Key Elements, Mechanism Analysis, and Evaluation Indicators for the Digital-Intelligent Integrated Transformation of Manufacturing: Postprint

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Abstract

The digital-intelligent integration transformation of manufacturing has become an important driving force for the high-quality development of traditional manufacturing enterprises. This study clarifies the main research threads and key issues concerning manufacturing digital-intelligent integration transformation from domestic and foreign scholars, identifies the objective elements, subject elements, and influencing factors in the development of manufacturing digital-intelligent integration transformation, and constructs a dynamic network model for this development based on the system feedback principle of system dynamics to analyze the interaction mechanisms among various system elements. On this basis, a scientific evaluation index system for integration is established, providing theoretical reference for further research on manufacturing digital-intelligent integration transformation development issues.

Full Text

Preamble

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Key Elements, Mechanism Analysis and Evaluation Indicators of Digital and Intelligent Integration Transformation and Development of Manufacturing Industry

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Abstract

The digital and intelligent integration transformation of manufacturing has become a crucial driving force for the high-quality development of traditional manufacturing enterprises. This study clarifies the main research trajectories and key issues in the digital and intelligent integration transformation of manufacturing both domestically and internationally, extracts the goal elements, principal elements, and influencing factors of this transformation process. Based on the system feedback principle of system dynamics, we construct a dynamic network model for the transformation and development of digital and intelligent integration in manufacturing, analyzing the interaction mechanisms among various system elements. On this foundation, we establish a scientific evaluation index system for integration assessment, providing a theoretical reference for further research on the transformation and development of digital and intelligent integration in manufacturing.

Keywords: manufacturing industry, digital and intelligent integration transformation, key elements, mechanism analysis, evaluation indicators

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1. Background Research on Digital and Intelligent Integration Transformation and Development of Manufacturing

Manufacturing serves as the backbone of China's national economy, representing the foundation for building a strong nation. With a complete range of industrial categories, manufacturing provides robust support for economic and social development. Since the reform and opening-up, China' s real economy, particularly manufacturing, has achieved remarkable progress. Since 2010, China' s manufacturing output has ranked first globally for 12 consecutive years, with substantial increases in the production of major industrial products and expanding development scale. Although China is now a veritable manufacturing and industrial powerhouse, the challenge of being "large but not strong" persists. To achieve high-quality development, improve product quality, and enhance production management efficiency, a fundamental shift in development models is necessary, requiring breakthroughs in core technologies and the elevation of digitalization and intelligence levels across all aspects of manufacturing enterprises.

This transformation can be realized through digital and intelligent integration.

In the term "digital and intelligent integration," "digital" represents digitization, emphasizing networks, technologies, and data at the information level, while "intelligent" represents intelligence, emphasizing smart infrastructure. Digital and intelligent integration transformation in manufacturing refers to the comprehensive process whereby manufacturing enterprises fully utilize effective information such as data, leverage the enabling role of digital technologies, and apply new-generation information technologies including big data, the Internet of Things, and artificial intelligence to conduct all-round, full-chain transformation of traditional manufacturing. This deepens the application of digital technologies across production, operations, management, and service segments, ultimately achieving digital, intelligent, and green development in manufacturing enterprises.

Currently, both government and manufacturing enterprises attach great importance to promoting this transformation. The government continuously improves the institutional environment and has introduced a series of policy measures to support high-quality manufacturing development. For instance, the *14th Five-Year Plan for Deep Integration of Informatization and Industrialization* proposes that deep integration represents the convergence and innovation of two historical processes—industrialization and informatization. This integration embodies the concentrated expression of a new type of industrialization with Chinese characteristics and serves as the only path for digital, networked, and intelligent manufacturing development in the new development stage. It also represents the convergence point for building a manufacturing powerhouse, cyber powerhouse, and digital China in the digital economy era. The plan emphasizes cultivating new products, models, and business forms; promoting digital transformation across industries; and stimulating new vitality among enterprise entities. These policy documents have, to a certain extent, facilitated the digital and intelligent integration transformation of manufacturing, providing important guarantees for high-quality development.

