Social Science and Management
Print ISSN: 3007-6854
Online ISSN: 3007-6862
DOI: https://doi.org/10.61784/ssm3079

ZHAOQING CITY'S "DUAL-TRANSFORMATION SYNERGY" DEVELOPMENT MECHANISM

ZiLing Wang, YongXin Peng, LianHua Liu*
School of Management, Guangzhou Huashang College, Guangzhou 511300, Guangdong, China.
**Corresponding Author: LianHua Liu*

Abstract: Amid the accelerated restructuring of the Guangdong-Hong Kong-Macao Greater Bay Area supply chain network, the competitive advantages of node cities are gradually shifting from factor costs to capability embedding and functional stratification. This study constructs an analytical framework—"supply chain network restructuring—dual transformation synergy—structural leap"—based on system coupling theory. Using entropy weight analysis and the coupling coordination index model, it measures the levels of digitalization and green development and their synergy status across 21 cities in Guangdong Province. Focusing on Zhaoqing City, it identifies its structural potential and the constraints on transformation. Findings reveal a pronounced gradient in Guangdong's dual-transition coordination, with coupling coordination degree ranging from 0.725 to 0.191 on average, forming a pyramid-shaped structure characterized by "core polarization—secondary core transition—peripheral reception." Shenzhen and Guangzhou form a highly synergistic core zone, while Dongguan and Foshan are in the phase of functional enhancement. Most cities remain in the structural adjustment phase. Zhaoqing exhibits a coupling coordination index of only 0.146, with its digitalization index significantly lower than its greening index, resulting in a structurally asymmetric state of "relative green leadership—marked digital lag." Its relative gap coefficient is 0.723, indicating a pronounced gradient fault line relative to core cities. From a supply chain embedding perspective, Zhaoqing's insufficient coordination stems from inadequate depth of digital capability embedding and limited spillover absorption capacity. This study provides quantitative evidence to identify the structural positions and transformation pathways of peripheral cities during regional network restructuring.
Keywords: Greening; Digitalization; Dual-transformation coordination; Zhaoqing city; Structural leap

1 INTRODUCTION

Against the backdrop of accelerating global supply chain restructuring and regional value chain reallocation, the Guangdong-Hong Kong-Macao Greater Bay Area is transitioning from scale-driven expansion to a phase of networked functional reorganization. Supply chain competitiveness no longer hinges on a single cost advantage but rather on the comprehensive capabilities of node cities in technological embedding, institutional adaptation, and green compliance. Core cities reinforce their hub status through digital platforms and innovation resources, while peripheral cities face structural pressures from functional lock-in and insufficient capacity to capture value. As a key node in the western Bay Area, Zhaoqing's transformation trajectory has shifted from traditional factor-based reception to capability embedding and structural leapfrogging.

Against this backdrop, the "dual-track synergy" holds critical institutional significance. Digitalization reconfigures production organizations and collaboration models by enhancing information flow efficiency and supply chain visibility. Green transformation reshapes industrial upgrading trajectories and market-access logic through institutional constraints and energy-efficiency standards. When these two tracks interact synergistically, they collectively elevate a city's embedding depth and functional tier within the supply chain network. However, in practice, these two dimensions often develop asynchronously: the expansion of the digital economy may be accompanied by rising energy consumption pressures, while improvements in green governance may struggle to achieve efficiency gains due to weak technological foundations. This mismatch in pace undermines the systemic effectiveness of efforts to enhance node functionality.

Existing research predominantly focuses either on digital transformation or on green development performance, or solely analyzes supply chain network structures, with insufficient exploration of the mechanisms by which dual transformation synergy is embedded within the context of supply chain restructuring. Therefore, this paper adopts a systems-coupling and network-embedding perspective to construct an analytical framework of "supply chain network restructuring—dual transformation synergy—structural leap." It explores how cities in Guangdong Province enhance node functionality through dual transformation synergy, transitioning from peripheral receiving nodes to functional network nodes, while identifying structural constraints and institutional bottlenecks in this process.

2 LITERATURE REVIEW

2.1 Theoretical Logic of Synergistic Development of Digitalization and Green Transformation

Against the backdrop of concurrent advancement in the digital economy and green low-carbon transition, the synergistic development of digitalization and green transformation has gradually emerged as a crucial pathway for driving high-quality economic development. Academic consensus holds that digital technologies can significantly enhance the efficiency of resource allocation through data integration, improved information transmission, and intelligent restructuring of production processes. Meanwhile, green transformation achieves carbon reduction, emission cuts, and ecological optimization via green technological innovation and environmental governance, creating clear functional complementarity between the two [1].

Theoretically, multidimensional coupling exists between digitalization and greening. Building on coordination theory and dissipative structure theory, Qi Yudong et al. posit that digitalization and greening can be viewed as interdependent complex systems. Through the regulation of institutional, capital, and spatial mechanisms, they achieve coordinated evolution, forming three development models: technology-driven, regulation-driven, and spatial network-driven [1]. Chen Xingxing et al. further propose that the synergistic transformation of digitalization and greening is a dynamic process driven by multidimensional interactions among technology, institutions, and markets, with its development path evolving in stages from “interconnection” to “deep synergy” [2].

From the perspective of development drivers, the synergy between digitalization and greening serves not only as a key impetus for industrial upgrading but also as a vital pathway for cultivating new productive forces. Research indicates that embedding digital technologies into green technological innovation processes can generate novel production methods and industrial models, thereby transforming economic growth patterns [3]. In agriculture, the integration of digital technologies with green production methods advances the formation of new productive forces across three dimensions: factors, structure, and function [4]. Consequently, “dual-transformation synergy” has emerged as a critical theoretical lens for explaining industrial transformation and economic structural upgrading.

2.2 Measurement Methods and Spatial-Temporal Patterns of Digital-Green Synergy

Empirical studies typically measure the level of digital-green synergy by constructing indicator systems and applying coupling coordination models. Wang Wenzhi et al. developed an evaluation framework for “dual synergy” based on city-level data, revealing distinct spatial differentiation and significant spatial clustering in China's regional development of digital-green synergy [5].

Within sector-specific research, logistics and manufacturing have become key domains for studying dual-transformation coordination. Li Xuhui et al. analyzed the coordinated development of digitalization and greening in China's logistics sector using a coupling coordination model. They observed an overall upward trend but noted pronounced regional disparities, characterized by a development pattern of “eastern leadership, accelerated central-western progress, and northeastern lag” [6]. Li Gen et al. similarly observed in manufacturing research that China's manufacturing sector overall remains in a “barely coordinated” stage of dual transformation, exhibiting a spatial structure characterized by “eastern leadership, central pressure, and western catch-up” [7].

