

Path and Effect Analysis of Digital Transformation for Small and Medium-sized Manufacturing Enterprises

Yinzhen Lin*

Hainan Vocational University of Science and Technology, Haikou, 571126, China

*Corresponding author: 15108901858@163.com

Abstract: *Small and medium-sized manufacturing enterprises face a structural contradiction between resource limitations and transformation complexity, and their digital transformation paths and effects present a unique logic. From the perspective of intrinsic capabilities, this study systematically explores the micro-foundations, path differentiation, and effect generation mechanisms of the transformation. The study reveals that digital mapping constitutes the micro-foundation of the transformation, organizational ambidexterity and resource orchestration mechanisms determine the efficiency of resource allocation, and digital technology embedding enhances the collaborative resilience of production networks. The transformation paths present three differentiated trajectories: gradual embedding based on the modularization of production processes, value extension based on the product-service system, and niche transition based on platform-based collaboration. The transformation effects manifest as structural improvements in operational efficiency, endogenous growth in innovation efficacy, and heterogeneity with non-linear characteristics in economic performance. The analytical framework constructed in this study provides a theoretical reference for understanding the micro-mechanisms of digital transformation in small and medium-sized manufacturing enterprises.*

Keywords: *Small and Medium-sized Manufacturing Enterprises; Digital Transformation; Transformation Paths; Operational Efficiency; Innovation Efficacy; Economic Performance*

Introduction

Digital transformation in the manufacturing industry is an important topic in the research of industrial organization and enterprise management. As the micro-level entities of the industrial system, small and medium-sized manufacturing enterprises present a unique logic in their transformation process that differs from that of large enterprises. Compared with large enterprises with abundant resources, small and medium-sized manufacturing enterprises face multiple constraints in terms of capital, talent, and absorptive capacity during the digitalization process, and the generation of transformation paths and effects exhibits stronger contingency characteristics and contextual dependence. Existing studies mostly focus on the technological or macro-industrial level, and they lack sufficient exploration of the internal relationships among enterprise internal capability structures, resource orchestration mechanisms, and the differentiation of transformation paths. From the perspective of intrinsic capabilities, this study focuses on the micro-foundations, path differentiation, and effect generation mechanisms of transformation, aiming to reveal the inherent logic of enterprises achieving digital breakthroughs under conditions of limited resources. It provides a theoretical reference for understanding the heterogeneity and processuality of digital transformation in small and medium-sized manufacturing enterprises, and also offers analytical tools and decision-making bases for enterprises to choose their transformation methods.

1. The Internal Logic of Digital Transformation and the Reconstruction of Core Elements

1.1 The Micro-Foundations and Value Drivers of Digitalization in Manufacturing Enterprises

The digitalization process of small and medium-sized manufacturing enterprises begins with the digital mapping of core elements on the production site. The micro-foundation of this process is embodied in the accurate description and computable representation of manufacturing resources,

process parameters, and operational workflows, which involves the standardization of data interfaces at the equipment level, the deployment of sensor network nodes, and the data integration of the manufacturing execution system. By transforming physical processing actions, material flows, and equipment statuses into structured data streams, an enterprise constructs a bidirectional mapping relationship between the digital space and the physical space, thereby providing a fundamental information carrier for subsequent optimization decisions. The degree of digitalization at this level directly determines the level of refinement an enterprise can achieve in areas such as process improvement, quality control, and cost management, and it constitutes a fundamental constraint on the depth of transformation^[1].

Based on these micro-foundations, the driving effect of digital technology on value creation in manufacturing enterprises is reflected in the reconstruction of coupling relationships across various links of the value chain. The previously fragmented activities of design, process, production, and delivery in traditional manufacturing operations are transformed into a continuous and traceable information flow through data integration, which effectively suppresses the efficiency losses and information distortions originally existing at the interfaces between processes. The introduction of data elements changes the temporal structure and spatial distribution of value creation, enabling an enterprise to complete a full closed loop from order acquisition to product delivery within a shorter response cycle. Meanwhile, the real-time data-based mechanism for operational status monitoring and anomaly warning reduces the uncertainty of the manufacturing process, enhances the enterprise's autonomous capacity to adjust to production fluctuations, and provides technical support for the stable output of value creation.