Scholars both domestically and internationally have studied this transformation from various perspectives. Representative research includes: (1) **Resource allocation perspective**: Improving enterprises' resource allocation capabilities, enhancing production efficiency, and breaking traditional resource allocation models can further promote digital and intelligent integration transformation [1,2]. (2) **Production cost perspective**: Research shows that applying digital technologies can improve quality and efficiency, elevate digital and intelligence levels, and effectively reduce production costs [3-5]. (3) **Innovation-driven perspective**: Establishing an innovation-driven development model, conducting research and development on key core technologies, and continuously innovating products can enhance product performance while effectively promoting transformation [6-8]. (4) **Product quality perspective**: Data, as a new production factor, can be deeply mined and processed through digital technology applications to analyze potential problems, improve supply chain efficiency and product quality, and facilitate transformation [9,10].

2. Key Elements of Digital and Intelligent Integration Transformation and Development in Manufacturing

During the transformation process, various elements interact and integrate with each other, forming a complex nonlinear development system. This process involves multiple continuous, interconnected, and mutually reinforcing cycles and feedback loops carried by key elements. Based on industrial linkage theory and system dynamics feedback principles, we systematically analyze the key elements—including goal elements, principal elements, and influencing factors—emphasizing dynamic rather than static analysis and holistic rather than partial examination of changes in element behaviors. This approach enables sustained and healthy operation and development of the process, facilitating deeper scientific research.

2.1 Goal Elements of Digital and Intelligent Integration Transformation and Development

The goal elements of this transformation include: through rapid development of digital and intelligent integration, continuously strengthening the manufacturing foundation, accelerating integration and upgrading, significantly enhancing innovation-driven capabilities, substantially improving quality and efficiency, gradually perfecting governance systems, and comprehensively promoting green development. Ultimately, this achieves a virtuous cycle of digital and intelligent integration transformation and development in manufacturing.

2.2 Principal Elements of Digital and Intelligent Integration Transformation and Development

The transformation process can only be completed through the participation of various principal elements, which play a leading role. The capabilities and subjective initiative of these principals determine the transformation outcomes. Digital and intelligent integration transformation constitutes an open and complex ecosystem composed of different principal elements. This system is led and supported by digital innovation, driven by industrial convergence for economic development, achieves multi-stakeholder governance, and evolves alongside the overall enhancement of digitalization and intelligence levels.

(1) Government Agencies. On one hand, the government has introduced a series of policies to provide guidance and support for transformation. On the other hand, through data sharing, tax reductions, and fee cuts, the government lowers transformation costs and risks while improving efficiency.

(2) Manufacturing Enterprises. As both the implementers and carriers of transformation, manufacturing enterprises represent the core principal element. Supported by new-generation information technologies such as big data, IoT, AI, and cloud computing, these enterprises integrate traditional industries with emerging products, update production processes and workflows, and continuously improve production efficiency to facilitate transformation.

(3) Universities and Research Institutes. The realization of transformation relies on support from highly skilled talent and R&D of key core technologies. Through government-industry-academia-research collaboration, universities, enterprises, and research institutes jointly build technology innovation and service platforms, promoting technology transfer and achievement transformation, thereby injecting continuous momentum into manufacturing transformation.

(4) Platform Enterprises. These enterprises provide services by building platforms for data storage, sharing, browsing, and interaction. As aggregation points for various data, platforms help enterprises quickly and accurately obtain effective information, reducing data resource search costs and thereby facilitating transformation.

(5) Intermediary Organizations. Transformation realization is closely related to financial institutions, data management centers, and other intermediaries. Transformation requires long-term substantial investment, and financial institutions can effectively facilitate financing needs. Data management centers promote orderly and secure data circulation among enterprises, gradually releasing data factor dividends and supporting high-quality manufacturing transformation.

