Research on the Evaluation of the Effectiveness of Digital Transformation in Manufacturing Industries

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Abstract: As China's economy transitions from a phase of rapid growth to one of high-quality development, the digital economy, as a pivotal force in reshaping the global competitive landscape, has been incorporated into the core pillars of national strategic planning. Based on a systematic review of existing literature and case studies of leading enterprises, this paper identifies prominent issues such as the prevalence of single-dimensional evaluation criteria in current manufacturing digital transformation efforts. To address these bottlenecks, the study proposes establishing a multi-dimensional indicator system to facilitate the development of a quantifiable, traceable, and comparable evaluation framework for digital transformation outcomes in manufacturing enterprises, thereby providing a reference framework that combines theoretical depth with practical guidance for industrial policy formulation and corporate management decision-making.

Keywords: Manufacturing Industry; Digital Transformation; Effectiveness Evaluation

1. Introduction

As the Chinese economy transitions toward high-quality development, the digital economy has become one of the core areas of national strategic deployment. The year 2022 marked the beginning of a new era for China's digital economy, characterized by deeper application, orderly regulation, and inclusive sharing. In the same year, relevant major policy directives at the national level further emphasized the need to accelerate the development of the digital economy, promote its deep integration with the real economy, and build internationally competitive digital industry clusters. Against this backdrop, the digital economy has not only become a new engine driving economic growth but has also demonstrated significant advantages in optimizing resource allocation, improving production efficiency, and facilitating industrial coordination. By strengthening the construction of digital infrastructure, promoting the market-oriented allocation of data elements, and cultivating digital industrial ecosystems, the digital economy is accelerating its penetration into traditional industries such as manufacturing, energy, and transportation, thereby helping to build a modern industrial system supported by digital technologies. At the same time, building internationally competitive digital industry clusters has become a key pathway to enhancing national innovation capacity and global industrial chain positioning. Against the backdrop of increasingly fierce global competition, rapid advancements in information technology, and widespread internet adoption, digital transformation has become an unavoidable priority for enterprises. For the manufacturing sector, digital transformation not only helps seize international market opportunities and enhance global competitiveness but also effectively addresses practical challenges such as difficulties in expanding into new markets, rising customer acquisition costs, supply-demand imbalances, quality disparities, and cost pressures. On May 11,2024, the State Council reviewed and approved the "Action Plan for Digital Transformation in Manufacturing," explicitly stating that "accelerating the digital transformation of manufacturing is a key measure for advancing new industrialization and building a modern industrial system" and highlighting its pivotal role in driving the manufacturing sector toward higher-end, smarter, and greener development. This policy direction underscores the national emphasis on the digital transformation of manufacturing and provides systematic support for its digital upgrading.

Digital transformation is fundamentally reshaping the manufacturing landscape, permeating every aspect from production processes and operational management to value creation, driving comprehensive innovation across industrial ecosystems. It serves not only as a critical safeguard for manufacturers to navigate external uncertainties but also holds significant potential for value enhancement and business expansion. By integrating production equipment, supply chains, and operational management into digital networks, enterprises can achieve real-time monitoring and intelligent optimization of production workflows, substantially boosting efficiency and resource utilization. Digital transformation enables precision predictive maintenance to effectively reduce equipment failure rates. Leveraging data analytics and AI technologies, companies gain greater flexibility in responding to market changes, facilitating personalized customization and rapid product iteration. Furthermore, digitalization connects the entire value chain from R&D to services, fostering supply chain synergy, lowering operational costs, and transitioning business models from standalone product manufacturing to integrated "product + service" solutions. These advancements not only strengthen corporate core competitiveness but also lay a solid foundation for achieving intelligent, green, and sustainable development in manufacturing.

However, the manufacturing sector still faces numerous challenges in advancing its digital transformation. Long-standing issues in traditional manufacturing—such as high energy consumption, low output, lengthy supply chains, and information asymmetry—have not been fundamentally resolved. Outdated technologies and processes, coupled with increasing environmental pressures, further complicate the transformation. Small and medium-sized enterprises, in particular, encounter multiple constraints in procurement, sales, financing, and management, leading to developmental challenges. Although the value of digital transformation for manufacturing is widely recognized, the specific pathways and practical outcomes for driving high-quality manufacturing development remain insufficiently studied or supported by empirical evidence, necessitating further in-depth exploration. Against this backdrop, conducting comprehensive and systematic evaluations of digital transformation within the manufacturing sector has become particularly urgent.

