% of pesticide usage and 90% of water usage" [**?**]. Industrial products in the metaverse era can not only operate at the front end but also have near-end support from big data, artificial intelligence, and computing power, remote personnel support, control, operation, and management, and even data, knowledge, and intelligent iterative upgrades based on the overall Internet ecosystem.

6.4.3 More Aesthetic and Humanized Industrial Products Traditional industrial products give people a cold feeling, but entering the metaverse era, whether consumer-facing products such as mobile phones, refrigerators, color TVs, and automobiles, or professionally applied machine tool equipment and construction machinery, will pay more attention to human feelings and experiences. In terms of product application, they will also combine human capabilities, behaviors, and psychology to make products more aligned with human needs.

Industrial design is based on aesthetics, involving psychology, sociology, ergonomics, etc., and is a cross-product of various disciplines, technologies, and aesthetic concepts. On the basis of meeting industrial product functional requirements, through reasonable materials, structures, processing, and decoration, products are given new visual quality, conforming to contemporary trends, coordinating application scenarios, and providing people with aesthetic enjoyment.

6.5 Industrial Metaverse Applied in Many Scenarios of Industrial Manufacturing Process

Traditional industrial manufacturing processes include design, production, sales, and application, but in the metaverse era, marketing becomes more important, so personalized production and order-based production will occupy an increasing proportion. Supply chain collaborative manufacturing, regional collaborative manufacturing, remote manufacturing, and even cross-border manufacturing and cloud manufacturing based on the Internet will become trends.

Entering the metaverse era, industrial product information will undergo tremendous changes, from informatization to digitalization, meaning information becomes more precise, from qualitative to quantitative. The completeness, timeliness, and real-time nature of information will also be greatly improved. Due to enhanced network capabilities, producers can establish stronger communication scenarios and better communication models with customers and consumers, thereby achieving better communication effects. For example, what was previously transmitted were two-dimensional drawings, while what will be transmitted in the future may be three-dimensional models; motion models can be transmitted to express product functions; simulation models can be transmitted to express product stiffness and strength. During the manufacturing process, customers and consumers can grasp production progress in real-time; producers can quickly resolve problems when they arise to avoid larger-scale losses; and if there are new ideas, they can be implemented promptly. In the product application stage, technologies such as the Internet, IoT, and mobile networks can be used to achieve real-time remote simulation, control, and maintenance from digital twins to cyber-physical systems.

6.5.1 New Marketing Models When customers purchase products, the core is to meet certain needs. However, customer needs are often not definite, requiring communication between supply and demand parties. Communication content includes not only product information but also enterprise production capacity, management level, price, and cost. "For example, when CSR Ziyang Locomotive Company participated in a U.S. project bid, it addressed local defects in existing products raised by the U.S. side by modeling based on provided product drawings, conducting simulation analysis using finite element software, and re-optimizing product design, ultimately winning the order" [**?**]. In the metaverse era, communication with customers, production process control, and industrial product application services increasingly need to shift online. Therefore, industrial enterprises need to actively consider how to use virtualization technology to better showcase products, production capacity, and guarantee capabilities to meet customer needs and win development opportunities for enterprises.

6.5.2 Design Model Innovation Industrial products are often relatively complex, involving multiple fields, so product design is a complex process that can be called an open complex giant system. Typical examples are personalized products and customer-customized products—not all components need customization, and customers cannot do whatever they want but must conform to a process of external diversity and internal standardization, comprehensively considering product delivery time, quality, cost, and service convenience.

Industrial product design is also a process. In the metaverse era, more emphasis is placed on individual creativity, including not only customer and consumer needs but also ideas from middle and senior management and ordinary employees, gradually transforming from uncertainty to certainty. The virtualization

stage includes sketches, two-dimensional drawings, three-dimensional models, analysis models, and processing models. Entering actual production also often requires a process, as general enterprises will have prototype products, preliminary design products, and finalized products.

Communication and collaboration are ubiquitous throughout the entire design process, typically including collaboration between designers, process personnel, and warehouse logistics personnel, collaboration between enterprise personnel and related supply chains, and collaboration between enterprise personnel and customers, consumers, and even management agencies. These collaborative scenarios all require improved information content. In terms of digital technology, there is a need for deepened application of software for three-dimensional design, assembly models, industrial styling, simulation analysis, and optimization design. Physically, there is a need to use camera cloud arrays, advanced network technology equipment, and large-screen display equipment to better display, interact, and experience to achieve better product design.