(6) Consumers. The ultimate purpose of transformation is to maximally satisfy consumers' customized and personalized needs while improving customer experience. Conversely, consumer feedback can also promote enterprise transformation, enabling more targeted improvements and facilitating the transformation process.

2.3 Influencing Factors of Digital and Intelligent Integration Transformation and Development

Transformation development is influenced by multiple factors from various perspectives, primarily including driving factors and obstacle factors.

2.3.1 Driving Factors **(1) Digital Infrastructure Construction.** Digital infrastructure refers to the new infrastructure system applying new-generation information technologies. Traditional manufacturing infrastructure is relatively backward with low digitalization and intelligence levels. The completeness of internet platforms and smart equipment construction directly determines transformation effectiveness, thus exerting a strong driving effect.

(2) Talent Team Building. A well-structured talent team is a decisive factor. As transformation deepens, demand for digital-intelligent talent grows dramatically. Establishing a contingent of composite talents proficient in both technology and business substantially promotes transformation, as talent has become the backbone of this process.

(3) Policy and Institutional Environment. The transformation has received high-level national attention with a favorable policy environment. A series of policies provide sufficient preconditions and environmental guarantees, offering clearer direction and making transformation easier to achieve.

(4) Innovation-Driven Capability. Enhanced innovation-driven capability helps manufacturing enterprises break away from traditional, backward development models, improve production and management, and optimize production lines. Through technological innovation, enterprises enhance production and management efficiency, improve product quality, and ultimately achieve transformation.

(5) Corporate Culture. A positive corporate culture and correct value orientation serve as incentives. Transformation involves not only extensive application and innovation of digital technologies but also the creation of a digital corporate culture and atmosphere—where entrepreneurs possess digital knowledge structures and knowledge exchange occurs within the enterprise environment.

(6) Market Structure and Demand Changes. Traditional production and management models can no longer adapt to current market structures and demand changes. As consumer demand shifts toward personalization and customization, manufacturing enterprises must achieve digital-intelligent enhancement across all processes from R&D to production and sales to strengthen market competitiveness.

(7) International, Domestic, and Industry Contexts. Globally, the manufacturing landscape has undergone profound changes. Domestically, China' s low-cost advantage is gradually diminishing, and the overall technology gap with industrial powers remains significant, revealing weaknesses in traditional manufacturing. In this context, China urgently needs transformation to achieve high-quality development.

(8) Value Chain Driving. Currently, China' s manufacturing sector remains at a lower position in the global value chain, related to late transformation and insufficient technological support. To change this situation, China implements a "bottom-up" manufacturing upgrading route with substantial development potential. Thus, value chain driving can promote transformation development.

2.3.2 Obstacle Factors **(1) Insufficient Industrial Foundation and Technical Support.** China' s manufacturing core key technologies remain relatively weak, with some enterprises' equipment not yet basically automated, lacking core competitiveness compared with developed economies. Under such weak foundations, transformation faces constraints, lacks security and stability, and risks being restricted or impacted by developed economies.

(2) Data Openness and Sharing Obstacles. Data has become a crucial strategic resource for transformation. Although China has made significant progress in public data opening, a standardized, interconnected public data platform system has not yet formed, resulting in low data practicality, weak accessibility, and unremarkable application outcomes, thereby hindering high-quality transformation.

(3) Data Security Risks. Manufacturing data covers equipment, products, operations, and other aspects. Leakage during collection, storage, and application would cause severe data security risks. Once data is tampered with or disseminated, it could disrupt production processes and threaten enterprise and customer privacy.