2. Literature Review on Digital Transformation

Amid the current wave of digital technology, digital transformation has emerged as a pivotal global development trend; however, the academic community has yet to reach a unified consensus on its definition. Yang Zhusan and Li Xin [1] note that digital transformation is often referred to as digital reform or the digitalization process, with its core lying in organizations leveraging digital technologies to reshape their business models and value delivery methods, thereby enhancing operational efficiency, driving business innovation, and optimizing customer experience. Synthesizing existing research, corporate digital transformation can be understood as a deep integration of "enterprise + technology + data," characterized by model innovation, value creation, and the emergence of new economic forms.

To align with the digital economy development trend, numerous developed countries have incorporated promoting the digital transformation of traditional real economies into their national strategies. In research on the key actors driving corporate digital transformation, scholars predominantly focus on three roles: enterprises, governments, and platforms. Chudaeva et al. [2], based on practical industrial operations, proposed innovative digital transformation recommendations aimed at enhancing corporate efficiency and market competitiveness through improved data processing, organizational restructuring, and upgraded production equipment. Additionally, some studies emphasize the pivotal role of governments in this transition; Chen et al. [3] demonstrated that government support and policy incentives significantly influence corporate digital transformation. Beyond governmental support, digital technologies themselves—as critical enabling factors—have garnered widespread attention for their transformative impact on business operational models. In this context, Fan Decheng and Wang Ya [4] argue that corporate digital transformation enables online transactions through data circulation and sharing, freeing business processes from temporal and spatial constraints.

The advancement of digital transformation is influenced by a complex interplay of multiple factors, with numerous studies identifying key success factors across various industries and theoretical perspectives. In the construction sector, Zhong et al. [5] identified 15 critical success factors and extracted the three most significant ones. Research on knowledge-intensive service enterprises demonstrates that digital technology, transformative leadership, and open innovation exhibit strong synergistic effects, while collaboration networks between professional communities and public sectors prove crucial. Chang and Chen [6] developed a key factor model for digital transformation using personnel, process, and technological frameworks, highlighting innovation and integration as key indicators of transformation success. Additionally, Buccieri [7] emphasized that internal/external resource utilization, dynamic capability building, and strategic execution are pivotal drivers of corporate digital transformation. Liu Huiling and Qi Ruili [8], based on the TOE theoretical framework, validated the predictive power of five variables—the proportion of R&D personnel, R&D investment levels, organizational financing constraints, the development of inclusive finance, and industry competitiveness—on corporate digital transformation.

Based on the identification of these key factors, exploring pathways for digital transformation has naturally extended to both practice and research. In this context, Margiono [9] categorizes such pathways into two types: offensive and defensive. The offensive approach emphasizes rapid expansion of digital operations through proactive investments and mergers and acquisitions, while the defensive approach focuses on gradually building internal digital capabilities through a step-by-step transformation strategy. Alqoud et al. [10] employed a multi-criteria decision-making method to evaluate various digital transformation options, providing a basis for pathway selection. Overall, researchers worldwide generally agree that digital transformation creates multiple value propositions for enterprises, including upgrades to production models and enhanced competitive advantages.