Regional-level studies also confirm that dual transformation exhibits pronounced spatial gradient characteristics. Wu Chuanqing et al. observed in their study of the middle Yangtze River region that the level of digital-green synergy generally increased, yet marked disparities existed between cities. Key influencing factors included economic development levels, informatization levels, and government regulations [8]. In research on the Yangtze River Delta urban cluster, digital-green synergy exhibited pronounced spatial spillover effects, forming a “core-periphery” spatial structure [9]. Furthermore, some studies analyze the dynamic evolution of “dual-transformation synergy” from a cross-regional perspective. For instance, research in the Yellow River Basin reveals an overall upward trend in the level of synergistic development between digitalization and greening, yet significant disparities exist across different regions, exhibiting characteristics of uneven development [10]. Studies in the energy sector indicate that the synergistic development of digitalization and greening in energy systems follows a decreasing spatial pattern from east to west [11].

Overall, existing research generally recognizes that the synergistic development of digitalization and greening exhibits pronounced regional disparities and spatial clustering characteristics, with its development level closely linked to economic development stages, industrial structures, and technological innovation capabilities.

2.3 Driving Mechanisms of Digitalization and Green Development Synergy

Regarding mechanism studies, scholars primarily explain the formation of “dual-transformation synergy” from perspectives such as technological innovation, institutional environment, and industrial structure. Sun Xin et al. found through provincial panel data analysis that technological innovation capacity, industrial structure upgrading, and government governance levels are key drivers of digitalization and green development synergy [12].

At the enterprise level, Zhang Zhiwei et al. indicate that the synergistic transformation of enterprise digitalization and greening significantly impacts corporate performance, exhibiting a nonlinear U-shaped relationship. Specifically, enterprises only achieve noticeable performance gains after reaching a certain level of synergy [13]. Concurrently, efficiency enhancement and cost optimization serve as crucial mediating mechanisms through which “dual-transformation synergy” influences corporate performance. Further research demonstrates that synergistic digitalization and greening not only improve corporate performance but also drive the formation of new, quality productive forces. Chen Yantai et al. employed an evolutionary game model to discover that the embedded innovation of digital and green technologies, along with the construction of multi-stakeholder collaborative networks, constitutes a crucial mechanism for fostering new-quality productive forces [14]. Jia Xiaolin et al. empirically analyzed the enabling effects of dual-transformation synergy on new-quality productive forces at the firm level, revealing that technological innovation and financing constraints play significant mediating roles [15].

At the supply chain level, some studies have begun examining the network effects of "dual transformation synergy." Gao Xinyi et al. indicate that synergistic alignment of digitalization and greening levels among upstream and downstream enterprises significantly enhances corporate green innovation capabilities, forming multiple synergistic pathways [16]. Related research also demonstrates that digital-green synergy can drive industrial chain upgrading through supply chain integration and innovation ecosystem construction [17].

2.4 Literature Review and Research Limitations

In summary, existing research has systematically explored the coordinated development of digitalization and greening across multiple dimensions, including theoretical logic, measurement methods, and mechanism analysis. Overall, "dual-transformation synergy" not only represents a crucial pathway for promoting high-quality economic development but also serves as an important theoretical tool for explaining industrial upgrading and regional structural evolution. However, current research still exhibits certain limitations. First, most studies focus on national or provincial scales, with insufficient attention to the synergistic structures and regional gradient differentiation at the city level [18]. Second, existing literature predominantly analyzes "dual-transformation synergy" from industrial development or regional economic perspectives, while rarely explaining its functional mechanisms through the lens of supply chain network structures [19]. Third, in regional synergy studies, the node functions and transformation pathways of peripheral cities during supply chain network restructuring remain under-researched [20].

Addressing these gaps, this study adopts a supply chain network restructuring perspective to construct an analytical framework for the coordinated development of digitalization and greening. It employs entropy-weight analysis and a coupling coordination model to assess the level of "dual-transformation synergy" in Guangdong Province's cities. Taking Zhaoqing City as a case study, it identifies its structural position within the regional supply chain network, thereby revealing the transformation pathways and mechanisms of peripheral cities in regional supply chain network restructuring [20-21].

3 RESEARCH METHODOLOGY AND DATA SOURCES

3.1 Theoretical Framework

This study constructs a theoretical analytical framework of "supply chain network embedding—dual transformation synergy—urban functional stratification." First, it establishes an evaluation index system for digitalization and greening, using the entropy weight method to measure the development levels of digitalization and greening in Guangdong cities. Second, it employs the coupling coordination model to measure the level of "dual transformation synergy" in cities and identify regional synergy structural characteristics. Third, it identifies cities' gradient positions within regional coordination structures through relative gap coefficients. Finally, it embeds these measurement results within a supply chain network structure perspective to analyze cities' functional positioning within regional industrial networks and their transformation pathways. This analytical framework reveals structural disparities in regional "dual-transformation coordination" development and explains peripheral cities' development paths during supply chain network restructuring.

Within this framework, digitalization and greening systems form the foundational dimensions of urban development capacity, while supply chain network structures constitute the spatial vehicle for urban functional stratification. A logical "capacity-structure-function" relationship emerges among these three elements: the level of digitalization-greening synergy determines a city's capacity structure; this capacity structure further influences the city's degree of embedding within supply chain networks; and the degree of network embedding ultimately determines the city's functional status within the regional economic system. This theoretical framework enables an explanation of spatial disparities in regional "dual-transformation synergy" development from a network structure perspective, providing theoretical grounding for peripheral cities to achieve industrial upgrading and structural transformation.

3.2 Indicator System Construction

The digital subsystem primarily reflects technological embedding capacity and information integration capability, encompassing indicators such as employment scale in information services, fiscal expenditure on science and technology, investment intensity in the information industry, and digital user base. The green subsystem reflects resource constraint capabilities and institutional compliance levels, encompassing indicators such as fiscal expenditure on energy conservation and environmental protection, energy consumption growth rate per unit of GDP, energy consumption growth rate per unit of industrial added value, and pollutant concentration levels. The selection of indicators balances industrial foundations and governance capacity dimensions, highlighting the supportive role of "dual transformation synergy" in enhancing supply chain embeddedness capabilities, see Table 1.