6.5.3 From Intelligent Manufacturing to Smart Manufacturing The manufacturing process in the usual sense is a process of material change, including physical changes such as cutting, extrusion, boring, milling, and grinding, chemical changes such as synthetic pharmaceuticals, and transportation changes in geographical location. In the information age, these change processes will also include information changes. At the same time, the manufacturing process is also a human operation process. Although some work currently has no human involvement, such as fully automated factories and dark factories, this model is suitable for the internally standardized parts of industrial products, not complete products. As a complete industrial product, human-machine integration is needed. Germany' s Industry 4.0 emphasizes the datafication and intelligentization of supply, manufacturing, and sales information in production to achieve interconnection, reduce information asymmetry, and accelerate and strengthen connections and feedback among all parties, thereby achieving fast, effective, and personalized product supply.

In the metaverse era, smart manufacturing is an upgrade of intelligent manufacturing, emphasizing those hidden problems or problems that need improvement, emphasizing the macro rather than the micro, the qualitative rather than the quantitative, and experience rather than logic. Only by combining humans with intelligent equipment can truly satisfactory industrial products with high economic value be produced. Typical applications of metaverse concepts and technologies include: simulating the overall production process of the workshop before product production; wearing VR glasses to install complex parts under system guidance; enterprise production personnel better monitoring the status of production equipment; quickly solving problems in the production process; overseas customers remotely grasping the status of the production process to ensure products meet quality requirements; and enterprises improving and optimizing production lines, production processes, and industrial products.

6.6 Pain Points in Digital-Intelligent Transformation Are Opportunities

The industrial metaverse will provide the manufacturing industry with a completely new path for digital transformation. The necessary path for the industrial metaverse to boost manufacturing transformation is precisely the digital twin platform.

There are still many pain points in the application of digital twin technology in manufacturing: First, although enterprises possess massive amounts of GIS/BIM/OSGB (Geographic Information System/Building Information Modeling/3D model data format) and other spatiotemporal data, their value cannot be truly realized; data must not only be lightweight and structured but also integrate multi-source data, yet the technical threshold and cost for implementation remain high. Second, application development varies greatly across different industries, client needs frequently change, making it difficult to independently conduct secondary development and editing to quickly respond, integrate business, and deliver. Third, freely conducting the full-process development of digital twin applications requires professional talent. Fourth, digital twin technology systems require certain capital investment.

New pain points are new opportunities. These need to be addressed through digital twin PaaS platforms—through open source, sufficient automation, and low-code, making expensive technology accessible to the masses, allowing development teams or individuals without any graphics technology background to quickly apply it and effectively lower the threshold. Digital twins cannot be understood merely as visualization; "visualization" is only the appearance, while the essence is the interaction and integration between the digital virtual world and the physical real world: measuring, monitoring, or changing the real world with low latency through the digital world, while the dynamic real world is instantaneously mapped to the digital world. Currently, the application of digital twins is becoming increasingly popular. For example, in the port industry, through real-time driving of dynamic data, under digital twin full-element scenarios, it is possible to cover full-cycle operation simulation from cargo arrival, loading and unloading, transfer, warehousing, to departure; under 5G environmental perception of the full amount of industrial equipment in the port, it can also achieve digital twin full simulation of people, vehicles, objects, methods, and environment, etc. Digital twins are an indispensable step for digital transformation in manufacturing, logistics, service, and other industries.

Shenzhen Chuangwei-RGB Electronics Group Co., Ltd. (referred to as Chuangwei) cooperated with China Telecom to carry out the "5G+8K Flexible Smart Factory" project, achieving application of virtual on-site service scenarios. Using self-developed Chuangwei 8K VR all-in-one devices perfectly integrated with 5G, it forms an overall "cloud-pipe-end" solution. On-site operation and maintenance personnel wear Chuangwei 8K VR all-in-one devices and obtain visual guidance help based on information projected in front of their field of view.

When information assistance cannot solve problems, remote expert support is activated, and experts can clearly understand the on-site situation from a first-person perspective and provide real-time feedback to the VR glasses. The system can dynamically track suspected fault points, facilitating operation and maintenance personnel to quickly locate fault positions of production equipment. By recording suspected fault points, it automatically generates a review checklist for production equipment, achieving key point review and confirmation of the production equipment maintenance process. Through the application of this technology, Chuangwei' s on-site service efficiency has increased fivefold, color TV single-line production capacity has increased by 17.64%, first-line quality inspection staff has been reduced by 40%, and exports have increased by 71.25% [**?**].

