Development Path and Policy Safeguards for China' s Advanced Manufacturing Industry in the Context of the Fourth Industrial Revolution (Postprint)

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Abstract

Seizing the opportunity window opened by the Fourth Industrial Revolution and enhancing the international competitive advantages of advanced manufacturing have become important issues of concern for academic researchers and policy practitioners. Based on reviewing and summarizing the background, characteristics, and impacts of the Fourth Industrial Revolution on advanced manufacturing, this article categorically examines the development status and problems of four types of advanced manufacturing industries in China: digital-enabled new infrastructure industries, intelligent manufacturing high-end equipment industries, brand-dominated new consumption industries, and science-dominated industries. It specifically designs innovative development paths of "Innovation Integration," "Intelligent Manufacturing Upgrade," "Quality Enhancement," and "Early Positioning," and proposes policy recommendations including improving the advanced manufacturing innovation system, establishing a compatible and interoperable industrial standards system, enhancing the modernization level of advanced manufacturing, fostering an open and inclusive advanced manufacturing ecosystem, and promoting the sustained implementation of advanced manufacturing support policies.

Full Text

Preamble

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Development Path and Policy Guarantee of China' s Advanced Manufacturing Industry Under the Background of the Fourth Industrial Revolution

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Abstract

Seizing the opportunity window opened by the fourth industrial revolution to enhance the international competitive advantages of advanced manufacturing has become a critical concern for both academic researchers and policy practitioners. This article first reviews and summarizes the background, characteristics, and impacts of the fourth industrial revolution on advanced manufacturing. It then categorizes China' s advanced manufacturing into four types—digitally empowered new infrastructure industries, intelligent manufacturing high-end equipment industries, brand-oriented new consumption industries, and science-based industries—and examines their respective development status and challenges. Correspondingly, we design distinctive innovation-driven development paths: "innovation fusion" for digital infrastructure, "intelligent manufacturing upgrade" for high-end equipment, "quality enhancement" for brand-oriented consumption, and "early positioning" for science-based industries. Finally, we propose policy recommendations to improve the innovation system for advanced manufacturing, establish compatible and interoperable industrial standards, modernize the advanced manufacturing sector, cultivate an open and inclusive ecosystem, and ensure sustained implementation of supportive policies.

Keywords: fourth industrial revolution, advanced manufacturing industries, development path, policy guarantee
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Manufacturing is the foundation of national prosperity and strength. Advanced manufacturing represents the high-value segments of the manufacturing value chain and demonstrates a nation' s comprehensive power and core competitiveness. Against the backdrop of the fourth industrial revolution, emerging technologies such as new-generation information and communication technologies and cyber-physical systems are achieving breakthroughs in clusters, creating new tracks and advantages for advanced manufacturing development. Countries worldwide widely regard the fourth industrial revolution as an opportunity window to enhance their advanced manufacturing competitiveness [1]. To maintain its global leadership, the United States has introduced the *National Strategy for Advanced Manufacturing*; the United Kingdom has implemented the *Future of Manufacturing: 2050 Strategy* to revitalize its advanced manufacturing sector; and Germany has formulated the *Industrial Strategy 2030* to preserve its international competitiveness. The Chinese government has also attached great importance to advanced manufacturing development, issuing major strategies and policies such as *Made in China 2025* and the *14th Five-Year Plan for Intelligent Manufacturing Development*, which have effectively promoted the transformation and upgrading of China' s advanced manufacturing industry.

Existing research has conducted multi-dimensional studies on the development patterns [2], influencing factors [3], development paths and strategies [4], development trends [5], policy support systems [6,7], international cooperation [8], and international experiences [9] of advanced manufacturing, providing valuable references. However, most studies treat advanced manufacturing as a monolithic entity, largely overlooking the fact that it encompasses a comprehensive industrial system with multiple categories. Different types of advanced manufacturing exhibit distinct characteristics and face different development bottlenecks, requiring tailored innovation paths. Therefore, this paper, based on an understanding of the fourth industrial revolution' s background, characteristics, and impacts, categorizes advanced manufacturing into four types—digitally empowered new infrastructure industries, intelligent manufacturing high-end equipment industries, brand-oriented new consumption industries, and science-based industries—to analyze their respective development status and challenges in China. We then design differentiated innovation-driven development paths and propose policy measures to support them, offering valuable insights for China' s manufacturing power strategy.