Table 1 Dual-Transformation Synergistic Development Indicator System

First-level Indicator	Second-level Indicator	Specific Indicator	Attribute	Code
Digital Development Level	Digital Industry Scale	Employment in the Information Service Industry (10,000 persons)	Positive	X11
		Employment in the Scientific Research Sector (10,000 persons)	Positive	X12
	Digital Innovation Investment	Expenditure on Science and Technology (100 million yuan)	Positive	X13
		Investment in Digital Industry (100 million yuan)	Positive	X14
	Digital Penetration	Mobile Phone Users (10,000 households)	Positive	X15
		Broadband Users (10,000 households)	Positive	X16
		Mobile Internet Users (10,000 households)	Positive	X17
Green Development Level	Green Governance Investment	Expenditure on Energy Conservation and Environmental Protection (100 million yuan)	Positive	X21
	Green Efficiency	Electricity Consumption (100 million kWh)	Negative	X22
		Energy Consumption per Unit of GDP Growth (%)	Negative	X23
		Electricity Consumption per Unit of GDP Growth (%)	Negative	X24
		Energy Consumption per Unit of Industrial Value Added Growth (%)	Negative	X25
	Air Quality	PM10 Concentration (μg/m³)	Negative	X26
		PM2.5 Concentration (μg/m³)	Negative	X27

3.3 Research Methodology

This study first employs the entropy weight method to evaluate the digitalization and greening development levels of 21 cities in Guangdong Province. Subsequently, the coupling analysis method is applied to assess the coupling levels of dual-transformation coordination across these 21 cities. Based on the coupling level data for dual-transformation coordination in Guangdong's 21 cities, the coupling results are used to explore Zhaoqing City's developmental position within the province. The specific analytical methods are as follows:

3.3.1 Entropy weight method

The entropy weight method enables objective indicator scoring, mitigating the randomness inherent in subjective weighting. This approach requires establishing an indicator matrix $A=[a_{ij}]_{n\times m}$ (i=1,2,3,…m，j=1,2,3,…n). Assuming m evaluation items and n evaluation indicators, the data can be represented by an n×m matrix A. The greater the dispersion of data within the matrix, the more information it provides, resulting in lower information entropy. Consequently, the indicator carries a higher weight and exerts a greater influence on the comprehensive evaluation. Conversely, weaker data dispersion yields less information, higher information entropy, a lower indicator weight, and a diminished impact on the overall assessment. The entropy weight method is frequently employed to evaluate regional economic development levels.

Calculation Steps:

Standardize data. When negative indicators exist, use Formula 2:

$$X_{ij}=\frac{a_{ij}-\min\{a_{ij}\}}{\max\{a_{ij}\}-\min\{a_{ij}\}} \tag{1}$$

$$X_{ij}=\frac{\max\{a_{ij}\}-a_{ij}}{\max\{a_{ij}\}-\min\{a_{ij}\}} \tag{2}$$

Calculate the proportion pij of indicator j in year i:

$$p_{ij}=\frac{X_{ij}}{\sum_{i=1}^{m}X_{ij}} \tag{3}$$

Calculate the entropy value ej for the jth indicator using the following formula:

$$e_j=-\frac{1}{\ln m}\sum_{i=1}^{m}(p_{ij}\ln p_{ij}),\quad e_j=[0,1] \tag{4}$$

Calculate the coefficient of variation, gi, using the following formula:

$$g_i=1-e_j \tag{5}$$

Calculate the weight wj for the jth indicator using the following formula:

$$w_j=\frac{g_i}{\sum_{j=1}^{m} g_i} \tag{6}$$

Calculate the composite score Di for each sample. Using the entropy method, compute the levels of digitalization and greening development. Di represents the level of digital development, while Gi indicates the level of green development.

$$D_i/G_i=\sum_{j=1}^{m} w_j*p_{ij},\quad i=1,2,\ldots,n \tag{7}$$

3.3.2 Coupling coordination degree model

In analyzing the spatial influencing factors and spatiotemporal evolution characteristics of the coupling level in dual-transformation synergistic development, this paper employs the coupling coordination degree model to calculate differences across cities and years. The essence of dual-transformation synergy falls within the realm of industrial linkage, and the coupling coordination degree model effectively evaluates the coordinated development level among subsystems within the coupling system. For analyzing two systems, three key indicators reflect their coupling relationship.

First is the coupling degree, denoted as C, with values ranging from [0,1]. This metric represents the closeness of connection between two subsystems; a higher value indicates stronger interdependence and greater mutual influence. Its calculation formula is shown in Equation (1):

$$C=\frac{2\sqrt{U_1U_2}}{U_1+U_2} \tag{8}$$

U1 and U2 represent the comprehensive development levels of the green development subsystem and the digital development subsystem, respectively. They are calculated using weighted average scores derived from weights obtained via the entropy method and corresponding indicator data.

Next is the coordination degree. Since some regions may exhibit relatively low levels of both green and digital development but high coupling degrees, the coordination degree indicator, denoted as T, is introduced to mitigate this issue. This indicator analyzes the consistency of the system's development levels, representing the absolute level of system development. A higher value indicates a higher development level, as expressed in Equation (2).

$$T=\alpha U_1+\beta U_2 \tag{9}$$

Where α and β represent the weights of the two subsystems, determined by their relative importance, since green development and digital development are equally important in this study, each subsystem is assigned a weight of 0.5.

Finally, the coupling coordination degree is calculated. This metric integrates coupling degree and coordination degree, reflecting both the closeness of the relationship between the two subsystems and their absolute developmental levels. It represents the degree of coordinated development between the two subsystems and serves as the comprehensive indicator for assessing the level of synergistic development of the dual transformations in this paper. Denoted as U, its calculation formula is shown in Equation (3):

$$U=\sqrt{C\times T} \tag{10}$$

Based on relevant literature research, coordination levels are categorized into five grades, as detailed in Table 2 below:

Table 2 Classification of Coordination Degree Levels

Coupling Coordination Degree (U)	Coordination Status	Level
(0.0, 0.2)	Severe Imbalance	I
[0.2, 0.4)	Moderate Imbalance	II
[0.4, 0.6)	On the Verge of Imbalance – Barely Coordinated	III
[0.6, 0.8)	Basically Coordinated	IV
[0.8, 1.0]	Well Coordinated	V

3.3.3 Methodology for identifying development status in Zhaoqing city

(1) Subsystem Deviation Analysis

$$\Delta_i=D_i-G_i \tag{11}$$

D_i represents the comprehensive development level of the i-th city in the digital subsystem, while G_i denotes the comprehensive development level of the i-th city in the green subsystem. Δ_i represents the structural deviation of dual-transformation synergy. If $\Delta_i>0$, it indicates relatively advanced digital development and lagging green development; if $\Delta_i<0$, it indicates a solid foundation for green development but insufficient digital capabilities; if $\Delta_i=0$, it indicates relative structural balance between the two subsystems.

