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Data Elements Accumulation Enabling the "Three-izations" Upgrading of Manufacturing: Theoretical Mechanism

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Abstract: The data production elements are driving profound transformations in the real economy across production objects, methods, and tools, generating significant economic effects such as industrial structure upgrading. This paper aims to reveal the impact mechanism of the data elements on the "three transformations" (high-end, intelligent, and green) in the manufacturing sector, theoretically elucidating the intrinsic mechanisms by which the data elements influence these transformations. The study finds that the data elements significantly enhance the high-end, intelligent, and green levels of China's manufacturing industry. In terms of the pathways of impact, the data elements primarily influence the development of high-tech industries and overall green technological innovation, thereby affecting the high-end, intelligent, and green transformation of the industry.

Keywords: Data elements; Manufacturing; High-end; Intelligent; Green

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1. Introduction

With the rapid development of the digital economy and its growing significance in the overall economic framework, data has increasingly been recognized and valued as a production element. In April 2020, the Central Committee of the Communist Party of China and the State Council issued the Opinions on Building a More Perfect Market-Oriented Allocation System for Production Elements, formally designating data as the fifth production element, following land, labor, capital, and technology. As the most advanced and dynamic new production elements, data is driving profound transformations in the objects, methods, and tools of production in the real economy. Data's role as a production element not only accelerates the development of the digital economy and the formation of digital industry clusters but also generates significant economic effects, such as industrial upgrading and optimized resource allocation. In 2021, the General Secretary emphasized during the 34th collective study session of the Political Bureau of the CPC Central Committee that "data as a new production element has a profound impact on transforming traditional production methods." On January

4, 2024, the National Data Administration, alongside 16 other departments, issued the Three-Year Action Plan for "data×" (2024–2026), highlighting the multiplier effect of data in empowering economic and social development. Exploring the economic effects of data as a production element, its inherent empowerment, and multiplier effects is crucial for promoting high-quality economic development and advancing Chinese modernization.

As China's economy shifts toward high-quality development, the upgrading, intelligence, and green transformation of manufacturing have become key priorities. During the Second Session of the 14th National People's Congress in March 2024, the General Secretary emphasized that regions should "adopt practical, step-by-step, and tailored approaches based on local resource endowments, industrial foundations, and scientific conditions to selectively promote new industries, models, and growth drivers, while using new technologies to upgrade traditional industries and actively advance industrial upgrading, intelligence, and green transformation (referred to as the 'Three Transformations')." Indeed, data, as a new production element is not only driving production transformation but also serving as a key force in promoting the "Three Transformations" in manufacturing. Building on this, how to fully leverage data's role in transforming traditional production methods and how to achieve "data × Industrial Manufacturing" (as proposed in the Three-Year Action Plan to innovate R&D models and support enterprises in integrating design, simulation, and experimental data to foster data-driven product development) are critical focuses for future policy formulation. This paper addresses two key questions: Does data as a production element influence the "Three Transformations" in manufacturing and serve as a driver for industrial upgrading and high-quality economic development? What are the underlying mechanisms? By answering these questions, this study aims to identify the driving forces for industrial upgrading and high-quality economic development based on data in the new era, offering insights for policymaking.

In recent years, scholars have extensively focused on the field of data as a production element. Current literature primarily addresses three key issues:

(1) Concept and characteristics of data as a production element: Compared to traditional elements such as land, capital, and labor, data is a virtual resource dependent on information technology, leading to unique definitions and characteristics. Jones defined data as "the part of 'information' that is neither 'knowledge' nor 'creativity'" and emphasized its virtual nature as a core feature [1]. Additionally, researchers such as Veldkamp and Chung, Schaefer and Sapi, Xu *et al*. identified non-rivalry, non-excludability [2–4], increasing returns to scale, positive externalities, ambiguous property rights, and derivativeness as key technical-economic characteristics.

(2) Operational mechanisms of data as a production element: Research has explored data's mechanisms from micro, meso, and macro perspectives. Micro-level studies focus on the synergy between data and traditional elements like capital and labor, as well as mechanisms for improving operational efficiency. Meso-level studies emphasize data's role in promoting industrial integration, linkages, and innovation as a driver of high-quality economic development from Cai *et al* [5]. Macro-level research examines how data amplifies scale effects, innovation, and resource optimization to improve supply-demand matching and refine market and government behaviors.

(3) Data's contribution to economic growth: Existing studies analyze data's growth impact through its unique characteristics. First, data's virtual nature and reliance on information and communication technology (ICT) products make ICT integration a key growth pathway [6]. Second, data's non-rivalry, non-excludability, and low-cost replication amplify operational efficiency at the macro level, driving economic growth. Third, data's cross-boundary integration with financial resources alleviates liquidity

constraints for households and firms, stimulating growth through consumption and production. Furthermore, the self-reinforcing synergy between supply and demand sides generates increasing returns to scale and multiplier effects for growth.