1. Background and Impacts of the Fourth Industrial Revolution

Humanity has experienced three complete industrial revolutions characterized by "mechanization," "electrification," and "automation." Since the early 21st century, with the rapid development of new-generation information technologies such as artificial intelligence and 5G communication networks, the fourth industrial revolution characterized by "intelligentization" has emerged, driving comprehensive transformation across socio-economic systems (Table 1). The new concepts, technologies, models, and business forms brought by the fourth industrial revolution have profoundly impacted advanced manufacturing, which can be summarized into five dimensions: networking, intelligentization, personalization, servitization, and greenization.

Networking refers to connecting people and things, as well as things themselves, through new-generation information communication technologies and sensor technologies [10]. By aggregating human resources, intellectual resources, physical equipment, and other core capabilities that are geographically dispersed through platforms, this has broken the traditional vertically integrated industrial organization model of manufacturing value chains and supply chains. The transformation toward modular and networked organizational forms has driven the emergence of new business models such as crowdsourced R&D design, collaborative R&D networks, and collaborative manufacturing. For example, cloud manufacturing industrial clusters built on industrial internet can provide intelligent collaborative services across the entire industrial chain and product lifecycle.

Intelligentization means that design, production, management, and service processes in manufacturing possess intelligent perception, control, and decision-making capabilities [11]. By integrating digital manufacturing technologies, 5G communication, artificial intelligence, and robotics throughout the entire manufacturing chain, intelligent product design, intelligent manufacturing, and intelligent supply chain management can be ultimately achieved. For instance, leading enterprises in China' s cement production industry have established intelligent manufacturing systems covering the entire lifecycle of cement production by integrating industrial IoT, modern sensing technologies, and data analytics, achieving comprehensive intelligent processes that include full-factor collaborative coordination, fault diagnosis and early warning, automated factory operations, and visual management.

Personalization refers to highly reconfigurable flexible manufacturing systems that can meet mass customization demands. By constructing flexible manufacturing units, digital workshops, and digital factories through technologies such as industrial internet, the flexibility of manufacturing production systems can be enhanced to achieve mass personalization. For example, enterprises in China' s apparel industry specializing in personalized intelligent customization have pioneered a development path for mass customization. Consumers can submit personalized demands through mobile applications that directly connect to smart factories for production.

Servitization involves using digital technologies to promote deep integration between manufacturing and services. By digitally transforming various links in the manufacturing value chain, a "product + service" business model can be achieved, pushing manufacturing up the value chain. For example, leading enterprises in China' s wind power equipment manufacturing sector are undergoing servitization transformation, having explored and constructed intelligent large-scale wind farm operation and maintenance service systems that provide customers with remote intelligent monitoring, operation and maintenance, diagnosis, and early warning services for wind turbine equipment.

Greenization encompasses two aspects: energy structure transformation and resource recycling. The fourth industrial revolution has driven breakthrough innovations in clean energy technologies such as wind and solar power, providing energy solutions for green manufacturing transformation. Digital technologies have spawned internet platforms that strengthen connections among manufacturers, consumers, and logistics enterprises, providing channels for resource circulation and value transfer, enhancing product lifecycle management capabilities, and facilitating green transformation in manufacturing. For instance, Chinese "Internet + recycling" enterprises for electronic products have built green commercial ecosystems across the entire industrial chain of electronic consumer products, including production, consumption, recycling, and remanufacturing, through deep cooperation with manufacturing brands, e-commerce platforms, remanufacturers, and third-party logistics institutions.

2. Current Status and Challenges of China' s Advanced Manufacturing Under the Fourth Industrial Revolution

Based on technological and market characteristics, advanced manufacturing can be divided into four categories: digitally empowered new infrastructure industries, intelligent manufacturing high-end equipment industries, brand-oriented new consumption industries, and science-based industries, each with distinct development status and challenges (Table 2).