6.7 Replicating the Real World in the Digital World to Achieve Intelligent, Humanized, and Crowdsourced Innovative Management

In the industrial metaverse era, building smart (intelligent) factories through technologies such as industrial IoT, cloud computing, big data, artificial intelligence, and digital twins is an important way to accelerate digital transformation in manufacturing enterprises. For traditional manufacturing SMEs transforming to smart factories, they can choose to take the opportunity of centralized operation scheduling control, promote co-located office scheduling, achieve intelligent control and efficient collaboration, and strongly support scheduling system reform. Through digital twin technology and combined with visualization presentation capabilities, the factory' s production and sales integration management system goes online, helping the factory promote the "five departments in one" centralized control model for manufacturing, equipment, energy and environment, transportation, and security. Through smart factory project transformation, it helps achieve preliminary intelligence in five major theme scenarios: manufacturing control, equipment control, transportation control, energy and environment control, and security control.

6.7.1 Three-Dimensional Modeling for Production Management and Inspection Management Through full-stack three-dimensional visualization technology for fine modeling, the entire factory environment is created, from the park, workshop, production line, to equipment-level visibility, restoring factory workshop layouts, production equipment models, and production processes, and displaying the spatial positions of various types of equipment, clearly and completely showing the entire factory environment. At the same time, the overall production process is simulated and displayed according to the actual process flow from raw material entry to finished product exit (including inspection), showing key equipment actions, material flow directions, and production process smoothness; integrated with process flow systems, the status of process flows is simulated in real-time based on 3D scenes, such as normal, fault, and congestion. The system simulates and displays material and AGV (intelligent transport) vehicle aggregation, allowing users to adjust

specific process flow parameters to simulate process changes, debug optimal production plans, discover hidden production line problems, and improve actual production line work efficiency.

Based on the digital twin environment, a factory twin visualization environment can be built, allowing flexible planning of inspection operations as needed, supporting both active and passive inspection methods. Managers can view the completion status of inspection work and personnel positions in the park in real-time, or use robot technology to simulate virtual inspections, greatly improving implementation efficiency and later maintainability.

6.7.2 Building Business Decision Models to Help Enterprise Digital Operation Smart factories built based on digital twin technology can intuitively reproduce factory buildings and various management elements with precision, and based on 全域 data information, establish a series of business decision models that can assess current status, diagnose past problems, and predict future trends, providing comprehensive and precise scientific basis for business decisions. Smart factories built based on digital twin technology achieve full-element digitalization and virtualization of factories, real-time and visualization of production management, and collaborative and intelligent equipment operation and maintenance, helping manufacturing enterprises achieve digital operation.

6.7.3 3D Visualization and Intelligence in Warehouse Management Based on digital twin technology and guided by the concepts of intelligence, networking, integration, and visualization, warehouse management achieves hierarchical visibility of warehouses, storage areas, tanks, shelves, and equipment. Focusing on warehouse monitoring, it integrates video monitoring, inbound and outbound management, inventory counting, alarms, and other management systems to build a 3D visualization platform integrating warehouse management monitoring, early warning, diagnosis, and analysis. Through a one-stop digital twin visualization management platform, the real physical world is "replicated" in the digital world for simulation, monitoring, analysis, and control, achieving a visualization, intelligent, humanized, and crowdsourced innovative management model.

7. Improving Top-Level Design and Scenario Demonstrations to Promote Collaborative Agglomeration Ecology and Technology 攻关

On June 1, 2023, the *Opinions of the Guangdong Provincial Committee of the Communist Party of China and the People' s Government of Guangdong Province on High-Quality Construction of a Manufacturing Province* (referred to as the "22 Manufacturing Leadership Articles") were released, proposing the guiding ideology of "deepening supply-side structural reform, taking the real economy as the foundation, adhering to manufacturing leadership, taking