Studies on growth pathways primarily explore the relationship between data and traditional elements. Some scholars have constructed theoretical models to analyze the intrinsic mechanisms of data's contribution to growth, often grounded in endogenous growth theory, emphasizing data's role in knowledge production [7].

In addition, some scholars have conducted research on the challenges faced by the value activation of data production elements, including the participation of data production elements in distribution, the establishment of data production elements market mechanisms, and data property rights.

The issue of industrial "three transformations" has also received widespread attention. First, the driving elements of industrial high-endization. Research has found that consumption upgrading, enterprise technological innovation and management, human capital accumulation, tax incentives, and technology finance all promote industrial high-endization. Second, the internal mechanisms and economic effects of industrial intelligent transformation. In terms of internal mechanisms, research has found that industrial intelligence achieves industrial value creation and industrial structure upgrading by influencing production materials, productivity, and production methods. Big data resources, industrial internet of things, and intelligent robots are new elements for the intelligent transformation and upgrading of traditional industries. In terms of economic effects, research has found that industrial intelligent transformation can affect energy efficiency, regional industrial structure advancement, industrial green development efficiency, and industrial structure upgrading. Third, the measurement of industrial greening and the elements influencing green development. In terms of measurement, scholars have used comprehensive weighted decision analysis models, the entropy method to construct indicator systems, R clustering, and the coefficient of variation to measure the level of greening. In terms of elements influencing industrial green development, research has found that digitization, economic agglomeration, technological progress, and openness to the outside world have an impact on industrial greening [8–11].

The enabling role and multiplier effect of data have sparked extensive scholarly discussion, providing strong theoretical support for this study. However, gaps remain, such as limited exploration of the relationship between data and manufacturing industry transformation at the industrial level, with unclear intrinsic mechanisms. This study aims to address these gaps by clarifying the internal mechanisms through which data drives the "three transformations" (high-end, intelligent, and green) of the manufacturing industry. Its potential marginal contribution lies in elucidating these mechanisms, enriching theoretical research on data as a production element, and laying a foundation for future studies.

2. Theoretical analysis

High-end, intelligent, and green development is crucial for transforming China's manufacturing industry, which, despite its comprehensive system, faces challenges in high-precision and cutting-edge areas. High-end development is key to overcoming these shortcomings, intelligent development enhances efficiency and profitability, and green development shifts the industry away from extensive growth models. These transformations are vital for industrial upgrading, technological advancement, and high-quality development.

High-tech industries, representing industrial high-end development, are innovation-driven and significantly impact manufacturing transformation. Data, as the "new oil" of the digital economy, plays a pivotal role in empowering high-tech industries and driving high-end manufacturing.

(1) Data as a high-end production element: Embedded in manufacturing processes, data reduces resource matching and information retrieval costs, lowering marginal costs and increasing marginal benefits.

This drives high-tech industries while upgrading traditional sectors.

(2) Linking production elements: Data acts as a "bridge," reconfiguring resource allocation and leveraging agglomeration effects, enhancing resource flexibility and maximizing efficiency, thus supporting high-tech industries.

(3) Knowledge and technology diffusion: Data facilitates the spread of new knowledge and technologies, accelerating innovation, shortening R&D cycles, and transforming labor-intensive industries into knowledge- and technology-intensive ones.

(4) Intelligent production and talent development: Data enables intelligent production, replacing repetitive tasks and pushing high-tech enterprises to cultivate top-tier talent, improving productivity. It also enhances communication and collaboration, reducing costs and fostering innovation.

In summary, data drives high-tech industry development by enhancing technological innovation, optimizing resource allocation, and promoting intelligent production, providing a foundation for high-end manufacturing transformation.

In recent years, China has continuously promoted the development of industrial intelligence through top-level design. The "New Generation Artificial Intelligence Development Plan" issued by the State Council in 2017 explicitly proposed the goal of "accelerating the intelligent upgrading of industries." The "14th Five-Year Plan for Intelligent Manufacturing Development" jointly released by the Ministry of Industry and Information Technology and seven other departments in 2021 pointed out: "In the next 15 years, through a 'two-step' approach, we will accelerate the transformation of production methods: First, by 2025, the majority of large-scale manufacturing enterprises will achieve digitalization and networking, with key industry leaders initially applying intelligence; Second, by 2035, large-scale manufacturing enterprises will fully popularize digitalization and networking, with key industry leaders achieving intelligence." The "Guiding Opinions on Accelerating Scenario Innovation to Promote High-Quality Economic Development through High-Level Application of Artificial Intelligence" issued by the Ministry of Science and Technology and five other departments in 2022 supports universities, research institutes, and new research and development institutions in "exploring application scenarios of artificial intelligence technology for major scientific research and technological development. Encourage active engagement with the technological needs of cities and industries in the transformation of achievements, carry out industry-university-research cooperation in scenario innovation, enhance the market orientation of scientific research, and activate the innovation potential of researchers. Encourage researchers to participate in scenario entrepreneurship, tap into the creative potential of artificial intelligence research achievements, and accelerate the industrial application of artificial intelligence technologies." To achieve these goals, exploring how data affects the internal mechanisms of industrial intelligence is indispensable. As a new type of production element, data is the foundation of digitalization, networking, and intelligence. Digital technologies such as artificial intelligence, big data, and cloud computing not only enhance the intelligence, informatization, and technological level of traditional industries but also effectively promote the transformation of traditional industrial dynamics and collaborative innovation, nurturing new business models and cultivating new engines for economic growth, thereby driving the transformation and upgrading of traditional industries. The application of data encourages enterprises to increase investment in new technologies and tools, such as artificial intelligence, the Internet of Things, and big data analytics. These technologies can further drive improvements in production efficiency and product quality, promoting the development of industrial intelligence. Research has found that the main drivers of industrial intelligence are technology, human capital, and cost pressures. Further research has found that the main elements driving industrial intelligence are technological innovation, industrial structure upgrading, and openness to the outside