Digitally Empowered New Infrastructure Industries refer to leading foundational industries that drive manufacturing development [12], with representative sectors including 5G communications and industrial software. These industries provide platforms and interfaces for cross-industry integration and exhibit strong industrial driving effects. Currently, China' s digitally empowered new infrastructure industries have achieved first-mover advantages in both scale and quality. According to Gartner statistics, Chinese suppliers account for 3 of the top 10 global cloud computing providers by market share. However, these industries face uneven supply of key core technologies. For example, China' s industrial software industry exhibits an unbalanced pattern of "strong management software, weak engineering software; many low-end software, few high-end software." The shortcomings are particularly prominent in R&D and design software, with the domestic market share of Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) software at only 5%, and Electronic Design Automation (EDA) software at less than 5% [13]. The reasons are threefold: First, key core technology R&D in digital infrastructure is highly complex, has high technical barriers, and long development cycles, while China faces shortages in relevant R&D talent in both quantity and quality, leading to insufficient technological innovation capacity. Taking CAE as an example, leading U.S. industrial software companies invest an average of $350 million annually in R&D with an intensity of 19.7%, about 10 times that of their Chinese counterparts. Second, a healthy application ecosystem has not yet formed domestically. Key core technologies in digitally empowered new infrastructure industries often involve high knowledge tacitness and accumulation, requiring continuous trial-and-error and accumulation through application to achieve development and breakthroughs. However, Chinese adopters, influenced by brand effects and usage inertia, show insufficient willingness to adopt domestic products. Third, the application and promotion of new technologies lag behind. Due to information asymmetry between upstream and downstream in the industrial chain, significant stereotypes about domestic product disadvantages, high switching costs, and risks, prominent issues such as "unwilling to use," "dare not use," and "not good enough to use" have hindered the commercial application process of digitally empowered new infrastructure industries.

Intelligent Manufacturing High-End Equipment Industries refer to equipment industries with perception, analysis, reasoning, decision-making, and control functions. These industries are characterized by high technical complexity, with representative sectors including high-speed rail, large aircraft, and construction machinery. Large aircraft, for instance, consist of millions of independent components requiring joint supply from hundreds of suppliers worldwide [14]. Although China' s intelligent manufacturing high-end equipment industry boasts prominent full-industrial-chain scale advantages and preliminary regional clustering effects, it suffers from being "large but not strong." For example, China is already the largest consumer and producer of CNC machine tools, yet the top 10 global CNC machine tool manufacturers by revenue remain Japanese, German, and American enterprises, with high-end products still dependent on imports. The reasons include: First, poor multi-stakeholder coordination. Intelligent manufacturing high-end equipment industries are complex systems with high ecological dependency, but different stakeholders have divergent interests, easily leading to systemic failures such as missing elements, interaction gaps, and boundary misalignment, which hinder coordinated full-industrial-chain development. Second, insufficient willingness for domestic substitution. Due to information asymmetry in the industrial chain, significant stereotypes about domestic disadvantages, high conversion costs, and risks, issues like "unwilling to use," "dare not use," and "not good enough to use" have obstructed the rapid development of domestic high-end equipment [15]. Third, blockade and suppression by foreign leading OEM manufacturers. Based on their own interests, foreign leading OEM manufacturers employ strategies such as price cuts and lobbying key component suppliers to cut off supplies to suppress domestic OEM manufacturers' products.

Brand-Oriented New Consumption Industries refer to consumer goods industries that meet people' s needs for a better life. These industries are characterized by high personalization, with representative sectors including smart terminals and personalized custom clothing. The apparel and footwear industry, for example, features multi-size, multi-color, multi-style, and multi-functional requirements. China's brand-oriented new consumption industries show obvious agglomeration of regional characteristic industries, forming distinctive industrial clusters such as Shanghai' s fashion consumer goods, Shenzhen' s new energy vehicles, Qingdao' s smart home appliances, and Hohhot' s dairy products, with outstanding advantages in segments like smart terminals, new energy vehicles, and fast-moving consumer goods. However, these industries face the challenge of "weak domestic brands." For instance, among China' s top 20 cosmetics companies by market size, foreign enterprises account for 80%. Similarly, in 2022, China' s jewelry industry trade deficit reached $73.6 billion. The reasons are: First, relatively weak technological innovation capacity. For example, in the beauty industry, only four new cosmetic raw materials were approved for market entry in China over the past decade. Second, China remains a follower in fashion design and trend forecasting. Chinese enterprises mainly earn processing and manufacturing fees, with weak capabilities to enhance brand premium through creative design and cultural export. Third, severe shortage of professional talents in design and management. For example, only 1% of employees in China' s jewelry industry have received formal training. Fourth, the stereotype of brand disadvantage has not been completely overcome. Although China' s new energy vehicles and smartphones have reached the global first echelon in technical capabilities, some countries still do not grant market reputation commensurate with China' s technological status due to the stereotype that "Made in China" equals low-quality products.