innovation as the core driving force for high-quality development, accelerating the advancement of new industrialization, focusing on implementing the 'Five Major Enhancement Actions' of large industries, large platforms, large projects, large enterprises, and large environments, promoting high-end, intelligent, and green development of manufacturing, ensuring the independent controllability and safety and reliability of key manufacturing industry chains, and accelerating the leap from a large manufacturing province to a strong manufacturing province." By 2027, Guangdong' s manufacturing added value will account for more than 35% of regional GDP, manufacturing and producer services added value will account for 65%, high-tech manufacturing added value will account for 33% of industrial added value above designated size, more than 10 strategic industrial clusters with output value exceeding one trillion yuan will be cultivated, more than 10 manufacturing enterprises will enter the Fortune Global 500, manufacturing innovation capabilities will be significantly enhanced, scale and efficiency will improve simultaneously, and a number of leading enterprises and industrial clusters with strong international competitiveness will initially take shape, with their status in the global industrial division of labor and value chain significantly improved. The "22 Manufacturing Leadership Articles" represent the planning and design for Guangdong' s manufacturing development strategic goals for 2035.

7.1 Improving Top-Level Design and Comprehensive Scenario Demonstrations

7.1.1 Improving Top-Level Design and Strengthening Overall Coordination First, improve the promotion system. It is recommended that provincial-level industry and information technology and science and technology management departments focus on "implementing the 'Five Major Enhancement Actions' of large industries, large platforms, large projects, large enterprises, and large environments to promote high-end, intelligent, and green development of manufacturing," and carry out industrial metaverse planning work. Coordinate various departments, strengthen synergy among industrial, innovation, fiscal, financial, and regional policies, and jointly promote metaverse technology 攻关, standard formulation, and governance system construction. Optimize industrial layout and promote metaverse technology innovation and industrial development according to local conditions. Research and formulate implementation plans for the industrial metaverse in manufacturing, considering incorporating the industrial metaverse into the digital overall reform—digital economy system.

Second, advance research and formulation of laws, regulations, and standards. Encourage industry universities, research institutes, enterprise teams, and think tank experts to establish an industrial metaverse alliance, focusing on research on the application of industrial metaverse in manufacturing digital transformation and industrial asset ownership. Plan metaverse supervision regulations, focus on key issues such as technology enterprise monopoly, and improve the regulatory policy and standard system for promoting high-quality manufactur-

ing development.

Third, explore an innovation-encouraging policy environment. Learn from the venture capital models of Beijing, Shanghai, and Shenzhen, and recommend that relevant government departments fully connect and establish an industrial metaverse development fund. Establish and improve an inclusive, prudent, and flexible market access and regulatory environment.

Fourth, accelerate the digital transformation of manufacturing industrial chains and promote digital transformation of SMEs. Deeply implement the "Finance + High-End Manufacturing" project to improve the effectiveness of financial services for the real economy.

7.1.2 Building Comprehensive Scenario Demonstrations First, support the construction and optimization of urban "industrial brains," explore industrial metaverse scenario exploration and mining, support the establishment of "scenario innovation promotion centers" with third-party institutions, and form a number of replicable and promotable experience practices.

Second, support enterprise innovation and exploration. Encourage numerous digital enterprises such as Alibaba, Baidu, Tencent, Huawei, Inspur, and Dongtu Technology to jointly carry out industrial metaverse solution research with manufacturing enterprises, conduct scenario trial practices, and strive to form a number of solutions in key industries such as steel, ships, marine engineering, new energy, automobiles, construction machinery, home appliances, textiles, and food processing.

Third, actively layout industrial metaverse infrastructure, further promote new infrastructure construction such as 5G, industrial Internet, and industrial IoT, and select pilot parks to layout AI industrial blockchain facilities.

7.1.3 Building Collaborative Agglomeration Ecology First, create characteristic metaverse industrial parks, support future (high-end) industry pilot zones and new industry platforms as carriers to gather a number of industrial metaverse upstream and downstream enterprises.

Second, strengthen regional collaboration, support the construction of a number of cross-regional joint laboratories and key common technology platforms.

Third, actively hold competitions, seminars, and exhibitions in the industrial metaverse field to gather domestic and foreign expert talents and project resources, and take the lead in forming an industrial metaverse brand nationwide.

7.1.4 Building a Technology 攻关 System First, research and establish industrial metaverse science and technology special projects, support existing provincial key R&D plans to expand industrial metaverse-related technology special projects, and focus on formulating support policies for key technologies

such as 3D virtualization modeling and production tools, AI blockchain, and 6G high-speed communication.

Second, encourage joint technology 攻关. Since the industrial metaverse is a systematic project, encourage different universities, colleges, and enterprise teams to form industrial innovation consortia to carry out joint integrated technology 攻关.