1.2 Organizational Ambidexterity and Digital Resource Orchestration

Small and medium-sized manufacturing enterprises face a structural contradiction between resource limitations and transformation complexity during the process of advancing digital transformation, and organizational ambidexterity serves as a key variable to reconcile this contradiction. Exploration capability is embodied in an enterprise's active experimentation and adaptive learning regarding new digital technologies, new business models, and new production organization methods, with its core lying in the construction of a technology adoption mechanism that allows for trial and error and rapid iteration. Exploitation capability, on the other hand, is manifested in an enterprise's deep mining and efficiency optimization of existing manufacturing assets, process knowledge, and management experience, focusing on the effective integration of digital technology and enterprise-specific knowledge within the current production system. The balancing relationship between these two capabilities is not a static issue of resource allocation proportions, but rather an evolutionary process of organizational capability that an enterprise dynamically adjusts across different development stages and varying depths of technology embedding.

The digital resource orchestration mechanism determines the allocation efficiency and transformation effect of limited resources during the transformation process. Small and medium-sized manufacturing enterprises usually do not have the conditions for large-scale, systematic digital investment, and their transformation paths present bottom-up modular characteristics. That is, they prioritize the completion of digital transformation at key nodes on the production site, form independently operable digital units, and then achieve system integration among these units through resource orchestration. In this process, an enterprise needs to identify the key processes or bottleneck links that have a leverage effect on overall operational efficiency, and it should allocate digital resources preferentially to these high-value points, thereby driving system improvement through local optimization. The effectiveness of resource orchestration depends not only on the directional choice of technology investment, but also on the enterprise's ability to combine and restructure digital assets with tacit resources such as process knowledge and operational experience. This type of combinatorial innovation constitutes the internal logic for small and medium-sized manufacturing enterprises to achieve transformation breakthroughs with limited resources.

1.3 The Construction of Production Network Resilience through Digital Technology Embedding

The production activities of small and medium-sized manufacturing enterprises are deeply embedded in upstream and downstream collaboration networks, and the embedding of digital technology changes the information transmission methods and coordination mechanisms among network nodes. The linear collaboration structure under the traditional model, which is bounded by orders and buffered by inventory, gradually evolves toward a networked collaboration structure based

on real-time data sharing. Digital technology enables the transparent transmission of status information, capacity information, and constraint information among various nodes in the supply chain, and upstream and downstream enterprises can achieve collaborative scheduling of production plans and resource allocation on a unified digital interface. This deep coupling at the information level reduces the bullwhip effect caused by information asymmetry, and it enhances the adaptive adjustment capacity of the production network under scenarios of demand fluctuations and supply disturbances^[2].

From the perspective of resilience construction, the impact of digital technology on production networks is reflected in two dimensions: response speed and reconfiguration capability. At the level of response speed, real-time data collection and edge computing capabilities enable an enterprise to achieve early identification of production anomalies and supply chain disruptions, thereby shortening the time window from the occurrence of a problem to the initiation of countermeasures. At the level of reconfiguration capability, digital production resource management and capacity matching mechanisms provide an enterprise with the flexibility to reconfigure internal production capacity, quickly switch suppliers, or adjust production plans under sudden disturbances. For small and medium-sized manufacturing enterprises at the network periphery, their resilience no longer depends solely on their own inventory buffers or capacity redundancies; instead, they form a distributed risk-sharing mechanism through digital collaboration with other nodes within the network. This digital connection-based collaborative resilience enables small and medium-sized manufacturing enterprises to maintain production continuity and stability in the face of market fluctuations and supply chain uncertainties by leveraging the adaptive capacity of the overall network.