Science-Based Industries primarily rely on breakthroughs in major scientific theories that bring fundamental changes to principles, technical routes, and technology platforms [16,17]. These industries best represent a country or region' s basic research capabilities and are characterized by high uncertainty in both technology development and commercialization, with representative sectors including biopharmaceuticals, brain-inspired intelligence, and frontier new materials. New material technologies, for instance, have an average R&D time seven times longer than software technologies and commercialization costs 50 times higher [18]. China' s science-based industries have seen continuously increasing R&D investment, rapid overall improvement in scientific research strength, significant achievements in domestic substitution, and gradual climbing up the value chain. For example, in graphene materials, China holds 68% of global patent applications, ranking first worldwide. However, China' s science-based industries still face "weak original innovation."For instance, China's frontier new materials innovation ranks in the global second echelon [19], still in the catching-up stage. China' s contribution rates to global biopharmaceutical R&D product numbers and new drug launches are 13.9% and 6.0%, respectively, significantly lower than the United States' 49.3% and 67.6% [20]. The reasons include: First, relatively low R&D investment in China. For example, biopharmaceutical R&D investment in the United States and other countries is 5–14 times that of China [21]. Second, lack of channels for achievement transformation, efficient technology market intermediaries, and high-level technology broker teams. China' s technology broker team development is still in its infancy, with low average quality among intermediaries and insufficient capacity to serve the transformation of scientific and technological achievements. Third, insufficient patient capital to support long-cycle innovation. According to data from international investment platform PitchBook, from 2016–2020, seed and angel round financing for U.S. biopharmaceutical industry—supporting basic research achievement transformation and concept-phase project incubation—was about 10 times that of China.

3. Design of Advanced Manufacturing Development Paths

Under the fourth industrial revolution, China' s advanced manufacturing should build upon existing industrial foundations and development trends, focus on the overarching goal of becoming a manufacturing powerhouse, pursue the main thread of promoting high-level technological self-reliance and high-quality development, and prioritize breakthroughs in "bottleneck" key core technologies, achievement of independent and controllable industrial chains, enhancement of international brand competitiveness, and strengthening of original innovation capacity. Accordingly, we design distinctive innovation-driven development paths: "innovation fusion" for digitally empowered new infrastructure industries, "intelligent manufacturing upgrade" for intelligent manufacturing high-end equipment industries, "quality enhancement" for brand-oriented new consumption industries, and "early positioning" for science-based industries.

3.1 "Innovation Fusion" Path for Digitally Empowered New Infrastructure Industries

Addressing the "uneven development" challenge in China' s digitally empowered new infrastructure industries and leveraging their strong industrial driving effects, we design an "innovation fusion" development path to promote breakthroughs and integrated applications of key core technologies, leading the development of new infrastructure industries.

(1) Promote breakthroughs in key core technologies of digitally empowered new infrastructure industries. First, strengthen the key core technology innovation system. Reinforce enterprises' principal role in innovation and cultivate leading digital technology enterprises. Encourage these leading enterprises and platform companies to strengthen original and leading scientific and technological 攻关 in 短板领域 such as intelligent sensors, industrial chips, and intelligent modules, aligned with future digital economy application needs and frontier technology directions. Second, strengthen national strategic scientific and technological forces around source innovation. Accelerate the implementation of major national science and technology projects with strategic, overall, and forward-looking significance, accelerate the planning and layout of landmark major scientific and technological infrastructure, and promote breakthroughs in interdisciplinary and large-scale collaborative basic research and applied basic research to enhance the modernization level of digitally empowered new infrastructure industries. Third, leverage the advantages of the super-large-scale market. Strengthen open-source community construction, accelerate the domestic substitution of industrial software and operating systems, form a market-driven autonomous chip industry ecosystem, and provide ecological support for competition over underlying technical standards and routes in 5G communications, cloud computing, and industrial internet.