Third, build a number of industrial metaverse research institutions, learn from the construction experience of future industry research institutes in developed countries, integrate regional new R&D institution construction models, and encourage the establishment of interdisciplinary, large-scale collaboration, and high-intensity industrial metaverse collaborative innovation basic platforms.

7.2 Building a Metaverse-Centered Industrial Chain to Seize Opportunities in International Competition

We should adhere to innovation-driven development, release the integrated innovation momentum of the metaverse, and drive the cross-border integrated development of related technologies. We should focus on both making up for shortcomings and strengthening longboards, accelerate breakthroughs in key core metaverse technologies, and promote the industry to accelerate its march toward high-end development. We should adhere to scenario traction, explore metaverse application scenarios, drive the landing and application of metaverse technology and products through scenario construction, and form a high-level development situation where demand drives supply and supply creates demand. We should adhere to integration and mutual promotion, grasp the virtual-real integration characteristics of the metaverse, build a virtual mapping of the physical world, stimulate the enabling, superimposing, and multiplying effects of digital technology, and enhance productivity in both digital and physical spaces. We should adhere to safety and reliability, coordinate development and security, strengthen policy guidance and standard leadership, promote the construction of metaverse governance systems, consolidate industrial foundations, enhance the resilience of industrial chains and supply chains, and improve security capabilities. We should adhere to open collaboration, deepen international exchanges and cooperation, actively participate in international governance, achieve mutual benefit and win-win results, strengthen industry-university-research-application collaboration, effectively allocate resources, and promote the deep integration of innovation chains, industrial chains, capital chains, and talent chains.

7.2.1 The U.S., Japan, EU, etc., Are Actively Developing the Metaverse Industry Looking globally, in March 2021, the listing of the first metaverse concept stock Roblox attracted market attention to the metaverse concept. In October 2021, Facebook announced its official transformation and name change to Meta, opening an important chapter in the metaverse, with major enterprises entering the metaverse one after another. The U.S. military

has formulated metaverse plans, and enterprises represented by Google, Meta, NVIDIA, and Tesla have begun layout in B-end scenarios such as industrial design. In early 2021, BMW and NVIDIA used digital twin technology for online testing, improving planning phase efficiency by about 30% and achieving one vehicle every 56 seconds in the vehicle manufacturing phase. In August 2021, Tesla began building digital scenarios to simulate real camera data and conduct AI simulation testing and fitting. Additionally, in 2021, South Korea established the "Metaverse Alliance" and held related activities; Japan released a virtual reality plan in July 2021, striving to make achievements in industrial virtual modeling; the EU focuses more on regulation and rule issues in the metaverse world.

Microsoft acquired gaming giant Blizzard Entertainment (headquartered in California, USA) for $68.7 billion in January 2021 to layout the metaverse. NVIDIA (NASDAQ: NVDA, an artificial intelligence computing company founded in 1993 and headquartered in California, USA) not only provides developers with software for drawing virtual worlds but also provides the computing power needed to build virtual worlds. In 2021, it officially launched the Omniverse platform for virtual collaboration and simulation building, positioned as the "engineer's metaverse." This is a set of tools to help software developers build three-dimensional virtual worlds, using more computing power from NVIDIA chips in the process. In the domestic market, Tencent has also proposed the concept of "true Internet," highlighting four key technical points of the virtual-real integrated world: reality virtualization, virtual realizations, holographic Internet, and intelligent executors. As one of the important pillars of the metaverse, blockchain plays an important role in ensuring the security and sustainability of the metaverse. DeFi (Decentralized Finance) has built a foundation for economic activities in the metaverse.

In September 2021, there were already more than 500 listed companies worldwide involved in metaverse business. Some international consulting firms predict that the economic scale of the metaverse will reach $800 billion to $1.5 trillion in 2024. According to the *2023 China Metaverse Industry Market Prospects and Investment Research Report*, China' s metaverse market size is expected to maintain a continuous growth trend from 2022 to 2027, reaching 126.35 billion yuan by 2027. "In October 2022, the *China Metaverse Development Report (2022)* released at the 2022 China International Fair for Trade in Services Web 3.0 Development Trend Summit Forum shows that the output value of China' s metaverse upstream and downstream industries exceeds 400 billion yuan" [**?**]. Enterprises laying out the metaverse include various types such as technology development, investment, education, logistics, and healthcare, covering capital supply and scenario design required by the metaverse, continuously spreading and extending to form a multi-field integration situation, rapidly building an industrial chain centered on the metaverse. Currently, international competition regarding the metaverse has begun, mainly concentrated in fields such as talent, technology, financing, and market.