2. Path Differentiation Characteristics and Evolution Mechanisms of Transformation

2.1 The Gradual Embedding Path Based on Production Process Modularization

Production process modularization constitutes the gradual embedding path for the digital transformation of small and medium-sized manufacturing enterprises. The essential characteristic of this path lies in the decomposition of the complete production system into relatively independent and clearly bounded digital transformation units, with each unit being functionally self-consistent and maintaining standardized interfaces, thereby allowing digital transformation to be initiated from a single process, a single piece of equipment, or a single production segment. Based on its own resource endowments and technological absorptive capacity, an enterprise preferentially selects production links that have a significant impact on overall operational efficiency or that involve lower transformation costs as the starting points for digital embedding. Through localized transformation, it accumulates technical experience and organizational experience, and then gradually extends to upstream and downstream processes, forming an evolutionary trajectory from point-based breakthroughs to linear integration and finally to area-wide coverage.

The evolution mechanism of the modular path is reflected in the gradual deepening of the coupling degree among digital units. In the initial stage of transformation, each digital unit mostly operates in an independent manner, and its optimization effect is limited to the improvement of production efficiency within the unit. As the standardization level of interfaces between units increases and data interaction mechanisms are established, the previously isolated digital units gradually form an interconnected digital network, and the production process shifts from segmented operations to continuous and collaborative operations. This evolutionary process is not simply a superposition of multiple digital units; instead, it achieves the unified coordination of production rhythms through the integration of information flows, systematically compresses the inter-process buffer inventory, and enables the rapid transmission of abnormal information across units, thereby allowing the enterprise to achieve system-level efficiency improvements while maintaining production flexibility.

2.2 The Value Extension Path Based on the Product-Service System

The construction of a product-service system represents a transformation path for small and medium-sized manufacturing enterprises from traditional product delivery to composite value provision. The core logic of this path lies in using the physical product as a carrier of value transmission. By embedding sensing, computing, and communication capabilities into the product, an enterprise enables the product to continuously generate data streams related to operating status, usage environment, and operational behavior during its use. With the help of these data streams, the enterprise gains insights into the actual performance and usage scenarios of the product at the customer's site, and it extends the

originally one-off transaction relationship into a sustained interactive relationship covering the entire product lifecycle. This transformation of value form allows the enterprise to obtain value-added revenue beyond product sales through services such as preventive maintenance, operational optimization, and payment-by-performance, thereby forming a virtuous cycle in which products and services reinforce each other^[3].

The evolution mechanism of the value extension path is based on the enterprise's capability for deep development of data assets. The data generated during product use do not automatically translate into value by themselves; instead, the enterprise needs to construct a technical chain for data collection, transmission, storage, and analysis, and it must convert the analysis results into specific services that customers can perceive. This process requires the enterprise to gradually cultivate data processing capabilities, domain knowledge modeling capabilities, and service delivery capabilities in addition to its traditional manufacturing capabilities. As the volume of accumulated data grows and analytical models iterate, the enterprise's understanding of product operational patterns deepens, and its service provision evolves from passive, responsive fault handling to active, predictive state management. The expansion of service scope simultaneously feeds back into the product design stage, enabling the enterprise to optimize product structures and parameter settings based on real-world usage data, thereby forming a virtuous cycle in which manufacturing and services mutually reinforce each other.

2.3 The Niche Transition Path Based on Platform-Based Collaboration

The platform-based collaboration path reflects the transformation mode in which small and medium-sized manufacturing enterprises leverage industrial platforms to achieve capability upgrading and market position shifts. In this path, an enterprise no longer restricts its digital construction to the transformation of its internal production system; instead, it proactively accesses industrial internet platforms, industry vertical platforms, or supply chain collaboration platforms built by leading enterprises, and it opens up its manufacturing capabilities, process expertise, and production capacity resources on these platforms through standardized interfaces. Through the intermediary and integration functions of the platform, the enterprise breaks free from its fixed role in the original division of labor within the industrial chain, matches its own capabilities with broader market demands, and obtains value creation opportunities beyond its original business boundaries. Platform-based collaboration enables small and medium-sized enterprises originally at the downstream or supporting positions of the industrial chain to participate, by virtue of their specialized manufacturing capabilities, in production division systems with higher added value.