With the accelerated advancement of digital transformation, how to scientifically and effectively evaluate corporate digitalization levels has become a central issue of shared concern among both academia and practitioners. Scholars have developed diverse evaluation models and methodologies from multiple perspectives, providing robust theoretical foundations and practical tools for accurately measuring corporate digital transformation progress. Current research primarily focuses on the construction of evaluation frameworks, methodological innovations, and empirical applications. Regarding evaluation frameworks, numerous scholars have established multi-dimensional assessment systems based on maturity models. Li [11] developed a digital maturity evaluation framework for small and medium-sized enterprises across four dimensions—digital strategy, operational technology, cultural organizational capabilities, and ecosystem—and employed the AHP-DEMATEL method to examine the impact mechanisms of digitalization on product transformation capabilities. Similarly, Chen et al. [12] comprehensively applied the decision laboratory method, network analysis hierarchy method, and fuzzy comprehensive evaluation to assess the digital maturity of small and medium-sized manufacturing enterprises. Liu Lu and Zhao Huijuan [13] utilized the analytic hierarchy process, identifying digital equipment and technology adoption as key factors influencing the digital transformation capabilities of automotive manufacturers. In terms of evaluation methods, the entropy weighting method, TOPSIS, and its extended variants have been widely adopted. Zhang Chengxin [14] analyzed real-world data using entropy weighting and TOPSIS methods, demonstrating that digital transformation positively drives corporate growth. Liu and Wang [15] determined weights based on information entropy and employed the TOPSIS and PDHL-TOPSIS methods based on DHHFLTSS for evaluating digital transformation capabilities. Additionally, Zhang Lingang et al. [16] combined the improved entropy weight method with the grey relational model to assess the level of digital transformation in the manufacturing sector across various regions of China. Some studies focused on analyzing the performance and impact mechanisms of digital transformation. Liu Zhaoning and Zhang Shushan [17], on the other hand, systematically evaluated the effectiveness of digital transformation in promoting the "coordinated development of efficiency and resilience" in enterprises through a coupling coordination model.

Furthermore, several scholars have conducted systematic evaluation studies focusing on specific industries or macro-level contexts.

Zhang Jingyu [18] integrated the Cloud Model, IPA Model, and PSM-DID Model to establish a digital transformation benefit evaluation framework tailored for power grid enterprises. Fu Yuhan et al. [19], leveraging large-scale corporate data and the Analytic Hierarchy Process (AHP), found that digital transformation in Chinese manufacturing enterprises remains largely in its infancy, with business transformation continuing to be a widespread challenge.

3. Issues in Performance Evaluation and Their Solutions

A systematic review and in-depth analysis of existing literature reveal that scholars worldwide have achieved substantial research outcomes and significant progress in defining the connotation of digital transformation, identifying its multidimensional driving factors, and establishing mainstream evaluation methodologies. These studies provide a solid theoretical foundation for understanding the fundamental logic of digital transformation, identifying key influencing variables, and constructing preliminary analytical frameworks. However, regarding the core issue of accurately measuring and comprehensively evaluating transformation outcomes, existing research still exhibits several critical shortcomings, which are specifically manifested in the following two aspects.

First, while existing research extensively explores pathways for transformation implementation, key influencing factors, and the construction of macro-theoretical frameworks, it generally lacks a systematic and actionable performance evaluation framework. Most studies focus on qualitatively describing transformation processes and their phased characteristics, with insufficient attention paid to quantifying the actual performance improvements achieved. Specifically, the absence of unified quantitative metrics and standardized data standards makes it difficult for enterprises to accurately measure the tangible returns from substantial digital investments across various dimensions—such as economic benefits (revenue growth, cost savings, profit improvements), operational efficiency (shortened production cycles, enhanced inventory turnover rates, improved equipment utilization efficiency), and innovation capabilities (new product development speed, R&D investment conversion rates, and digital service generation capacity). More critically, the lack of comprehensive evaluation tools prevents enterprises from identifying value creation opportunities and resource misallocation during transformation, hindering timely strategic adjustments. This deficiency not only limits corporate performance attribution capabilities and investment decision-making but also impedes academic efforts to conduct cross-case comparisons and theoretical synthesis regarding digital transformation outcomes.

Second, existing research predominantly adopts macro-level industrial policy or meso-level regional cluster perspectives for analysis—focusing on national digital strategy frameworks, industry-wide digital penetration rates, or digital synergies within specific industrial parks and clusters. While these approaches help capture overarching trends and policy directions, they lack sufficient depth and granularity in examining corporate operational dynamics at the micro level. Specifically, current literature rarely provides refined, differentiated comparative analyses tailored to variations in enterprise size, industry characteristics, and lifecycle stages. In terms of scale, large conglomerates and small-to-medium manufacturing firms exhibit significant differences in digital resource acquisition capabilities, organizational resilience to transformation, and risk appetite for digitalization. Regarding industry attributes, discrete manufacturing versus process manufacturing, and high-tech industries versus traditional labor-intensive sectors, demonstrate markedly distinct pathways for realizing digital value due to differences in production processes, supply chain structures, and market demand patterns. Across corporate lifecycle stages—startups, growth phases, maturity phases, and even decline phases—enterprises exhibit distinct transformation objectives, investment intensities, and evaluation priorities. Ignoring these heterogeneity factors often leads to one-size-fits-all evaluation conclusions with limited external validity, failing to effectively guide differentiated corporate practices.