(2) Deepen integrated applications of digitally empowered new infrastructure industries. First, establish a fusion-application-oriented innovation

R&D mechanism. Encourage universities and research institutes to establish risk-sharing, collaborative development, and achievement-sharing cooperation mechanisms with enterprises based on technology application scenarios and actual enterprise needs. Second, leverage the digital empowerment role of fusion infrastructure construction. Deeply apply technologies such as 5G communications, artificial intelligence, and software to support the transformation and upgrading of traditional infrastructure in steel, mining, and other fields. Third, accelerate multi-industry scenario application implementation and promotion. Targeting scaled and specialized fusion development goals, carry out multi-scenario application promotion projects to deepen the organic integration of digitally empowered new infrastructure industries in traditional manufacturing fields such as food production, resource processing, and machinery manufacturing, and promote scaled application pilots in qualified industries. Fourth, strengthen top-level standard system design. Build a fusion application standard system, focusing on promoting the construction of basic common standards such as industrial internet identification resolution systems, edge computing, data specification systems, and industrial software. Fifth, accelerate commercialization and application processes. Encourage large group companies to engage in fission-style entrepreneurship and academic entrepreneurship, promoting the commercial application of emerging technologies in digitally empowered new infrastructure industries.

3.2 "Intelligent Manufacturing Upgrade" Path for Intelligent Manufacturing High-End Equipment Industries

Addressing the "large but not strong" problem in China's intelligent manufacturing high-end equipment industry and leveraging its high technical complexity, we design an "intelligent manufacturing upgrade" development path to promote full-industrial-chain technological innovation and industrial transformation and upgrading, and drive domestic substitution of high-end equipment.

(1) Strengthen full-industrial-chain technological innovation. First, explore a new national system for key core technology 攻关. Implement industrial foundation reengineering and high-end equipment 攻关 projects to promote breakthroughs in key core technologies for high-end equipment such as integrated circuits, key components, and industrial 母机. Encourage "chain master" enterprises in high-end equipment industries to form innovation consortiums with supporting enterprises such as key component suppliers and research institutes to conduct joint 攻关 on "bottleneck" technologies in industrial chain links, resolutely win the battle for key core technologies, and enhance full-industrial-chain independent and controllable levels. Second, strengthen enterprises' principal position in scientific and technological innovation. Improve the enterprise technology capability gradient cultivation system and dynamic mechanism from "technology-based SMEs—technology backbone enterprises—technology leading enterprises—world-class enterprises." Enhance the domestic adoption rate of high-end equipment by encouraging collaborative R&D between complete machine enterprises and key component enterprises, demonstration applications by ecosystem-dominant enterprises, and active supply chain opening by state-owned enterprises. Support complete machine enterprises to establish long-term strategic partnerships with upstream and downstream enterprises, leveraging full-industrial-chain advantages and super-large-scale market advantages to respond to suppression and containment by foreign leading enterprises. Third, promote the digital transformation of traditional equipment manufacturing industries. Focusing on "digital transformation" and "factor upgrading," continuously increase enterprise technology upgrading efforts, promote the construction of digital workshops and smart factories, and enhance the breadth and depth of informatization and intelligentization applications. Fourth, promote the servitization transformation of intelligent manufacturing high-end equipment industries. Utilize new-generation information technologies such as industrial internet and cloud computing to promote deep integration between high-end equipment manufacturing and modern services. Through model innovations of "intelligent + equipment" and "product + service," cultivate new models and business forms such as general contracting, product lifecycle management, service-derivative manufacturing, and supply chain operation management. Explore new integration paths between key high-end equipment sectors such as intelligent manufacturing equipment, marine engineering equipment, and aerospace equipment and modern productive services. Fifth, promote value chain upgrading in high-end equipment industries. Around common service needs in high-end equipment manufacturing, encourage complete machine manufacturers to marketize their productive services, providing professional services such as incubation, R&D design, and testing for upstream and downstream enterprises in the industrial chain. Sixth, promote green transformation of high-end equipment. Implement energy conservation and carbon reduction projects in key industries, support enterprises in replacing traditional energy with new energy, develop and promote advanced applicable technologies for low-carbon, zero-carbon, and negative-carbon applications, and vigorously develop remanufacturing and recycling industries to improve resource utilization efficiency.

