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Research on the Mechanism and Pathway of Digital-Real Integration Empowering Green Transformation of Chongqing Manufacturing Industry

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Abstract

As a vital engine for developing new quality productive forces, digital-real integration also serves as a core lever for Chongqing to promote the high-end, intelligent, and green transformation of its manufacturing industry. Drawing on data from Chongqing's "33618" modern manufacturing cluster system and digital economy development, this paper systematically analyzes the current state of manufacturing green transformation and digital-real integration. It identifies the following problems in digital-real integration's empowerment of manufacturing green transformation: weak digital foundations in traditional industries, insufficient connectivity of data elements, mismatch between green technology supply and industrial demand, and an inadequate digital-intelligence green collaborative governance system. Optimization paths are proposed along four dimensions: consolidating the digital foundation, tackling key green technologies, improving collaborative governance, and strengthening factor guarantees.

Keywords

digital-real integration, green transformation of manufacturing, "33618" industrial clusters

1. Introduction

The deep integration of the digital and real economies (hereafter "digital-real integration") is a core feature of the new round of scientific and technological revolution and industrial transformation, and a key variable in promoting the green and low-carbon transformation of manufacturing. General Secretary Xi Jinping has noted that traditional manufacturing is the foundation of the modern industrial system, and that it is necessary to accelerate digital transformation, promote advanced and applicable technologies, and strive to raise levels of high-end, intelligent, and green development. Against the dual backdrop of the "dual carbon" goals and the cultivation of new quality productive forces, how to leverage digital-real integration to drive the green transformation of manufacturing and achieve the decoupling of economic growth from carbon emissions has become a major topic of shared concern in both academia and policy circles. Through the penetration and empowerment of data elements, digital technologies can reshape production processes, optimize resource allocation, and innovate business models, providing technological pathways and institutional possibilities for manufacturing to leap from an extensive model characterized by high input, high emissions, and low efficiency to a green model that is intensive, clean, and efficient.

As a major industrial hub in western China, Chongqing is home to 39 of the country's 41 major industrial categories and all 31 major manufacturing categories. Its industrial system is comprehensive, but high-energy-consuming traditional industries such as steel, chemicals, building materials, and nonferrous metals have deep roots. Chongqing's primary energy resources are characterized as "poor in coal, devoid of oil, and endowed with natural gas," and its pressure for energy conservation and carbon reduction is far greater than that of most cities. In recent years, Chongqing has taken the "33618" modern manufacturing cluster system as its main lever and the "Digital Chongqing" initiative as its overarching driver, innovatively constructing an "industry brain + future factory" digital-intelligence transformation model while simultaneously advancing green, low-carbon, and circular development. During the 14th Five-Year Plan period, Chongqing supported an average annual economic growth rate of 5.6% with an average annual energy consumption growth rate of approximately 2.2%; in 2025, both its energy consumption per unit of GDP and carbon emissions were over 30% better than the national average. In 2025, within the "33618" modern manufacturing clusters, the value added of intelligent connected new energy vehicles grew by 13.4%, and the share of value added from the municipality's strategic emerging industries in industrial enterprises above designated size rose to 34.6%. Chongqing has thus forged a distinctive path of digital-intelligence empowerment and green transformation. Nevertheless, measured against the goal of building a nationally important advanced manufacturing center and the requirements of the "dual carbon" strategy, Chongqing's manufacturing still faces deep-seated problems in the coordinated advancement of digital-real integration and green transformation, including weak digital foundations in traditional industries, data silos constraining energy efficiency optimization, and insufficient green technology supply.

The current academic literature on the integrated development of the digital and real economies has formed three relatively clear research strands. The first strand examines the relationship between the two. Existing evidence indicates that the impact of the digital economy on the real economy is not monotonic: in the initial stage of digitalization, there is a certain resource crowding-out effect (Jiang et al., 2022), but as development levels rise, it releases significant growth dividends by empowering the transformation and upgrading of industrial structure (Tian et al., 2022; Sun et al., 2023), exhibiting an overall U-shaped evolutionary pattern (Jiang & Sun, 2020). The second strand focuses on the theoretical foundations and measurement techniques of digital-real integration. Englmaier (2008) used a global game model to mathematically characterize the conditions and mechanisms of integrating informatization with industrialization; Schroth (2007), focusing on the industrial application scenarios of information service networks, argued that the key to whether such networks can effectively serve the industrialization process lies in their ability to tangibly eliminate various efficiency losses in industrial operations. The third strand assesses the economic and social effects of digital-real integration. Scholars generally agree that digital-real integration makes multidimensional and comprehensive positive contributions to economic growth. Kuang and Peng (2020) summarized its positive roles in safeguarding industrial and supply chain security, attracting foreign investment, expanding employment, raising incomes, and promoting consumption; Chao (2022), from the perspective of development economics, pointed out that the deepening of digital-real integration is an important breakthrough for resolving the structural contradictions in current high-quality development. However, existing studies lack systematic case analyses of specific regions, particularly typical cities such as Chongqing that combine the transformation pressures of an old industrial base with the institutional advantages of a direct-controlled municipality, and there is insufficient distillation of the process mechanisms and models through which digital-real integration empowers green transformation. Based on the practice of Chongqing's "33618" manufacturing cluster system, this paper systematically reviews the real landscape of digital-real integration empowering manufacturing green transformation, distills the mechanisms and typical models, identifies practical bottlenecks, and proposes optimization paths, with a view to providing useful references for the green transformation of old industrial bases in Chongqing and across the country.