Addressing the aforementioned research gaps, this paper draws extensively on and critically incorporates existing approaches to model design for effectiveness evaluation. It aims to develop a more explanatory and applicable evaluation model for the digital transformation of China's manufacturing sector, grounded in its specific context and industrial characteristics.

The model seeks to achieve dual objectives: theoretically, to further enrich the research framework on digital maturity and performance evaluation, filling gaps in existing literature regarding micro-level analysis, heterogeneous comparisons, and systematic indicator construction; practically, to provide manufacturing enterprises with intuitive diagnostic tools and decision-making references, enabling them to identify their strengths, weaknesses, and areas for improvement during the transformation process, thereby optimizing resource allocation and enhancing the return on digital investments.

At the level of specific research design and methodological framework, this paper strictly adheres to a systematic technical approach—from indicator screening and weight allocation to model evaluation and strategy optimization—ensuring the rigor of the research process and the reproducibility of its findings.

First, in the indicator selection phase, this study employs the Technology, Organization, and Environment (TOE) framework—a theoretical model proposed by Tornatzky and Fleischer in 1990. The framework posits that three factors—technology, organization, and environment—collectively influence an enterprise's adoption and implementation of new technologies. The technology dimension encompasses elements such as existing IT infrastructure, digital tool compatibility, and data security standards; the organizational dimension includes factors like senior leadership support, employee digital literacy, and organizational cultural agility; while the environmental dimension involves market competition pressures, supply chain collaboration requirements, and government policy support. By addressing common pain points and value anchors identified in manufacturing transformation practices, the study meticulously selected multidimensional evaluation indicators. Key pain points include challenges in equipment interoperability, severe data silo phenomena, and a shortage of interdisciplinary talent; value anchors focus on cost reduction and efficiency improvement, quality enhancement, flexible production, and service-oriented extensions. To ensure the final indicator set combines theoretical rigor with industry relevance, the study combined bibliometric analysis with expert interviews to preliminarily identify over thirty candidate indicators. These were refined through two rounds of the Delphi method, ultimately forming an evaluation system comprising four primary dimensions—technology foundation, organizational capability, environmental support, and performance outcomes—with twelve secondary indicators each.

Secondly, in the weight allocation process, to balance the guiding role of expert judgment with the variability in objective data distribution, this paper comprehensively employs both the sequential relationship analysis method and the criterion-related importance method based on indicator correlation to derive subjective and objective weights respectively. The sequential relationship analysis method, commonly referred to as the G1 method, is an improved version of the Analytic Hierarchy Process (AHP). It allows experts to rank indicator importance and assign rational ratios between adjacent indicators, thereby eliminating the cumbersome consistency check required in traditional AHP while preserving the structured guidance value of expert knowledge. The criterion-related importance method, abbreviated as the CRITIC method, quantifies information content based on the internal variation (standard deviation) of indicators and their inter-indicator conflict (correlation coefficient), being entirely data-driven and effectively mitigating human judgment biases. Crucially, to address potential weight polarization or subjective errors associated with single-weighting methods, this study innovatively incorporates equilibrium concepts from game theory, establishing a combined weighting model integrating the G1 and CRITIC methods. The core logic of this model treats the subjective and objective weight vectors as two players in a game, optimizing their compromise solution to minimize overall deviation between combined and individual weights. This approach significantly reduces information loss and conflicts, ensuring the scientific rigor and robustness of the final weight allocation scheme. Compared to simple weighted averages or multiplicative combinations, game-theoretic combination weighting offers greater flexibility in adapting to the varying data characteristics of different indicators and the differing levels of confidence in expert judgments, making it particularly suitable for evaluation scenarios like manufacturing digital transformation, which are characterized by both complexity and ambiguity.