7.2.2 Over 10 Cities Including Shanghai Formulate "Metaverse" Key Technology 攻关 Action Plans In May 2022, Hangzhou' s first "Metaverse" industry-university-research alliance was formally established and held the Qiantang Metaverse New World opening ceremony. The alliance was initiated by universities such as Zhejiang University, Zhejiang Gongshang University, Southeast University, Xidian University, Hangzhou Dianzi University, Zhejiang Sci-Tech University, China Jiliang University, and Zhejiang University of Media and Communications. The alliance will give full play to the advantages of metaverse-related disciplines and majors in various universities, encourage research team personnel to actively participate in industry-university-research-application cooperation research on new business forms such as the metaverse, inject university talent wisdom into the metaverse industry, and help high-quality development of the digital economy. In the future, it will focus on metaverse core underlying technologies such as digital twins, artificial intelligence, and virtual digital humans, as well as new metaverse application scenarios such as games, social networking, and education, and introduce and cultivate a number of innovative SMEs.

On June 21, 2022, the Shanghai Municipal Government executive meeting studied and approved in principle the green and low-carbon, metaverse, and smart terminal development action plans. The action plans pointed out the need to seize opportunities, grasp industrial trends and directions, and promote the growth and strengthening of high-tech, high-growth SMEs. It also emphasized promoting the deep integration of technology, products, and applications to foster industrial cluster development. In June 2023, the *Shanghai "Metaverse" Key Technology 攻关 Action Plan (2023-2025)* was officially issued, injecting strong momentum into metaverse key technology 攻关 [**?**].

Meanwhile, breakthroughs such as large models represented by ChatGPT and MR immersive devices represented by Apple Vision Pro are also catalyzing tremendous changes in the metaverse. An Alibaba subsidiary led the angel round investment in AR glasses company Beijing Zhi Jing Wei Lai Technology in July 2023, and in August 2023, Alibaba's Hangzhou Haoxing Enterprise Management Partnership (Limited Partnership) invested in Singularity Technology (Shanghai) Co., Ltd. Singularity Technology is a scientific and technological innovation startup enterprise focusing on all-weather smart glasses as its core direction. Wu Dezhou, founder of Zhi Jing Wei Lai Technology and Singularity Technology, previously served as General Manager of Huawei Honor Product Line and President of ByteDance' s New Stone Laboratory [**?**].

MultiMetaVerse (referred to as "Metaverse Holdings"), the substantive holding company of Shanghai Jupiter Creative Design Co., Ltd. from Shanghai, successfully went public on NASDAQ through a SPAC (Special Purpose Acquisition Company, Model Performance Acquisition) on January 5, 2023 (stock code: MMV). Metaverse Holdings (MMV) is an animation entertainment company dedicated to building an open community of anime viewers, gamers, and content creators for its global users through original content, user-generated

content, and professional user-generated content. "According to Metaverse Holdings' prospectus, the total consideration for the acquisition and merger is $300 million, paid in the form of 30 million newly issued common shares at $10.00 per share" [**?**].

7.2.3 Summer Davos Forum Lists Metaverse in 2023 Top Ten Emerging Technologies Report The 14th Annual Meeting of the New Champions of the World Economic Forum (also known as the Summer Davos Forum) held in Tianjin from June 27-29, 2023, released the *2023 Top Ten Emerging Technologies Report*, among which three emerging technologies—generative artificial intelligence, metaverse for mental health improvement, and flexible neuroelectronics —are all related to the metaverse [**?**]. First, generative artificial intelligence (AIGC): this new type of AI attracted public attention due to the release of ChatGPT by OpenAI (U.S. AI research company) at the end of 2022; generative AI will trigger disruptive changes in multiple industries such as education and research. Second, metaverse for mental health improvement: the future metaverse, combined with next-generation wearable devices that can provide users with touch or respond to users' emotional states, can become a good remedy for improving mental health. Third, flexible neuroelectronics: brain-computer interfaces enable direct communication between the brain and external computers, with potential to change human health conditions in medicine and neuroscience fields, such as treatment for epilepsy, depression, or paralysis. Breakthroughs have emerged in flexible electronics and more biocompatible materials, meaning patients can have less invasive and more comfortable experiences.