2. Current State and Problems of Digital-Real Integration in Chongqing

2.1 Current State of Digital-Real Integration in Chongqing

2.1.1 Digital Infrastructure Is Iterating and Upgrading, and the Integration Foundation Continues to Solidify

Guided by the "Digital Chongqing" initiative, Chongqing is accelerating the construction of an "industry brain + future factory" dual-wheel drive model. The National Top-Node for Industrial Internet Identifier Resolution (Chongqing) has been connected to 54 secondary nodes across ten western provinces (autonomous regions and direct-controlled municipalities), with cumulative identifier registrations exceeding 44.7 billion, cumulative identifier resolutions exceeding 42.6 billion, and connected enterprise nodes surpassing 40,000. By the end of 2025, the municipality had cumulatively built 1,231 digital workshops and 211 smart factories, and certified 20 future factories; 22 enterprises had been named national world-class smart factories (7 in 2024 and 15 in 2025), ranking first in western China; and the number of national-level 5G factories had reached 34 (including 21 added in 2025). In September 2025, the first batch of 30 industrial intelligent agent products was released, covering five major categories: R&D and design, production and manufacturing, supply chain management, marketing management, and operations and maintenance services. The digital R&D and design penetration rate among industrial enterprises above designated size reached 86.7%, and the digital control penetration rate in key production processes reached 65.6%, with both indicators ranking first in western China. Twelve industry brains and eleven sub-sector industry brains have been launched, covering fields such as intelligent connected new energy vehicles, high-end motorcycles, and new energy storage.

2.1.2 Benchmark Cases of Digital-Intelligence Transformation among Leading Enterprises Are Emerging, and Integration Results Are Accelerating

Seres' Liangjiang Super Factory has deployed over 3,000 robots, with industrial data collected in real time into the industry brain, connecting more than 300 partners. According to the company's public disclosures, product R&D time has been shortened by over 20%, and on-time order delivery rates have improved by 13%. Hithium Energy Storage's Chongqing base was named the world's first energy storage battery "Lighthouse Factory," with self-developed AI participating in material screening and performance prediction, shortening the R&D cycle by 31%. Huafon Chongqing Spandex was named a "Global Lighthouse Factory" in early 2026, becoming the first enterprise in the global chemical fiber industry to receive this honor. Longshui Town in Dazu District built the country's first hardware industrial internet platform, connecting the full chain of production, supply, sales, and inventory.

2.1.3 Digital Technology and Green Low-Carbon Development Are Accelerating Their Integration, and Synergistic Effects Are Initially Emerging

The application of digital technologies in energy consumption monitoring, carbon footprint management, and green process optimization continues to deepen. Seres has built a smart energy-carbon management system, achieving online visibility, analyzability, and manageability of energy consumption data across the entire plant. Changan's Digital Intelligence Factory has installed a 36-megawatt distributed photovoltaic system, generating over 25 million kilowatt-hours of electricity annually. According to the 2025 Chongqing Municipal Ecological and Environmental Status Bulletin, the cumulative trading volume in Chongqing's carbon market reached 54.2184 million tons, with a transaction value of 1.32 billion yuan. At the end of 2025, the balance of medium- and long-term manufacturing loans reached 276.29 billion yuan; the municipality had cumulatively extended over 16.8 billion yuan in carbon emission reduction loans and deployed over 5 billion yuan through the carbon emission reduction support tool, providing strong financial guarantees for green technology upgrading.

2.2 Problems and Shortcomings in Digital-Real Integration's Empowerment of Manufacturing Green Transformation

Although Chongqing has achieved remarkable results in digital-real integration and manufacturing green transformation, measured against the requirements of the "dual carbon" goals and the needs of building an advanced manufacturing center, the coordinated advancement of the two still faces numerous bottlenecks, and the green empowerment effect of digital-real integration has yet to be fully released.