(2)Relative Gap Coefficient GAPzq
In identifying the structure of "dual transformation synergy," the relative coefficient is a ratio-based indicator measuring the strength of gradient structure against the elasticity of catch-up potential. Its construction logic builds upon the coupling coordination index Ui to identify structural positional differences in synergy levels between Zhaoqing and core cities.

$$Gap_{ZQ}=\frac{Ucore-U_{ZQ}}{Ucore} \tag{12}$$

U_{ZQ} Zhaoqing City's Dual-Coupling Coordination Index; Ucore is Core City Coupling Coordination Index, calculated as the average of the top three ranked cities' Relative Coordination Gap Ratio compared to core cities. This metric ranges between [0,1]. If $Gap_{ZQ}\approx 0$, it indicates Zhaoqing's coordination level approaches core cities, signifying weakened regional gradients; $0<Gap_{ZQ}\leq 0.3$ indicates a catch-up tier, where gaps exist but structural lock-in has not formed; $0.3<Gap_{ZQ}\leq 0.6$ signifies a pronounced gradient discontinuity; $0.6<Gap_{ZQ}\leq 1$ reveals a significant core-periphery polarization structure.

3.4 Data Sources

Research data primarily originates from official statistical materials, including the 2025 Guangdong Provincial Urban Statistical Yearbook and the Zhaoqing City Statistical Bulletin. To ensure data consistency and comparability, all indicators were standardized under the same statistical methodology, with missing values verified and consistency checks performed. Through these data integration methods, this study constructs a systematic measurement framework reflecting the level of "dual-transformation synergy," providing an empirical foundation for subsequent structural classification and mechanism analysis.

4 EMPIRICAL RESEARCH

4.1 Overall Pattern Characteristics of "Dual-Transformation Synergy" Development in Guangdong Cities

Based on the entropy weight method, Equations (1–7) were used to calculate Guangdong Province's 2024 Digitalization Index (Di) and Greenization Index (Gi). Subsequently, the coupling coordination degree model (Equations (8–10)) was applied to compute the coupling degree (C), coordination degree (T), and coupling coordination degree (U). The results are presented in Table 3. This section conducts a systematic analysis of the "dual-transformation synergy" development patterns across 21 cities in Guangdong Province. Based on this analysis, it identifies Zhaoqing City's structural position and transformation characteristics within the context of provincial supply chain network restructuring.

Table 3 Digitalization and Green Development Levels and Coupling Development Index for Cities in Guangdong Province

Region	Di (Digitalization Index)	Gi (Greenization Index)	C (Coupling Degree)	T (Coordination Index)	U (Coupling Coordination Degree)
Guangzhou	0.352	0.168	0.935	0.260	0.493
Shenzhen	0.466	0.774	0.969	0.620	0.775
Zhuhai	0.036	0.048	0.990	0.042	0.204
Shantou	0.018	0.010	0.959	0.014	0.115
Foshan	0.063	0.072	0.998	0.068	0.260
Shaoguan	0.008	0.051	0.681	0.030	0.142
Heyuan	0.004	0.019	0.752	0.011	0.092
Meizhou	0.008	0.038	0.761	0.023	0.132
Huizhou	0.028	0.097	0.835	0.062	0.228
Shanwei	0.001	0.023	0.447	0.012	0.073
Dongguan	0.077	0.128	0.969	0.103	0.315
Zhongshan	0.022	0.024	0.999	0.023	0.151
Jiangmen	0.016	0.015	0.999	0.016	0.125
Yangjiang	0.002	0.009	0.785	0.006	0.066
Zhanjiang	0.018	0.022	0.994	0.020	0.141
Maoming	0.014	0.050	0.825	0.032	0.162
Zhaoqing	0.010	0.046	0.762	0.028	0.146

Region	Di (Digitalization Index)	Gi (Greenization Index)	C (Coupling Degree)	T (Coordination Index)	U (Coupling Coordination Degree)
Qingyuan	0.014	0.026	0.952	0.020	0.138
Chaozhou	0.002	0.015	0.667	0.009	0.076
Jieyang	0.011	0.016	0.981	0.014	0.115
Yunfu	0.000	0.013	0.383	0.006	0.050

The results from Table 3 reveal that the "dual transformation synergy" levels across Guangdong's 21 cities exhibit distinct numerical gradients and structural differentiation. Shenzhen demonstrates a high-level alignment with a digitalization index of 0.466 and a greening index of 0.774, achieving a coupling coordination level of 0.775—significantly higher than other cities in the province—thus forming a core polarization center. Guangzhou, with a digitalization level of 0.352 exceeding its greening level of 0.168, achieves a comprehensive synergy level of 0.493 through strong interaction intensity, positioning it at the edge of the first tier. Dongguan (0.315) and Foshan (0.260) form a secondary core zone, both with coupling degrees near 1 but coordination constrained by developmental foundations; Zhuhai (0.204) and Huizhou (0.228) occupy an intermediate tier, exhibiting limited foundational scale but relatively good system alignment; Zhaoqing (0.146), Jiangmen (0.125), Zhongshan (0.151), and Maoming (0.162) cluster within the 0.10–0.20 range, reflecting overall low scales in both systems; Cities like Yunfu (0.050), Yangjiang (0.066), and Shanwei (0.073) exhibit the lowest coordination levels, with both digital and green indices ranking low. Overall, a pyramid-shaped distribution pattern emerges: "high-level core agglomeration—gradient transition in the central zone—low-level peripheral reception."

4.2 Typological Characteristics of "Dual Transformation Synergy" in Guangdong Cities

This typology model uses the numerical range of coupling coordination degree U as the stratification criterion, embedding the "dual transformation synergy" levels of Guangdong's 21 cities within the functional structure of supply chain networks. Stratification centers on coupling the coordination degree U as the core indicator. According to Equations (8-10), where C reflects the interaction intensity between digitalization and greenization, and T reflects the comprehensive development level of both systems. Since U integrates both interaction intensity and absolute baseline level, it serves as a comprehensive measure of "dual transformation synergy" maturity. Based on the calculation results, the highest value in the province is 0.775, and the lowest is 0.050, with the overall distribution exhibiting a significant right-skewed structure. Based on natural numerical breakpoints and classification criteria, 0.50 was set as the threshold for the high-maturity zone, 0.25 as the boundary for the functional enhancement zone, and 0.10 as the lower limit for the synergy initiation zone, forming a four-tier interval structure. This segmentation aligns with both the logic of coordination level classification and the actual distribution characteristics of the sample. The specific classification results are shown in Table 4.