7.2.4 The Relationship Between Generative AI (AIGC) and the Metaverse Yu Yi (2023), Global Vice President of Accenture and President of Accenture' s Enterprise Technology Innovation Business Division in Greater China, believes that AI technology is bringing us entirely new perspectives and possibilities, and this technology will also be a key point for future productivity efficiency improvement. The diffusion and evolution of technology have a process, which may not be a simple unidirectional curve as we think, but may even be nonlinear changes. For blockchain, cloud computing, metaverse, and even generative AI, I am more inclined to view them as changes brought about by combinatorial technological innovation. It is not an either/or relationship but a mutual integration. For example, in the metaverse, it also needs the capabilities provided by generative AI; at a more fundamental technical level, the metaverse definitely also needs computing power support based on cloud computing. "Cloud computing, metaverse, and artificial intelligence, these three key technology trends will define the next decade and drive the integration and interweaving of the real world and the digital world. This round of generative AI technology breakthroughs will have far-reaching impacts. Enterprises need to take immediate action to make large-scale investments in data, talent, and customized basic models to meet enterprise needs and realize technology value" [**?**].

Currently, enterprises are facing comprehensive business reshaping, and business logic is undergoing significant changes. The source of the last wave of digital dividends was changes in business models, while the next wave of dividends we will embrace will be new improvements in overall efficiency with the help of AI. To promote the healthy development and standardized application of generative AI, safeguard national security and social public interests, and protect the legitimate rights and interests of citizens, legal persons, and other organizations, the Cyberspace Administration of China, together with the National Development and Reform Commission, Ministry of Education, Ministry of Science and Technology, Ministry of Industry and Information Technology, Ministry of Public Security, and National Radio and Television Administration, announced the *Interim Measures for the Management of Generative AI Services* on July 13, 2023 [**?**], which came into effect on August 15, 2023. The Measures propose that the state adheres to the principle of balancing development and security, and combining promotion of innovation and law-based governance, taking effective measures to encourage the innovative development of generative AI, implementing inclusive and prudent and classified and graded supervision of generative AI services, clarifying overall requirements for providing and using generative AI services, proposing specific measures to promote the development of generative AI technology, clarifying requirements for training data processing activities and data annotation, and also stipulating systems such as security assessment, algorithm filing, and complaint reporting, and clarifying legal responsibilities.

Sam Altman, CEO of OpenAI, stated in Bill Gates' podcast "Unconfuse Me" in January 2024 that "AI will trigger the 'fastest' technological revolution in human history." Bill Gates also believes that "AI will force us humans to adapt to this change at an unprecedented speed."Altman said: "I think technology will rapidly develop toward systems with 100,000 or 1 million times the computing power of GPT-4." "Every technological revolution has become faster, and this will be the fastest by far. The labor market will change rapidly due to AI, but many people are not prepared." "Large models will be able to process data from multiple media such as text, images, and video. OpenAI has already released functions supporting image and audio input and output, with responses more enthusiastic than expected" [**?**].

8. Conclusion

The virtual world in the sense of the metaverse is a three-dimensional, interactive, ubiquitous, and eternally online ontological existence. It is in this sense that the emergence of the metaverse (whether already emerged or yet to emerge) is a major event for humanity, because it signifies the arrival of a new world. In this new world, individuals achieve a great expansion of perception, opening up a surreal and super-historical possible spatiotemporal dimension. Its participation, interactivity, openness, and the creativity it stimulates are incomparable to the original real world. "Under ideal conditions, that is, in the sense of breaking through various selves to form a common world, the metaverse will in fact

achieve a global society in the digital world that is currently difficult to achieve in reality, or rather, we may first realize what Marx called 'human society or socialized humanity' in the virtual world, developing toward a 'union of free individuals,' and this possibility and orientation undoubtedly helps the real construction of a community with a shared future for mankind (Shen Xiangping, 2022)" [**?**].

8.1 Industrial Metaverse Will Boost Transformation and Change in Chinese Manufacturing Enterprises

The report of the 20th CPC National Congress points out: "We will continue to focus our economic development on the real economy, advance new industrialization, and move faster to boost China' s strength in manufacturing, product quality, aerospace, transportation, cyberspace, and digital development." "We will promote the high-end, intelligent, and green development of the manufacturing sector." Currently, digitalization, networking, and intelligence are changing human society in an irreversible manner, helping manufacturing transformation and innovation. The industrial metaverse will boost transformation and change in Chinese manufacturing enterprises, helping them integrate value-added services that can bring market value into all aspects of the product full lifecycle.