3. Development Logic and Path of Digital and Intelligent Integration Transformation in Manufacturing

The transformation can be viewed as a dynamic development process based on causal relationships. The preceding analysis reveals numerous elements with complex interrelationships, forming a "stable yet dynamic" development process. Against this backdrop, traditional manufacturing utilizes digital technologies, relying on open and shared data resources, to achieve digital-intelligent integration across R&D, production, sales, and other processes, continuously catalyzing digitalization and intelligence in manufacturing. To more comprehensively and intuitively demonstrate causal relationships among elements and clarify the mechanism of transformation, we construct a network model based on the earlier analysis of goal elements, principal elements, and influencing factors.

Flow diagrams use clear, intuitive symbols to depict logical relationships among system elements, clarify variable properties, and illustrate feedback forms and control laws of complex processes. The four basic elements include: state variables (describing accumulation effects and serving as core process variables), rate variables (corresponding to state variables and describing the speed of accumulation effect changes), and auxiliary variables and constants (directly or indirectly affecting stocks or flows to describe causal feedback relationships). In our model, the state variable is the development level of digital-intelligent integration transformation, while rate variables include transformation development effectiveness and transformation development maladaptation.

3.1 Logic Analysis of Digital and Intelligent Integration Transformation Development

To construct the network model, we analyze the transformation logic under different principal drivers.

(1) Government-Driven Logic. On one hand, digital government construction enhances government regulation capacity, significantly improves government information disclosure and application, achieves effective aggregation of social data information, and reduces information dispersion, thereby promoting data resource accessibility. However, without data security policies, this may increase risks of enterprise privacy data leakage. Meanwhile, fundamental changes in government governance models create new digital-intelligent government operation forms, providing support for transformation. On the other hand, as government policies continuously improve, they encourage producer services and other industries to provide collaborative feedback to manufacturing through innovative development, effectively assisting transformation and enhancing market competitiveness. These achievements, in turn, increase demand for government support, forming a beneficial cycle.

(2) Enterprise-Driven Logic. With government policy support, manufacturing enterprises strengthen talent team building, improve digital infrastructure, and enhance new-generation IT application, thereby elevating digital-intelligent production management levels. Additionally, enterprises prioritize innovation-driven development, continuously increasing innovation resource investment and improving transformation efficiency, which enhances digital-intelligent levels, strengthens green development capabilities, and boosts market competitiveness, forming a positive feedback loop.

(3) University and Research Institute-Driven Logic. Universities cultivate high-quality, high-skill talent for manufacturing enterprises, strengthening talent teams and enhancing digital-intelligent levels and market competitiveness. Meanwhile, universities and research institutes are vital components of government-industry-academia-research collaboration, effectively aggregating resources including talent and data through this cooperation model. By jointly building innovation service platforms with government and enterprises, they increase capital support for core technology R&D and enhance achievement transformation capabilities, ultimately improving transformation levels. This positive feedback continuously increases enterprise demand for digital-intelligent talent, further motivating universities and research institutes.

(4) Platform Enterprise-Driven Logic. With participation of digital platform enterprises, data resources can be effectively integrated, improving resource allocation efficiency and data integration capabilities. This enhances online and offline information interaction, accelerates effective information acquisition, reduces data search costs, and improves transformation capabilities. Furthermore, through the construction of digital manufacturing and service systems, real-time monitoring of production operations optimizes production lines, forming a beneficial cycle that continuously improves transformation levels and elevates China' s manufacturing position in the global value chain.

(5) Intermediary Organization-Driven Logic. With government policy support, improving enterprise innovation financing systems enables financial institutions to provide funding for production, talent cultivation, R&D, and marketing, alleviating financing pressure and enhancing financial risk response capabilities, thereby promoting transformation. Financial institutions continue increasing investment after receiving returns, forming a virtuous cycle. Simultaneously, data management centers facilitate orderly, secure data circulation among enterprises, guiding them to improve data-driven resource allocation capabilities and better achieve digital-intelligent integration, thereby enhancing market competitiveness and supporting high-quality transformation.