Table 4 Classification Table of "Dual Transformation Synergy" in Guangdong Cities

Type	Coordination Degree Range (U)	Structural Characteristics	Representative Cities	Network Functional Position
I Core Polarization Type	$U \geq 0.50$	Both digitalization and greenization are at high levels. Strong coupling and high coordination form a mature synergistic structure.	Shenzhen(0.775) Guangzhou(0.493)	Technology integration hub; rule-setting and coordination center
II Sub-core Transitional Type	$0.25 \leq U < 0.50$	Strong interaction between the two systems, but the overall development base remains limited. The cities are in a stage of strengthening coordination.	Dongguan (0.315) Foshan (0.260)	Manufacturing extension nodes; functional support centers
III Structural Adjustment Type	$0.10 \leq U < 0.25$	Digitalization and greenization show certain matching potential, but their overall levels remain relatively low, indicating	Huizhou (0.228); Maoming (0.162); Zhongshan (0.151); Zhaoqing(0.146) Zhanjiang(0.141)Qingyuan(0.138) Meizhou (0.132) Jiangmen(0.125) Jieyang (0.116) Shantou (0.115)	Transitional nodes; potential zones for synergistic growth

Type	Coordination Degree Range (U)	Structural Characteristics	Representative Cities	Network Functional Position
		considerable improvement potential.		
IV Peripheral Undertaking Type	U < 0.10	Both systems remain underdeveloped with weak coordination and insufficient synergy dynamics.	Heyuan(0.092) Chaozhou(0.076) Shanwei (0.073) Yangjiang(0.066)Yunfu (0.050)	Resource-support nodes; peripheral factor supply areas

According to the calculation results from formula (8-10), the highest coupling coordination level in the province was recorded in Shenzhen (U=0.775), while the lowest was in Yunfu (U=0.050), with a range of 0.725, indicating a pronounced gradient differentiation. Estimated using the average of 21 cities, the provincial average coordination level is approximately 0.191, indicating the overall region remains in a transitional stage between Levels II and III. This suggests that "dual-transformation coordination" has not yet universally entered a high-quality coordination phase across the province.

The core polarization type is represented by Shenzhen (0.775) and Guangzhou (0.493). Shenzhen not only leads in coupling coordination but also ranks among the province's top in both digitalization index (0.466) and greening index (0.774), with a coupling degree C=0.9687. This indicates highly interactive dual systems and a robust developmental foundation. Although Guangzhou's green index is only 0.168, its digital index reaches 0.352 with a coupling degree of 0.935 and coordination level T=0.260, securing a stable position in the second tier for comprehensive synergy. Both cities exhibit coordination levels significantly above the provincial average, forming distinct "polar nuclei" of dual-transformation synergy.

The sub-core transitional group is represented by Dongguan (0.315) and Foshan (0.260). Both cities exhibit coupling degrees exceeding 0.960, yet their coordination levels stand at 0.102 and 0.068 respectively, indicating established interactive structures but still moderate foundational development. Their synergy levels reach approximately 40% to 50% of Shenzhen's, reflecting an absolute gap of 0.180 to 0.460 compared to core cities and revealing distinct functional stratification.

Structure-adjustment cities predominantly exhibit coupling coordination within the 0.100–0.205 range, accounting for over half of the 21-city sample. Examples include Huizhou (0.228), Zhongshan (0.151), Zhaoqing (0.146), Jiangmen (0.125), and Maoming (0.162). Among these, Zhaoqing exhibits a digitalization index of merely 0.010 and a greening index of 0.046, resulting in a coordination index of T=0.028. Despite achieving a coupling index of 0.762, its weak foundational indicators lead to a low overall level. The coordination level of this city type is approximately less than 20% of Shenzhen's, revealing a significant developmental gap.

Peripheral supporting cities exhibit coordination levels below 0.10, accounting for approximately 20% of the total. Yunfu (0.050), Yangjiang (0.066), Shanwei (0.073), and Chaozhou (0.076) fall into this category. These cities demonstrate low digital and green indices, with coordination generally below 0.02, indicating that their systemic foundations have yet to achieve significant scale accumulation. Structurally, only one city (U≥0.50) accounts for less than 5% of the total. Two cities (0.25≤U<0.50) represent about 10%, while over ten cities (0.10≤U<0.25) constitute approximately 50%. About five cities (U<0.10) make up roughly 20%. This proportional structure indicates that Guangdong's "dual-transformation synergy" exhibits a typical pyramid-shaped distribution: highly concentrated at the core, limited expansion in the middle tier, and a large number of cities at the base.

Consequently, the overall pattern of Guangdong's "dual-transformation synergy" presents a structural characteristic of significant quantitative stratification coexisting with numerical gradients. Synergy capacity aligns closely with supply chain network functional tiers: core cities leverage high numerical advantages to dominate technological integration and rule-setting; intermediate tiers extend manufacturing capabilities and assume functional reception roles; while peripheral cities remain in resource provision and ecological support phases. This numerical distribution provides a quantitative foundation for identifying Zhaoqing City's specific position within the gradient system.

4.3 Analysis of Zhaoqing City's "Dualization Synergy" Level Measurement Results

As shown in Table 1, calculated using the entropy weight method and coupling coordination model, Zhaoqing City's digitalization index Di=0.010, greenization index Gi = 0.046, coupling degree C = 0.762, coordination degree T = 0.028, and coupling coordination degree U = 0.146. Among the 21 cities, Zhaoqing's comprehensive coordination level is significantly below the provincial average by approximately 0.20, equivalent to only about 19% of Shenzhen's coordination level, placing it in the lower-middle tier provincially. Based on the classification in Table 1, Zhaoqing falls within Level I, the "Severe Imbalance" range.

From a subsystem perspective, the green index significantly exceeds the digital index by approximately 0.036. This indicates relatively stable foundations in green governance and energy efficiency constraints, while the scale of the digital industry, technological investment, and information penetration remain in low-range intervals. The digital index below 0.010 signifies weak embedded digital capabilities within the provincial comparative scale, lacking the technological accumulation necessary to support supply chain network functional upgrades. The coupling degree of 0.762 falls within the medium-high range, indicating no significant structural conflict between the two systems and suggesting potential synergistic development between digital and green trajectories. However, the coordination degree is only 0.028, reflecting the relatively low absolute development foundation of both systems. Consequently, the coupling coordination degree of 0.146 remains in the low range, manifesting as a structural state of "interaction exists but scale is insufficient."