The evolution mechanism of niche transition is embodied in the transformation of an enterprise from a single value network participant to a multi-network node role. In the traditional industrial chain structure, small and medium-sized manufacturing enterprises usually form fixed supporting relationships with a few core enterprises, and their business development and market risks are highly dependent on a single customer. Through platform-based collaboration, an enterprise simultaneously accesses multiple value networks and plays differentiated roles in different networks. It can act as a specialized manufacturer in a specific domain to undertake customized orders, serve as a capacity provider to participate in distributed manufacturing networks, and provide technical solutions to other enterprises by virtue of its process expertise. This state of multi-network embeddedness reduces the enterprise's dependence on a single channel and expands its market space. At the same time, the transaction records, performance evaluations, and technical reputation accumulated by the enterprise during platform interactions constitute transferable digital assets, which provide verifiable proof of capability for its movement upstream or toward higher-value-added links in the industrial division system, thereby forming a cumulative mechanism for gradual niche transition.

3. Multidimensional Measurement of Transformation Effects and the Mechanisms of Efficiency Generation

3.1 Structural Improvement of Operational Efficiency and Optimization of Factor Allocation

The improvement of operational efficiency through digital transformation is reflected in the systematic optimization of the structural parameters of the production system. Under the traditional manufacturing model, there exist information time lags and transmission distortions among planning, supply, operation, and inspection processes, which lead to an excessively high proportion of non-value-added waiting time in the production cycle, while equipment utilization is constrained by the

empirical judgment of manual scheduling. Digital technology enables the real-time status of the production site to be presented on the management interface, and the scheduling method shifts from periodic production planning to dynamic scheduling. Indicators at the operational level, such as overall equipment efficiency, production cycle time, and work-in-process inventory level, undergo systematic changes, thereby forming a structural improvement in production efficiency^[4].

The optimization of factor allocation is the deep mechanism behind the improvement of operational efficiency. Small and medium-sized manufacturing enterprises face rigid constraints on factors such as labor, equipment capacity, and capital, and the efficiency of resource allocation determines the output boundary. Through its data collection and analysis capabilities, the digital system reveals the mapping relationship between factor inputs and actual outputs, enabling an enterprise to identify the key constraint links that affect efficiency and to allocate its limited factors toward processes or products with higher marginal returns. The precise measurement of material consumption, energy use, and equipment loss by the digital system provides quantitative bases for factor substitution, allowing an enterprise to make marginal adjustments among different factor combinations and to achieve a higher output level without increasing the total amount of resource inputs.

3.2 Endogenous Growth of Innovation Efficacy and the Mechanism of Knowledge Accumulation

Digital transformation gives rise to the endogenous growth of innovation efficacy. Traditional innovation activities rely on the empirical judgment of research and development personnel and physical experiments, and they are characterized by long cycles, high costs, and great uncertainty. Digital technology integrates design, process, and validation into a unified platform, thereby shifting the innovation process from a linear and discrete mode to a parallel and iterative mode. An enterprise completes manufacturability analysis, process parameter simulation, and quality prediction evaluation in a virtual environment, which significantly reduces the frequency and cost of physical trial and error. The shortening of the innovation cycle and the reduction of trial-and-error costs increase the number of innovation attempts per unit of time, forming a cumulative improvement in innovation efficacy.

The knowledge accumulation mechanism constitutes the micro-foundation for the growth of innovation efficacy. The process knowledge and operational experience of small and medium-sized manufacturing enterprises mostly exist in a tacit form within the individual cognition of technical experts, and their inheritance and reuse face significant obstacles. The digital system performs structured storage and correlation analysis on parameter settings, anomaly handling records, and improvement records from the production process, thereby gradually transforming tacit knowledge into retrievable and reusable explicit knowledge and forming enterprise-level knowledge assets. The long-term trend analysis capability formed by data accumulation enables an enterprise to identify process correlations and quality-influencing factors that traditional experience has failed to cover, generating new cognitive increments beyond the existing knowledge boundaries and driving the transformation of innovation activities from experience-driven to data-driven.