(6) Consumer-Driven Logic. Under the social influence of transformation, consumers increasingly participate by supervising and providing feedback on products and services. Public supervision platforms create channels for consumer voices. The public serves as both consumers and supervisors, strengthening oversight of enterprises and prompting targeted improvements. This supervision further enhances enterprise digital-intelligent integration levels, satisfying consumers' diverse, personalized, and digital experience needs, which further improves consumer supervision capabilities, forming a virtuous cycle.

3.2 Path Analysis of Digital and Intelligent Integration Transformation Development

Based on the preceding analysis of key elements and logic, and following principles of representativeness, priority, and conciseness, we select relevant variables according to system dynamics feedback principles and construct a comprehensive network model using Vensim PLE software [Figure 1: see original paper]. The model reveals 19 feedback loops, analyzing the cyclical process of interaction and joint advancement among system elements to uncover development mechanisms and operational laws, providing a theoretical basis for indicator system construction.

The model shows numerous factors acting on the system, while transformation development, in turn, affects internal variables. The system contains many feedback loops that complement and intersect each other. Vensim PLE identifies six core feedback loops reflecting actual system operation:

Path 1: Development level → Digital economy-manufacturing integration degree → Digital infrastructure completeness → Digital-intelligent production management level → Manufacturing green development capability → Market core competitiveness → Development level (positive).

Path 2: Development level → Digital government construction → Government digital strategy implementation → Government governance model transformation → Social information dispersion → Data resource accessibility → Enterprise data leakage risk → Development level (negative).

Path 3: Development level → Financial institution funding capacity → Enterprise financial risk response capability → Enterprise product sales revenue → Digital-intelligent level → Green development capability → Market competitiveness → Development level (positive).

Path 4: Development level → Government-industry-academia-research collaboration level → Core technology R&D achievements → Innovation and service platform construction → Product quality and innovation degree → Digital-intelligent level → Green development capability → Market competitiveness

→ Development level (positive).

Path 5: Development level → Innovation resource R&D investment → Production manufacturing efficiency → Innovation achievement transformation efficiency → Digital-intelligent production management level → Digital-intelligent level → Green development capability → Market competitiveness → Development level (positive).

Path 6: Development level → Public participation in governance → Public supervision role → Manufacturing digital-intelligent integration degree → Development level (positive).

Beyond these six main loops, other causal relationships exist among model elements, forming additional feedback loops. The analysis reveals that no principal element operates independently; each can influence others and impact the entire ecosystem. Every feedback loop has polarity—positive loops have self-reinforcing effects, while negative loops have self-regulating capabilities. The number of positive feedback loops exceeds negative ones, indicating that self-reinforcement outweighs self-regulation. Under the combined effects of both, the system ultimately reaches a stable state.

4. Evaluation Indicator System for Digital and Intelligent Integration Transformation Development

Building on the logic and path analysis, and combining relevant theoretical research, we construct an evaluation indicator system based on key elements and mechanism analysis. Using state variables from the network model as first-level indicators to reflect the actual status of system elements, and drawing from the six paths identified above, we design an evaluation system comprising 6 first-level indicators (industrial foundation, integration of informatization and industrialization, innovation-driven development, quality and efficiency improvement, governance system, and green development), 14 second-level indicators (digital foundation, enterprise foundation, digitalization level, etc.), and 36 third-level indicators . This indicator system applies to both horizontal evaluation of transformation levels across different regions and industry segments, and vertical evaluation across different development stages.

5. Conclusion

This study clarifies the main research trajectories and key issues regarding digital and intelligent integration transformation of manufacturing, extracting its goal elements, principal elements, and influencing factors. Based on industrial linkage theory, system dynamics theory, and related frameworks, we construct a comprehensive network model to analyze interaction mechanisms among elements. Through the operational mechanisms and paths revealed by this model, we establish an evaluation indicator system covering industrial foundation, integration of informatization and industrialization, innovation-driven development, quality and efficiency improvement, governance system, and green development, providing a theoretical reference for measuring and evaluating transformation development levels.

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