8.2 Industrial Metaverse Is a New Frontier for Digital Economy Innovation and Industrial Chain Expansion

In the *14th Five-Year Plan for Digital Economy Development* released by China' s State Council on January 12, 2022, it was emphasized that "enterprises should be guided to strengthen digital thinking, improve employees' digital skills and data management capabilities, and comprehensively and systematically promote the digital transformation of enterprise R&D design, production and processing, operation management, and sales services."Manufacturing enterprises must seize the time to accelerate the full lifecycle digital transformation of R&D design, production and manufacturing, operation management, and market services, and continuously promote in-depth digital-intelligent transformation. The metaverse is considered the prototype of the next-generation Internet. At the 2021 Global Partners Conference, Microsoft proposed the "enterprise metaverse" solution, launching two software products, Mesh for Teams and 365 Connected Spaces, for online meetings and enterprise data management from Microsoft' s 擅长的 office application scenarios. Microsoft will also develop a fully immersive metaverse game series through the Xbox platform. Microsoft CEO Satya Nadella (2021) stated when talking about the company' s metaverse platform: "What we show today is just the beginning. Today' s metaverse, this new platform and new application, is no different from when we talked about networks and websites in the early 1990s" [**?**].

In January 2022, the Metaverse Industry Committee of China Mobile Communications Federation announced the first batch of member acceptance lists; Shanghai, Beijing, Hangzhou, Wuhan, and other places have successively writ-

ten the metaverse industry into government development plans, representing a concentrated statement by Chinese local governments on the development of metaverse-related industries. "The metaverse points to the 'ultimate form' of the Internet, is a more concrete synthesis of the digital future, and a new frontier for digital economy innovation and industrial chain expansion. With the improvement of maturity of technologies such as AR, VR, 5G, and cloud computing and the realization of immersion, participation, and sustainability, the metaverse will reconstruct social, life, and even economic and social systems in reality in the digitalized world (Xing Jie et al., 2021)" [**?**].

8.3 Industrial Metaverse Is a New Spatiotemporal Dimension for Integrated Development of Digital Economy and Real Economy

In December 2023, the Central Economic Work Conference proposed using scientific and technological innovation to promote industrial innovation, especially using disruptive and frontier technologies to spawn new industries, new models, and new drivers, and develop new quality productive forces. New quality productive forces are contemporary advanced productive forces spawned by revolutionary technological breakthroughs, innovative allocation of production factors, and deep industrial transformation and upgrading. They take the qualitative change of workers, means of labor, objects of labor, and their optimized combinations as the basic connotation, and the improvement of total factor productivity as the core sign [**?**]. As one of the forms of integrated development of digital technology and the real economy, the industrial metaverse is also a concept that is continuously enriched, improved, and developed, representing a systematic dynamic evolution process of digital survival. The industrial metaverse is a new path for the digital transformation of manufacturing and a new spatiotemporal dimension for the deep integrated development of the digital economy and the real economy. In the process of digital transformation, manufacturing enterprises should formulate feasible transformation plans based on their current status and level of digital technology application and promote implementation step by step. They should actively explore the establishment of cross-regional and cross-platform collaborative innovation mechanisms for various industrial clusters, promote the integration and sharing of innovation elements, build a regional digital development ecology for manufacturing innovation collaboration, complementary advantages, and supply-demand linkage, and enhance the collaborative supporting capabilities of industrial chains and supply chains. They should consolidate the foundation of manufacturing digital-intelligent innovation development and improve public service systems for standards, technology, talent, and capital. They should support higher education institutions in strengthening metaverse-related discipline and professional talent training, deeply promote industry-university-research cooperation, encourage enterprises to jointly train talents with universities and research institutions, support the construction of metaverse technology and skill talent training bases, and enhance the supply of high-level talents. As long as the government, industry, academia, research, and application work together to promote the digital-intelligent trans-

formation of manufacturing and drive manufacturing toward green and high-end development, China' s manufacturing industry will surely become a model of integrated development of digital and real industrial technologies in the metaverse era and a main force in building Chinese-style modernization!

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Note: Figure translations are in progress. See original paper for figures.