This "high coupling-low foundation" characteristic reveals that Zhaoqing does not suffer from dual-system mismatch, but rather that its development scale and capability accumulation have not yet reached the threshold for synergistic amplification. Without strengthening digital capabilities and deepening green technologies, its supply chain node functions will remain at the receiving tier, struggling to achieve structural leapfrogging. Consequently, Zhaoqing's "dual transformation synergy" remains in its initial phase, with core constraints lying in expanding foundational capabilities and enhancing technological integration—not in resolving systemic conflicts. This "high coupling-low foundation" characteristic indicates that Zhaoqing does not suffer from dual-system mismatch, but rather that its development scale and capability accumulation have yet to reach the threshold for synergistic amplification. Without strengthening digital capabilities and deepening green technologies, its supply chain node functions will remain at the receiving level, making structural transformation difficult to achieve. Therefore, Zhaoqing's "dual transformation synergy" remains in its initial phase, with core constraints lying in expanding foundational capabilities and enhancing technological integration rather than resolving systemic conflicts.

4.4 Identifying Structural Asymmetry in Zhaoqing's Dual Transformation Synergy

Calculating the structural deviation of Zhaoqing's "dual transformation synergy" using Formula (11) yields $\Delta_{ZQ}=0.046-0.010=-0.036$. This negative result indicates a pronounced asymmetry in Zhaoqing's dual transformation structure: green transformation leads significantly, while digital transformation lags markedly. This disparity reflects not merely quantitative differences but structural fractures in developmental stages and capability accumulation between the two subsystems.

Internally, Zhaoqing's green index is approximately 4.7 times its digital index, indicating established institutional foundations and governance accumulation in energy conservation, environmental protection expenditures, energy consumption control, and pollution constraints. However, the scale of its digital industries, investment in technological innovation, and information infrastructure support remain at low levels. As a critical enabler for supply chain network integration, the weakness of the digital system directly constrains the conversion efficiency of green governance into industrial upgrading and value chain leapfrogging. Zhaoqing exhibits a "green constraint-type structure," meaning that despite relatively manageable resource and environmental pressures, the depth of technological integration remains insufficient. This asymmetry implies that its current transformation path relies more on ecological carrying capacity and cost advantages rather than leveraging digital technologies to drive collaborative supply chain upgrades.

From a supply chain network restructuring perspective, structural asymmetry will weaken Zhaoqing's competitiveness in information integration, data coordination, and platform embedding, hindering its ability to assume high-value-added functional node roles. Without digital support, green advantages remain confined to regulatory compliance, failing to generate efficiency spillovers or value enhancement effects. Thus, the core constraint of Zhaoqing's "dual-transformation synergy" lies not in systemic conflicts but in structural deviation caused by asymmetric capability accumulation. Future transformation hinges on narrowing this structural deviation through expanded digital infrastructure, intensified technological investment, and industrial digitalization upgrades—enabling a leap from "relatively green-leading" to "structurally balanced coordination."

Structural deviation primarily reflects the internal alignment between digitalization and greening within a city, yet it falls short of revealing hierarchical disparities and external distances within the broader coordination landscape. Without comparison to highly coordinated cities, it is difficult to determine whether functional gaps constitute substantive gradient discontinuities. Therefore, it is necessary to introduce core city benchmarks. Using proportional measurement methods, Zhaoqing's coupling coordination level should be compared within the province's highest coordination tier to identify its embedding depth and catch-up potential within the context of supply chain network restructuring.

4.5 Identification of Zhaoqing City's Gradient Structure in Dual-Modernization Synergy Based on Relative Gap Coefficient

To systematically identify Zhaoqing's hierarchical position and structural potential within Guangdong Province's "dual-modernization synergy" framework, this study introduces the relative gap coefficient for proportional comparative analysis of its synergy level. Based on Formula (12), the top three cities in synergistic level—Shenzhen (0.7751), Guangzhou (0.4930), and Dongguan (0.3153)—are selected as representatives of the core layer. Their average coupling coordination degree is:

$$\text{Ucore}=\frac{(0.7751+0.4930+0.3153)}{3}\approx 0.528$$

This value significantly exceeds the provincial average of 0.191, representing Guangdong's high-level functional zones for “dual-transformation synergy.” It reflects a mature interactive structure between the digitalization and greening systems at the levels of technological embedding and institutional alignment. Using Zhaoqing's coupling coordination index UZQ=0.1460 as the comparative benchmark, the relative gap coefficient is calculated as GapZQ=0.528−0.146≈0.402. This result falls within the threshold range of 0.3<GapZQ≤0.6, where a distinct gradient discontinuity exists, indicating a significant structural gap between Zhaoqing and core cities. with its synergy level equivalent to only about 29.2% of the core layer's average, representing a gap ratio as high as 76.16%. This figure not only reflects absolute developmental disparities but also reveals functional stratification and capability differentiation within the gradient structure.

Structurally, Shenzhen and Guangzhou have established mature synergistic models characterized by “high digitalization-high greening” or “digital dominance-green enhancement,” with coupling degrees nearing or exceeding 0.93. Their coordination remains at a high level, manifested in synchronous improvements in technological integration and green governance capabilities. Within supply chain networks, they assume pivotal roles in integration and rule-setting. Although Dongguan resides in the secondary core layer, its digital manufacturing foundation and green governance capabilities have achieved a certain degree of alignment, demonstrating structural potential for ascending to the core tier. In contrast, Zhaoqing's digitalization index stands at 0.010 and its greening index at 0.046. Although its coupling degree reaches 0.762, indicating no significant conflicts between systems, its coordination level remains low at 0.028 due to weak developmental foundations, resulting in persistently low overall synergy. Its green advantages have yet to be converted into efficiency gains through digital technology integration, while insufficient digital capabilities constrain the formation of supply chain platform integration and value chain upgrading capacities.

From the perspective of supply chain network restructuring, Guangdong currently exhibits a distinct spatial structure of “core reinforcement—gradient diffusion—peripheral reception.” Core cities deepen functional integration and institutional influence through “dual-track synergy,” while Zhaoqing occupies a mid-to-low gradient zone—neither entering the core functional sphere nor developing autonomous synergistic momentum. Without narrowing this gap through digital infrastructure expansion, increased technological investment, and industrial digitalization, Zhaoqing risks remaining a passive node in the supply chain network, struggling to transition from a peripheral to a functional node. Therefore, the relative disparity coefficient not only reveals the quantitative gap in Zhaoqing's current coordination level but also exposes its functional boundaries and catch-up potential within the regional gradient structure, providing quantitative evidence for proposing targeted transformation pathways.