Finally, during the model measurement phase, addressing the inherent ambiguity and randomness prevalent in evaluating digital transformation effectiveness, this study employs the Kuo-Tuo Cloud Model for comprehensive assessment of sample enterprises. The Kuo-Tuo Cloud Model is a hybrid evaluation tool integrating the material-element transformation theory from Kuo-Tuo Science with cloud-based uncertainty representation methods. Kuo-Tuo Science establishes classical domains, partition domains, and correlation functions to effectively characterize the evolutionary patterns of qualitative-to-quantitative changes, while the cloud model utilizes three numerical metrics—expectation, entropy, and super-entropy—to convert qualitative descriptions (e.g., "significant transformation outcomes," "moderate outcomes," or "poor outcomes") into quantitative membership distribution scores, while preserving the inherent fuzziness and randomness of the evaluation process. This integration enables the model to facilitate bidirectional conversion between qualitative concepts and quantitative values, accurately mapping transformation effectiveness rankings and evolutionary trends. In practice, the study first defines four evaluation tiers—excellent, good, average, and poor—and calculates each sample's cloud correlation scores across these tiers based on indicator data. Subsequently, weighted aggregation using game-theoretic weighting formulas determines each enterprise's effectiveness tier and its proximity to adjacent tiers. Building on this framework, the study proposes targeted optimization strategies addressing both common weaknesses (e.g., widespread data governance deficiencies across industries) and heterogeneous challenges (e.g., significant variations in organizational agility among enterprises of different sizes). In response to these issues, this paper recommends: for small and medium-sized enterprises (SMEs), providing lightweight, low-cost, and modular digital transformation toolkits; for the process manufacturing industry, enhancing equipment interconnectivity and real-time monitoring capabilities; and for mature enterprises, guiding them to transition from efficiency improvements to business model innovation.

In summary, this paper starts from the theoretical gap and constructs a digital transformation effectiveness evaluation model for China's manufacturing sector by integrating the theoretical framework of technology and organizational environment, the game-theoretic combination weighting method, and the extensible cloud model. The model balances the systematicness and specificity of indicators, the scientific rigor and robustness of weights, as well as the precision and ambiguity of measurements, making it highly valuable as a reference for both academic research and corporate management practices. Future studies could further expand the sample scope, incorporate longitudinal tracking data, and explore dynamic evaluation and intelligent early-warning mechanisms to continuously enhance the model's applicability and explanatory power.

4. Conclusion

Against the backdrop of digital transformation deeply permeating global industrial chains, establishing a scientific, dynamic, and actionable performance evaluation system has evolved from a long-term corporate strategy into an urgent core strategic imperative. This urgency stems from the interplay of multiple real-world pressures: Externally, intensifying industry competition and the capital market's rigorous scrutiny of growth certainty compel companies to provide quantifiable evidence demonstrating how substantial digital investments translate into differentiated business value and sustainable competitive advantages. Internally, the organizational restructuring, process reengineering, and equipment upgrades inherent to transformation often incur enormous costs. Without a navigation mechanism grounded in precise return-on-investment analysis to guide resource allocation and path alignment, enterprises risk losing strategic direction amid complex technology selection decisions and transformational uncertainties. Without this critical feedback loop for performance evaluation, digital transformation risks degenerating into a blind race of technological accumulation—resulting in excessive resource consumption without cultivating future-oriented core competitiveness, instead plunging companies into a vicious cycle where higher investments lead to greater deviations from strategic objectives.

Building on a profound analysis of these fundamental challenges, this paper adopts a methodologically tailored approach to strike an optimal balance between scientific rigor and explanatory power in evaluation. To address the limitations of single-weighting perspectives, the study employs the Order Relationship Analysis Method (G1 method) to capture the subjective biases inherent in expert expertise, while utilizing the CRITIC weighting method to identify objective conflicts and volatility within indicator data, thereby calculating both independent and correlated weights for evaluation metrics. To mitigate extreme deviations between subjective and objective weights caused by information dispersion, the paper introduces equilibrium negotiation principles from game theory, establishing a G1-CRITIC hybrid weighting model that minimizes discrepancies between weight vectors to ensure scientific validity and robustness of the manufacturing digital transformation evaluation framework. Furthermore, addressing common challenges in transformation effectiveness assessment—including ambiguous evaluation boundaries and difficulties in converting qualitative insights into quantitative data—the study employs the Extensible Cloud Model as its core measurement tool. This model integrates the logical advantages of matter-element extension theory in resolving contradictory issues with the flexible representation capabilities of the Normal Cloud Model for uncertain knowledge, enabling precise characterization of transformation outcomes across multidimensional hierarchical scales. This framework provides solid methodological support for accurate evaluation and targeted policy implementation in manufacturing digital transformation initiatives.

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