world, with contribution rates of 48.83%, 24.87%, and 19.02%, respectively, cumulatively accounting for 92.72% [12]. In summary, the development of data can drive technological innovation, which in turn can promote industrial intelligence.

"Green development is the foundation of high-quality development, and new quality productivity itself is green productivity [13]. It is essential to accelerate the green transformation of development methods to support the goals of carbon peak and carbon neutrality." In the context of the new era, it is crucial to explore how data influences the green upgrading of industries. The high technological content and low environmental cost characteristics of data inherently make their introduction more conducive to harmonizing production and environmental coordination, reducing energy and material consumption, and minimizing environmental impact [14]. Compared to other production inputs, digital technologies driven by data not only improve resource allocation efficiency but also contribute to environmental improvement [15]. Therefore, the introduction of data inherently supports the green development of the manufacturing industry.

The core driver of green development is green innovation. Green innovation aims at energy conservation, pollution prevention, and waste recycling, encompassing innovations in product design, processes, management support, and implementation. It not only enhances enterprise value but also achieves specific environmental goals and sustainable development. Compared to traditional innovation, green innovation requires simultaneous consideration of economic benefits and environmental quality, making it more challenging, with higher risks and uncertainties. This necessitates stronger financial guarantees and more directional innovation efforts for green innovation. Data contributes to strengthening the financial security for green innovation, reducing the costs associated with green innovation, and improving the quality of green innovation, thereby promoting the development of green innovation.

Financial security and cost efficiency of data in green innovation: Data exhibits increasing returns to scale—larger and more diverse datasets generate greater information and knowledge, exponentially increasing their value and providing robust financial support for green innovation. Data also reduces costs by enabling low-cost collaboration platforms, overcoming barriers of time, geography, and economics, and lowering search and identification costs for knowledge resources. By integrating data into production and sales, entities gain accurate, timely information, reducing costs related to sales, idle capacity, and inventory, while expanding financial flexibility for green innovation. Additionally, data guides the flow of other elements, fostering economies of scale through spatial agglomeration, lowering green innovation costs, and enhancing green technological innovation. Impact of data on green innovation quality: Data enables the use of the internet and big data to analyze user habits and preferences, improving market demand identification. This shifts green innovation from experience-based to data-driven, enhancing R&D relevance and decision accuracy. Integrating data with AI and deep learning boosts experimental prediction accuracy, screening efficiency, and innovation quality. Data also guides the flow of other innovative elements, improving inter-city and inter-industry matching efficiency and reducing resource misallocation. The synergy between data and other elements enhances green economic efficiency, further improving green innovation quality.

3. Conclusions and implications

The high-end, intelligent, and green transformation of China's manufacturing industry is vital for high-quality economic development and modern industrial system construction. Data, as a new production element, drives these transformations by promoting high-tech industries, innovation, and green technology. Key conclusions and policy implications include:

(1) Enhancing data element system: Data is crucial but underdeveloped compared to traditional elements. The establishment of the National Data Bureau and local data bureaus, along with the "East Data West Computing" project, is forming a new data market. Establishing data circulation standards will optimize data property rights, pricing, and usage, unlocking its value as a resource, asset, and capital. However, data flow may initially reduce consumption and economic growth but will ultimately drive technological progress and industrial upgrading, as seen in BYD's new energy vehicle advancements.

(2) Exploring industrial upgrading effects: Regions should leverage their strengths to boost data capabilities. Central and western China can utilize energy and cost advantages to establish data centers, promoting big data innovation and computing efficiency. Prioritizing investments in data infrastructure and talent development, supported by fiscal and tax policies for green industry data research. This will drive data technology breakthroughs, facilitate green industry transformation, and cultivate competitive data service enterprises and products.

Disclosure statement

The author declares no conflict of interest.

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