3.3 "Quality Enhancement" Path for Brand-Oriented New Consumption Industries

Addressing the "brand weakness" challenge in China' s brand-oriented new consumption industries and leveraging their high personalization characteristics, we design a "quality enhancement" development path to promote quality improvement and efficiency gains, enhance international competitiveness, and lead the development of brand-oriented new consumption industries.

(1) Promote quality improvement and efficiency gains in brand-oriented new consumption industries. First, promote digital transformation in brand-oriented consumption industries. Support state-owned enterprises and digital platform companies to increase investment in digital public infrastructure, leverage the bridging role of digital platform enterprises to drive digital transformation of new consumption SMEs, and create digital application scenarios for design, R&D, operation and maintenance control, and remote services to improve modern management levels, safety production guarantees, and resource allocation efficiency. Second, enhance technological innovation capacity in brand-oriented new consumption industries. Comprehensively utilize tax incentives, R&D subsidies, and other policies to promote product development, creative design, and packaging innovation in traditional industries such as apparel and jewelry, and increase R&D investment in emerging industries such as smartphones and smart vehicles. Third, actively develop intelligent logistics systems. Develop third-party logistics to encourage manufacturing enterprises to integrate, separate, and outsource logistics businesses, reduce circulation costs, improve circulation efficiency, and enhance market response capabilities of brand-oriented new consumption enterprises. Fourth, encourage universities and research institutes to create majors related to brand-oriented new consumption industries. Support universities and research institutes to jointly build training bases, professional courses, and teaching staff with leading enterprises, cultivating outstanding entrepreneurs and compound high-end talents who understand frontier trends and possess practical industry experience.

(2) Enhance international competitiveness of brand-oriented new consumption industries. First, implement an internationalization strategy for brand-oriented new consumption industries. Encourage enterprises to actively participate in the Belt and Road Initiative, build influential and controllable modern international network marketing systems through self-built marketing networks, cross-border e-commerce platforms, and overseas marketing network acquisitions. Second, promote the extension of production and processing enterprises to high-value links such as R&D and design. Support enterprises in using big data technology to predict fashion and trend directions, incorporate regional culture and value symbols into product R&D and design, create "hit products," and enhance value-added capabilities. Third, enhance the international influence of well-known brands. Encourage industry associations, chambers of commerce, and other organizations to help multinational and leading enterprises promote Chinese brands internationally, tell Chinese product stories well, and thoroughly change the stereotype of Chinese brand disadvantage. Fourth, strengthen international trend leadership capabilities. Support leading enterprises, industry associations, and professional institutions in brand-oriented new consumption industries to lead or participate in the formulation of international standards, host international industry conferences, and promote advanced technical means and modern quality management concepts and methods, leading the development of brand-oriented new consumption industries.

3.4 "Early Positioning" Path for Science-Based Industries

Addressing the "weak original innovation" problem in China' s science-based industries and leveraging their characteristics of high technological uncertainty and high commercialization uncertainty, we design an "early positioning" development path. This involves parallel layout of multiple technology routes and enhancing original innovation capacity to create new tracks and advantages.

(1) Adhere to parallel layout of multiple technology routes. First, establish a dynamic tracking and monitoring mechanism for science-based industry technologies. Timely identify disruptive and frontier technology development trends and market opportunities in science-based industries, adopt a strategy of "comprehensive layout with focused breakthroughs," conduct early accumulation in key core technologies, technical equipment, and manufacturing processes, and open up new fields and tracks for development while shaping new drivers and advantages. Second, promote reform of the science and technology planning system and mechanism. Drawing on the management system of the U.S. Defense Advanced Research Projects Agency (DARPA) for disruptive and frontier technologies, adopt a funding strategy of "parallel funding with dynamic exit" for multiple technology routes. Third, establish an elastic and inclusive prudential regulatory system. Provide trial-and-error space for disruptive and frontier technologies. Fourth, strengthen the design and development of new application scenarios for different technology routes. Based on the complexity, performance characteristics, and application scope of different technology routes, select specific market segments for commercial application to accelerate the market application process of frontier technologies. Fifth, strengthen application standard construction. Through building innovation alliances and technology licensing, promote standards related to China' s advantageous technology routes to become international standards, enhancing the global influence of China' s science-based industries.