3.3 Heterogeneity Characteristics and Nonlinear Evolution of Economic Performance

The impact of digital transformation on economic performance presents significant heterogeneity characteristics. Factors such as the specific sub-industry in which an enterprise operates, its technology intensity, market positioning, and existing management foundation jointly determine the path and efficiency of converting digital investment into financial performance. For technology-intensive manufacturing enterprises, the deep integration of digital systems with core processes is more likely to generate product performance or quality advantages, thereby obtaining market premium space. For labor-intensive manufacturing enterprises, performance improvement is more reflected in labor cost savings and enhanced production stability. An enterprise's position in the value chain also affects its performance outcomes. Enterprises closer to the end market are more likely to obtain customer demand information through digitalization and convert it into product improvement directions, while the performance improvement of supporting enterprises depends more on the coordination requirements and data-sharing extent of core enterprises^[5].

The nonlinear evolution of transformation effects manifests as a relationship that is not simply linear between digital investment and performance output. In the initial stage of transformation, concentrated investments in hardware procurement, system deployment, and personnel training occur, and the running-in process between the digital system and the existing production system may cause short-term efficiency fluctuations, resulting in a lag period for performance improvement. As the

coverage of digital units expands and the degree of system integration increases, the synergistic effects among various modules gradually release, and performance output exhibits an accelerating growth trend. When digital transformation reaches a certain depth, the enterprise enters a relatively stable range of performance improvement, where the marginal returns of further investment diminish. This S-shaped evolution trajectory indicates that the transformation effects are constrained by the interaction of multiple factors, including technological absorptive capacity, organizational adaptation, and system integration depth, and the release of economic performance presents phased characteristics^[6].

Conclusion

This study constructs a systematic analytical framework covering the internal logic, transformation paths, and effect measurement of digital transformation. The study reveals that the digital mapping of manufacturing resources constitutes the micro-foundation of the transformation, that organizational ambidexterity and resource orchestration mechanisms determine the efficiency of resource allocation, and that digital technology embedding enhances the collaborative resilience of production networks. The transformation paths present three evolutionary trajectories: gradual embedding based on the modularization of production processes, value extension based on the product-service system, and niche transition based on platform-based collaboration. The transformation effects manifest as structural improvements in operational efficiency, endogenous growth in innovation efficacy, and heterogeneity with nonlinear characteristics in economic performance. This study provides a theoretical reference for understanding the micro-mechanisms of digital transformation in small and medium-sized manufacturing enterprises, and future research can further explore the interaction mechanisms among transformation paths and the moderating effects of enterprise capability structures.

References

- [1] Huang Ying. *Path and Effect Analysis of Digital Transformation for Manufacturing Enterprises*. 2025. Guangdong University of Finance and Economics, MA thesis.
- [2] Cao Lu. "Research on the Digital Transformation Path of Small and Medium-sized Manufacturing Enterprises." *Wisdom China*, no.9 (2025): 118-119.
- [3] Fu Qiang. *Research on the Path of Data-Enabled Digital Transformation and Upgrading for Manufacturing Enterprises*. 2025. Harbin University of Science and Technology, MA thesis.
- [4] Wang Wen. *Analysis of the Effect of Policy Support for Digital Transformation of Small and Medium-sized Manufacturing Enterprises*. 2024. Taiyuan University of Technology, MA thesis.
- [5] Zhu Xiaoteng. *Three-Stage Path of Digital Transformation for Manufacturing Enterprises: Theoretical and Empirical Analysis*. 2023. Jiangsu University of Science and Technology, PhD dissertation.
- [6] Yuan Rongrong. *Research on the Digital Transformation Path and Strategy of Small and Medium-sized Manufacturing Enterprises*. 2021. Southeast University, MA thesis.