2.2.1 Weak Digital Foundations in Traditional Industries and a Pronounced “Digital Divide” in Green Transformation

Traditional manufacturing accounts for approximately 60% of Chongqing’s total industrial output. A large number of small and medium-sized manufacturing enterprises remain in the transition from mechanization to automation, with relatively low equipment digitalization and networking rates. A research report from Banan District noted that “many small and medium-sized enterprises have a large proportion of old equipment, and indicators such as the industrial equipment digitalization rate and equipment networking rate are low, with severe divergence.” Energy consumption and emissions data collection relies on manual meter reading, making real-time monitoring and precise management impossible. Digital transformation requires large investment and long payback periods, and the problem of small and medium-sized enterprises being “unwilling to transform, afraid to transform, and unable to transform” is prominent. Although individual enterprises in high-energy-consuming sectors such as steel, chemicals, and building materials have relatively high digitalization levels, gaps among enterprises within these sectors are significant, and small enterprises in some districts and counties still use outdated, high-energy-consuming equipment. Simultaneously advancing process greenization and digital transformation faces dual constraints of capital and technology. The unevenness of digital foundations directly constrains the large-scale application of digital technologies in energy efficiency optimization and carbon emissions management.

2.2.2 Insufficient Connectivity of Data Elements and “Information Silos” Constraining Full-Chain Carbon Reduction

Manufacturing green transformation involves multiple departments, including energy, environmental protection, economy and information technology, and market regulation, with enterprise data on energy consumption, emissions, capacity, and technology scattered across different systems. Chongqing has, through the “negative list for data sharing” system, broken down data barriers among 23 municipal-level departments and achieved an 89% cross-departmental business collaboration rate. However, inter-departmental data sharing mechanisms remain inadequate, and standards are not unified. Within enterprises, data fragmentation likewise exists across R&D and design, production and manufacturing, and supply chain management; ERP, MES, and EMS systems are insufficiently interconnected, making it difficult to support full-process energy optimization and carbon footprint traceability. Data barriers between upstream and downstream enterprises in industrial chains are even more pronounced: leading enterprises struggle to obtain authentic energy consumption and carbon emissions data from suppliers, and full-lifecycle carbon management and green supply chain coordination lack a data foundation. Although Seres’ “factory-within-a-factory” model has achieved data connectivity with core suppliers, such deep collaboration remains an exception across the municipality, and green data connectivity in most industrial chains is still in its infancy.

2.2.3 Mismatch between Green Technology Supply and Industrial Demand, and Weak Commercialization of Innovation Outcomes

Although Chongqing has promoted over 1,200 units (sets) of green technology and equipment, a disconnect persists between green technology innovation and actual industrial demand. Green technology outcomes from universities and research institutes tend to remain at the laboratory stage, with insufficient capacity for pilot-scale verification and engineering application—Kaizhou District only built the municipality's first district/county-level "factor supermarket" in July 2026, indicating that technology commercialization platforms are still under development. The R&D investment intensity of enterprises, as the main innovation actors, still lags: Chongqing's R&D investment intensity for industrial enterprises above designated size has remained above 2.9% for three consecutive years, but there remains room for improvement compared with developed eastern regions. Interdisciplinary talent at the intersection of digital technology and green processes is scarce, and the supply of compound talent who understand both industrial mechanisms and data modeling is insufficient. Green technology trading markets and commercialization platforms are underdeveloped, and supporting services such as technology assessment, intellectual property protection, and industrialization financing are weak, with the result that a number of advanced green technologies struggle to be translated into real green productive forces.

2.2.4 Inadequate Digital-Intelligence Green Collaborative Governance Systems and Policy Synergy Needing Strengthening

The coordination mechanisms between digital economy policies and green low-carbon policies in both formulation and implementation are still being refined, and Chongqing is advancing a "four-side" coordinated initiative to break down barriers. Standards, norms, and evaluation systems for enterprises' digital-intelligence green collaborative transformation remain inadequate; although Chongqing has launched the "industrial green efficiency code," there is still no unified accounting methodology for the effects of digital technology in enabling energy conservation and carbon reduction. The articulation among market-based mechanisms such as the carbon market, energy use rights trading, and green electricity trading needs strengthening. The energy consumption of new infrastructure such as data centers has begun to emerge as an issue; Chongqing has explicitly required that new data centers at national hub nodes achieve an 80% green electricity consumption ratio. In addition, fiscal support and financial services for the digital-intelligence green transformation of small and medium-sized enterprises lack precision. Data show that 60% of micro, small, and medium-sized enterprises have low loan approval rates due to insufficient collateral; the People's Bank of China Chongqing Branch has created the "Yulvrong" special policy product, with 18 billion yuan in dedicated relending quotas for agricultural and small business support, but green credit and carbon reduction tools tend to benefit large enterprises more, and the problem of difficult and expensive financing for small and medium-sized enterprises persists.