(2) Enhance original innovation capacity in science-based industries. First, conduct organized scientific research to pool innovation resources and enhance basic research capabilities in science-based industries. Coordinate the layout of China' s regional innovation system according to the three-tier system of global science and technology innovation centers, national science and technology innovation centers, and regional science and technology innovation centers. Optimize the strategic layout of national research institutions, national laboratories, innovation platforms, and large scientific facilities in each region based on their existing foundations and national strategic layouts in science-based industries such as biomedicine, new materials, and quantum computing. Support various regions in conducting research on basic scientific knowledge and industrial common technologies for disruptive and frontier technologies in key science-based industry fields to enhance scientific and technological foundation capabilities. Second, build an open technology innovation system. Steadily expand institutional openness in rules, regulations, management, and standards, stabilize open expectations, attract large multinational enterprises, R&D institutions, and testing centers in science-based industries to establish long-term cooperation mechanisms with local entities, and encourage domestic leading enterprises and large R&D centers to actively embed themselves in the global innovation network to rationally allocate international and domestic innovation resources and enhance original innovation capacity. Third, utilize digital technologies to empower science-based industries. Apply digital technologies such as materials genome programs and digital twins to various stages of R&D, testing, and application in science-based industries to improve R&D and application efficiency. Fourth, leverage the guiding role of government industrial funds. Guide venture capital toward basic research fields and cede more investment returns to industrial capital. Fifth, encourage research institutes and enterprises to jointly build technology transformation platforms such as concept verification centers and pilot test bases to open up channels from scientific research to industrial application and enhance the transformation capacity of science-based industry achievements. Sixth, strengthen scientific research talent team building. Implement more active and effective talent policies to enhance attractiveness to key talents such as international strategic scientists, first-class scientific and technological leading talents, and outstanding entrepreneurs, deepen talent development system and mechanism reforms, reform talent evaluation systems, and improve the strength and vitality of basic research talent teams.

4. Policy Measures and Guarantee Mechanisms for China' s Advanced Manufacturing Development

(1) Improve the innovation system for advanced manufacturing. First, perfect the multi-stakeholder innovation network involving industry, academia, and research institutes. Improve the collaborative innovation system with enterprises as the main body, market orientation, and deep integration of industry, academia, and research, and encourage upstream and downstream enterprises in industrial chains, universities, research institutes, and financial institutions to form innovation consortiums. Second, strengthen the construction of advanced manufacturing industrial clusters. Strengthen the construction of facilitating organizations, improve the public service system for advanced manufacturing clusters, promote the exchange and sharing of factors and information among cluster members, and establish collaborative innovation networks with close horizontal and vertical cooperation among cluster members. Third, explore and improve regional industrial collaboration networks. Encourage geographically adjacent regions with complementary advanced manufacturing industries to formulate regional innovation cooperation policies, establish regional achievement sharing mechanisms and regional innovation development coordination mechanisms, and promote the free and convenient flow of production factors and innovation elements. Fourth, embed into international science and technology innovation cooperation networks. Actively integrate into the global innovation network, expand the level of high-level cooperation and openness in advanced manufacturing, support leading manufacturing enterprises to attract global innovation resources, advanced production factors, and high-precision industrial projects through project cooperation and talent introduction, and encourage domestic leading enterprises and large R&D centers to proactively embed themselves in the global innovation network to rationally allocate international and domestic innovation resources.

(2) Establish a compatible and interoperable industrial standard system. First, improve top-level standard system construction. Accelerate the establishment of standard systems covering vertical dimensions (terminals, networks, platforms) and horizontal dimensions (technology, testing, planning, construction, operation and maintenance) according to the principles of "practicality, industrialization, and internationalization," and promote the coordinated development of national, industry, local, and group standards. Second, build industrial technical standards that balance general and specific scenarios. Based on in-depth summarization of typical application scenarios, construct technical standard systems that balance the needs of general and specific scenarios to promote intelligent transformation and integrated development in advanced manufacturing fields. Third, promote the formulation of internationally led standards by China. Based on typical scenario application needs, accelerate the formulation of urgently needed technical standards in key areas such as design requirements, equipment procurement technical specifications, and safety requirements for construction specifications, and support and encourage domestic institutions to actively participate in standard formulation by international authoritative standardization organizations such as ISO, IEC, and ITU to promote synchronized development of nationally ready standards with international standards.