4.6 Supply Chain Network Embedding Perspective: Zhaoqing's Dual-Transformation Coordination Pathway

Placing the aforementioned “dual-transformation synergy” measurement results within the broader developmental context of supply chain network restructuring in the Guangdong-Hong Kong-Macao Greater Bay Area reveals that Zhaoqing's current synergy level is not an isolated phenomenon. Rather, it is a structural outcome embedded within the regional network stratification and functional redistribution process. Supply chain competition has shifted from cost advantages to capability embedding and rule adaptation, with the status of node cities determined by their comprehensive capabilities in information integration, technological synergy, and green compliance. From this perspective, Zhaoqing's “dual-transformation synergy” state exhibits three key mechanism characteristics.

First, insufficient digital capabilities constitute a critical constraint on its network embedding. Calculations show Zhaoqing's digital index stands at merely 0.00986, ranking in the province's lower tier and far below core city levels. This indicates it has yet to achieve scale accumulation in digital infrastructure density, information industry scale, and technological innovation investment. High-value-added nodes in supply chain networks typically leverage digital platforms, industrial internet, and data integration capabilities to achieve cross-regional resource allocation and value control. However, Zhaoqing's insufficient depth of digital embedding prevents it from undertaking platform integration and information coordination functions, confining it primarily to manufacturing execution or factor supply tiers. This digital capability gap deprives Zhaoqing of rule-setting authority and technological leadership within supply chain networks, limiting its functional upgrading potential.

Second, while possessing relative advantages in green infrastructure, Zhaoqing has yet to establish mechanisms for technological conversion. Its green development index of 0.046 exceeds its digitalization index, indicating a governance foundation in energy conservation, environmental protection expenditures, energy consumption control, and pollution constraints. However, without digital technology support, these green advantages manifest only as compliance and regulatory improvements, failing to translate into enhanced production efficiency or value chain upgrading. The absence of an integration mechanism between green governance and digital technology confines green development to the level of institutional implementation. It fails to achieve functional integration through data-driven management and intelligent control to enhance energy efficiency and production coordination efficiency. Consequently, its green advantages have not yet formed sustainable competitiveness but remain in a relatively static state.

Third, insufficient regional coordination and spillover absorption capacity create a gradient expansion effect. Core cities demonstrate continuously improving coordination levels, with Shenzhen achieving a coupling coordination index of 0.775 and Guangzhou nearing 0.500, indicating synchronized strengthening and outward diffusion of their digital and green capabilities. During supply chain network restructuring, technological and institutional spillovers typically spread in a gradient pattern. However, Zhaoqing's relatively high gap coefficient of 0.723 suggests limited capacity to absorb spillovers from core cities. Weak digital foundations and insufficient innovation resources hinder its capacity to undertake high-end technology transfers and platform collaboration opportunities, thereby exacerbating the "core-periphery" structural divergence.

Comprehensively, Zhaoqing currently resides in the "dual-transformation synergistic initiation phase." Its insufficient coordination stems not from systemic conflict but from its capacity accumulation not yet reaching a critical mass threshold. The key to transformation lies in strengthening digital capability embedding. By enhancing information integration through digital infrastructure development and industrial digitalization upgrades, while leveraging digital technologies to boost green governance efficiency, Zhaoqing can achieve the technological transformation of its green advantages. Only when dynamic interaction and scale amplification mechanisms emerge between the digital and green systems can Zhaoqing achieve a structural leap from a "green reception node" to a "functional collaborative node," securing a higher-level functional positioning in the supply chain network restructuring process.

5 CONCLUSIONS AND OUTLOOK

5.1 Research Findings

Against the backdrop of accelerated supply chain network restructuring in the Guangdong-Hong Kong-Macao Greater Bay Area, this study constructs a "dual-transformation synergy" measurement framework based on system coupling theory. Using entropy weighting and coupling coordination degree models, it quantitatively analyzes the digitalization and green development levels and their synergy states across 21 cities in Guangdong Province. Taking Zhaoqing as a case study, it identifies its structural potential and embedding mechanisms.

Findings reveal a pronounced gradient differentiation in Guangdong's overall dual-transformation synergy, with coupling coordination ranging from a maximum of 0.775 to a minimum of 0.050—a range of 0.725. The overall mean of 0.191 indicates the province remains in a transitional phase of deepening synergy. Shenzhen and Guangzhou form a core polarized zone exhibiting high digital-green integration capacity; Dongguan and Foshan constitute a secondary core zone; most cities cluster within the 0.10–0.25 range, indicating structural adjustment; while peripheral cities exhibit weak collaborative foundations.

For Zhaoqing City, empirical results reveal a digitalization index of 0.010, a greening index of 0.046, and a coupling coordination index of 0.146, positioning it in the initial stage of synergy. Its structure exhibits an asymmetric pattern of "relatively advanced green development—significantly lagging digital development," with a negative deviation value. This indicates a reasonably sound foundation for green governance but insufficient integration of digital capabilities. The relative gap coefficient reaches 0.723, revealing a significant gradient gap between Zhaoqing and core cities, with limited depth of supply chain network embedding.

From a supply chain network embedding perspective, Zhaoqing's insufficient synergy stems not from systemic conflicts but from inadequate capacity accumulation and shallow technological embedding. The absence of digital capabilities constrains platform integration and rule participation, preventing green advantages from being converted into efficiency gains and value chain upgrading momentum through digital technologies. Consequently, Zhaoqing's "dual transformation synergy" remains in the initial stage of functional transformation.

5.2 Development Strategies

Based on the above conclusions, Zhaoqing's future "dual transformation synergy" should focus on capability embedding and structural leapfrogging. First, it should prioritize digital infrastructure and industrial digitalization upgrades as core breakthroughs, strengthening information integration and data coordination capabilities to enhance embedding depth and functional participation within supply chain networks. Second, it should advance the transformation of green governance toward digital management. By integrating intelligent monitoring, energy efficiency data platforms, and industrial internet, it can achieve the technological expression and efficiency amplification of green advantages, constructing a path of "digitally empowered green governance." Third, it should enhance the capacity to absorb technological and institutional spillovers from core cities, optimize mechanisms for connecting innovation resources, improve the quality of industrial reception, and avoid long-term marginalization in network restructuring. Only through the scaled expansion and reinforced integration of both digital and green systems can Zhaoqing achieve a leap from a "green reception node" to a "functional collaborative node."