3. Policy Recommendations for Digital-Real Integration to Promote Green Transformation of Chongqing's Manufacturing

3.1 Consolidating the Digital Foundation and Promoting Coordinated Digital-Intelligence Green Transformation of Traditional Industries

First, increase fiscal support for the digital and green transformation of small and medium-sized manufacturing enterprises by establishing special subsidy funds that subsidize enterprises' purchases of intelligent sensor devices, online energy consumption monitoring systems, and energy management platforms, thereby lowering the threshold for transformation. Second, promote "lightweight" digital tools, encouraging industrial internet platforms and cloud service providers to develop low-cost, rapidly deployable SaaS-based energy efficiency management applications for small and medium-sized enterprises, avoiding one-size-fits-all requirements for enterprises to build complex systems. Third, accelerate the functional expansion of "industry brains" into green and low-carbon domains. Promote the addition of energy consumption monitoring, carbon footprint tracking, and green supply chain management modules to more industry brains, and ensure that energy consumption data from key energy-using enterprises are connected wherever possible. Fourth, advance the transformation of high-energy-consuming sectors by category, formulating roadmaps for coordinated digital and green transformation in steel, chemicals, building materials, and other industries, with clearly defined phased energy efficiency benchmarks and digitalization targets.

3.2 Strengthening Data Connectivity and Building a Green Data Element System for Manufacturing

First, establish a municipal-level coordination mechanism for manufacturing green data sharing, led by the economy and information technology department in conjunction with ecological environment, energy, statistics, and market regulation departments, to unify data standards for energy consumption, carbon emissions, capacity utilization, and other indicators. Second, promote the interconnection of internal enterprise systems by implementing an "industrial equipment on the cloud" initiative, supporting enterprises in digitally retrofitting old equipment and achieving data interoperability among ERP, MES, EMS, and other systems to eliminate internal "information silos." Third, establish a carbon data sharing mechanism for industrial chains, building supply chain carbon management platforms based on "industry brains" and chain anchor enterprises. Fourth, explore the use of privacy-preserving computation, federated learning, and other technologies to enable cross-enterprise collaborative modeling of green data under the premise that "data do not leave their domain," balancing data sharing with trade secret protection.

3.3 Tackling Key Green Technologies and Improving the Digital-Intelligence Green Innovation Ecosystem

First, centered on the green transformation needs of the "33618" cluster system, fully leverage Chongqing's foundational advantages in digital-intelligence technology and green low-carbon fields, focusing on key technologies such as AI-driven process optimization, digital twin simulation, digitalization of carbon capture, utilization, and storage (CCUS), and intelligent screening of green materials. Second, strengthen the position of enterprises as innovation actors, supporting leading enterprises in forming digital-intelligence green innovation consortia with universities and research institutes such as Chongqing University, Southwest University, and Chongqing University of Posts and Telecommunications. Third, cultivate and attract interdisciplinary talent, incorporating talent in the digital-green intersection into the priority support scope of talent recruitment policies such as the "Hongyan Plan," and supporting enterprises and vocational colleges in jointly building digital-green skills training bases. Fourth, develop green technology trading markets to connect the "last mile" of green technology commercialization.

3.4 Improving Collaborative Governance and Strengthening Institutional Guarantees for Digital-Intelligence Green Transformation

First, establish a coordination mechanism between digital economy and green low-carbon policies, simultaneously assessing carbon reduction effects when formulating digital transformation plans and fully employing digital technology tools when deploying energy conservation and carbon reduction tasks, so as to avoid policy disconnect. Second, improve the digital-intelligence green standards system by researching and formulating evaluation standards for the coordinated digital and green transformation of manufacturing and accounting methodologies for the effects of digital technology in enabling energy conservation and carbon reduction, and conducting evaluations and tiered, categorized management of enterprises' digital-intelligence green transformation levels. Third, strengthen the coordination of market-based mechanisms, promoting linkages among the carbon market, energy use rights trading, green electricity trading, and green finance. Fourth, pay attention to the greening of digital infrastructure itself, coordinating the layout of data centers and computing facilities, guiding the siting of computing centers in regions rich in renewable energy, and promoting energy-saving retrofits of existing data centers to avoid the paradox of "enabling carbon reduction while increasing one's own carbon footprint." Fifth, strengthen international cooperation, introducing advanced green transformation technologies and experience from manufacturing powerhouses such as Europe and Japan, and promoting the "going global" of Chongqing's digital-intelligence green standards and products.

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