(3) Modernize the advanced manufacturing sector. First, deeply implement the manufacturing powerhouse strategy. Promote deep integration between new-generation information technology and manufacturing, increase support for technological transformation of traditional manufacturing, take the lead in deploying emerging and future industries, encourage manufacturing enterprises to develop new technologies, models, and business forms, and promote high-end, intelligent, and green development of manufacturing. Second, strengthen R&D and 攻关 of key "bottleneck" technologies. Increase the degree of domestic substitution in key core technology fields, appropriately advance deployment in frontier technology "blank" areas to form first-mover advantages. Third, promote supply chain stabilization, supplementation, consolidation, and strengthening. Encourage "chain master" enterprises to "weave chains and build networks" to construct a global value chain dominated by Chinese enterprises, strengthen coordination between main and supporting equipment and industrial chain collaboration, promote the integration of "little giant" specialized and new enterprises into the supply and innovation chains of industry leading enterprises, and establish independently controllable industrial and supply chains. Fourth, optimize manufacturing spatial layout. Clarify the comparative advantages and disadvantages of each region and the key points of complementary cooperation between regions, determine specific goals, key tasks, and policy measures for each region to promote high-quality development of advanced manufacturing, and promote complementary advantages and 错位 development between regions.

(4) Cultivate an open and inclusive ecosystem for advanced manufacturing. First, continuously cultivate various advanced manufacturing entities. Improve the gradient cultivation system for advanced manufacturing enterprises and 健全 the dynamic mechanism for enterprises to grow bigger and stronger. Increase policy support for service organizations such as industry associations, accounting firms, notary institutions, and inspection and testing agencies to guide them in providing high-quality third-party services to advanced manufacturing enterprises. Second, guide various production and innovation factors to concentrate in advanced manufacturing. Increase tax reduction efforts for advanced manufacturing, continuously reduce institutional, capital, land, and other costs for advanced manufacturing, encourage manufacturing enterprises to cultivate new models and business forms, and improve manufacturing profit margins. Accelerate institutional openness, enhance the linkage effects between domestic and international markets and resources, and improve resource supply security capabilities. Third, create a social atmosphere for high-quality development of advanced manufacturing. Shape manufacturing culture, advocate craftsmanship spirit, encourage universities to offer courses related to advanced manufacturing, support research institutes to jointly build internship bases with leading enterprises, and cultivate scientists, entrepreneurs, craftsmen, and skilled talents for manufacturing.

(5) Ensure sustained implementation of advanced manufacturing support policies. First, promote continuous implementation of supply-side policies. Ensure that tax incentives such as high-tech enterprise income tax reduction and R&D expense super-deduction are fully enjoyed, further increase the pre-tax super-deduction ratio and subsidy levels for enterprise R&D expenses, implement R&D expense post-subsidies for technology-based SMEs, and support enterprises in establishing R&D institutions and increasing R&D investment to improve the quality of enterprise and research institution invention patents. Second, improve demand-side policies for key advanced manufacturing fields. For frontier technology fields and "bottleneck" areas in digitally empowered new infrastructure industries, intelligent manufacturing high-end equipment industries, and science-based industries, create niche markets needed for technology upgrading through measures such as improving first-set (台套) and first-batch (批次) application insurance and subsidy policies for domestic equipment, expanding government procurement, and promoting exports of key core products. Third, continuously implement environment-optimization policies. Accelerate the construction of high-standard market systems, improve systems for property rights protection, market access, and fair competition, give full play to the market's decisive role in resource allocation while better leveraging the government's role, benchmark against international business environment evaluation systems, deepen "decentralization, regulation, and service" reforms, and effectively reduce institutional transaction costs by relying on the advantages of digital government large platforms, big data, and comprehensive services to stimulate market entity vitality and creativity.

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