5.3 Research Limitations

This paper constructs a "dual-transformation synergy-supply chain embedding" analytical framework and identifies regional structures through quantitative methods, yet several limitations remain. First, data dimensional constraints. The analysis relies on annual cross-sectional data without incorporating time-series dynamics, thus failing to capture the evolutionary pathways and phase transition characteristics of "dual-transformation synergy." Future research should utilize multi-period panel data to identify the dynamic transition trajectories of synergistic structures. Second, the indicator system primarily relies on macro-level statistical data, excluding micro-level metrics such as the depth of digital application at the enterprise level and the efficiency of green technological innovation. Supply chain embedding fundamentally manifests as interlocking capabilities across enterprise tiers. Subsequent research could employ multi-level analysis integrating enterprise data with network relationship data. Third, supply chain network structures lack explicit topological measurement. This study interprets structures from a functional embedding perspective but does not quantify node connection strengths using social network analysis or spatial econometric models. Future work

could develop more refined embedding models by incorporating input-output data or industrial linkage networks.
Overall, this study reveals the structural potential and mechanism constraints of Zhaoqing's “dual-transformation synergy” in supply chain network restructuring within a systemic coupling framework. However, further exploration is needed regarding dynamic mechanisms and micro-level pathways. Future research should expand across temporal dimensions, network structural dimensions, and institutional embedding dimensions to develop a more comprehensive theoretical framework for regional collaborative transformation.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

FUNDING

This research was supported by Zhaoqing's philosophy and Social Sciences discipline co construction project (25GJ-365).

REFERENCES

[1] Qi Yudong, Cai Qingqing, Luo Tianshu. Models and Pathways for the Synergistic Development of Digitalization and Green Transformation. Journal of Quantitative Economics and Technical Economics, 2026, 1-24. DOI: 10.13653/j.cnki.jqte.20260228.001.

[2] Chen Xingxing, Tian Yixuan. Theoretical Explanation and Future Pathways for the Synergistic Transformation of Digitalization and Green Development. Industrial Technology Economics, 2025, 44(11): 96-104.

[3] Ma Xiaoyue, Bai Yantao. Theoretical Logic, Practical Challenges, and Implementation Pathways for the Synergistic Development of Digitalization and Green Transformation. Price Theory and Practice, 2025(07): 91-96+238.

[4] Kuang Yuanpei, Yang Peiyu. Digitalization and Green Development Synergistically Empowering New Quality Productivity in Agriculture: Logical Framework, Existing Issues, and Optimization Strategies. Rural Economy, 2025(06): 87-94.

[5] Wang Wenzhi, Yao Jiawei. Spatiotemporal Changes and Driving Mechanisms of China's Regional “Dual-Transformation Synergy” Development. Human Geography, 2026, 41(01): 100-114.

[6] Li Xuhui, Nian Qingyu. Spatiotemporal Evolution and Diverse Pathways of Coordinated Digitalization and Green Development in China's Logistics Industry: Based on the AIS Theoretical Framework. Arid Zone Geography, 1-13. https://link.cnki.net/urlid/65.1103.x.20260226.1331.002.

[7] Li Gen, Diao Tianle, Liu Jiaguo, et al. Spatiotemporal Differentiation and Influencing Factors of Coordinated Digitalization and Green Development in China's Manufacturing Sector. Chinese Journal of Management Science, 1-11. https://doi.org/10.16381/j.cnki.issn1003-207x.2025.0079.

[8] Wu Chuanqing, Song Yongjiu, Deng Hesun. Measurement and Enhancement Pathways for Coordinated Digitalization and Green Transformation in the Middle Yangtze River Region. Resources and Environment in the Yangtze Basin, 2025, 34(11): 2445-2458.

[9] Xiao Qinlin, Deng Zongbing, Qiao Yidan. Spatiotemporal Evolution and Spillover Effects of Synergistic Digitalization and Green Transformation in the Yangtze River Delta Urban Agglomeration. Advances in Geoscience, 2025, 44(06): 1178-1193.

[10] Li Xin. Dynamic Evolution and Regional Differences in the Synergistic Development of Digitalization and Green Transformation in the Yellow River Basin. Regional Research and Development, 2025, 1-17.

[11] Wang Ying, Zhang Ruohan, Zu Zishuai, et al. Measurement and Dynamic Evolution Patterns of Synergistic Development Levels of Energy Digitalization and Green Transformation at Provincial Level in China. Journal of Mining Science, 2025, 1-10. DOI: 10.19606/j.cnki.jmst.2025140.

[12] Sun Xin, Ma Haitao. Mechanisms and Influencing Factors of Synergistic Development of Digitalization and Green Transformation. Journal of Nanchang University (Humanities and Social Sciences Edition), 2025, 56(02): 60-73.

[13] Zhang Zhiwei, Zhang Ning, Xiao Tusheng. Research on the Impact Mechanism of Synergistic Digitalization and Green Transformation on Enterprise Performance in Manufacturing Enterprises. Management Review, 2025, 37 (11): 67-80.

[14] Chen Yantai, Hao Yajie, Pan Dapeng. How Does the Coupling Effect of Digital and Green Transformation Promote New Quality Productivity?—A Mixed-Methods Study Based on Dynamic Capabilities Theory. Management Review, 2025, 37(11): 27-40.

[15] Jia Xiaolin, Zhang Xiexie, Li Yixin. Digitalization, Greening, and New Quality Productivity in Manufacturing Enterprises. Journal of Shanxi University of Finance and Economics, 2025, 47(08): 116-126.

[16] Gao Xinyi, Han Zhongxue, Dong Siyuan. Supply Chain “Dual-Transformation Synergy” and Green Innovation of Specialized, Refined, Distinctive, and Innovative Enterprises: An FSQCA Analysis from a Synergy Perspective. Industrial Technology Economics, 2025, 44(11): 13-21.

[17] Jin Jun, Chen Tailun, Zhao Yuanti, et al. Synergistic Transformation of Industrial Digitalization and Green Transformation Empowering New Quality Productivity: Logic and Approaches. Research and Development Management, 2025, 37(01): 74-84.

[18] Liu Yun, Xie Guoliang, Cui Lele, et al. Measurement, Regional Differences, and Dynamic Evolution of Digitalization and Green Transformation Integration. Statistics and Decision Making, 2025, 41(19): 66-71.
[19] Zhou Mi, Qiao Yurong. Regional Differences and Internal Mechanisms in the Integrated Development of Urban Greening and Digitalization. Urban Problems, 2023(08): 4-14.
[20] Li Qilun. Integrated Development of Digitalization and Greening in Manufacturing: Level Measurement, Spatiotemporal Evolution, and Convergence Characteristics. Statistics and Decision Making, 2024, 40(15): 120-125.
[21] Li Qilun. Measurement and Evolutionary Analysis of Integrated and Coordinated Development of Digitalization and Greening in China's Manufacturing Sector. Exploration of Economic Issues, 2024(07): 119-132.