




Research on the Spatiotemporal Evolution and Influencing Factors of Coupling Coordination Degree between Artificial Intelligence and Digital Economy Development: Based on Grey Relational Analysis

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Abstract. Using provincial panel data from China (2011-2023), this study integrates the Coupling Coordination Degree (CCD) model and Grey Relational Analysis to evaluate the synergistic development between Artificial Intelligence and the Digital Economy, analyzing its spatiotemporal evolution patterns and influencing factors. Results show that the CCD improved from "disorder" to "coordination," though this progression was significantly disrupted by the COVID-19 pandemic, displaying non-linear dynamics. Spatially, the "high in the east, low in the west" gradient pattern has intensified, with the eastern region demonstrating greater resilience. In terms of influencing factors, urbanization serves as a common foundation, but core drivers vary regionally: the east relies on network infrastructure, the center requires enhanced human capital, and the west faces dual constraints in both human capital and infrastructure. These findings provide a basis for formulating differentiated regional coordination policies.

Keywords: Artificial Intelligence, Digital Economy, Coupling Coordination Degree, Grey Relational Analysis.

1 Introduction

Currently, a new wave of technological and industrial revolution, driven by artificial intelligence and the digital economy, is reshaping the global economic landscape. With its capacity for autonomous learning and decision-making, AI serves as the core engine for intelligent transformation, while the digital economy, centered on data as a key factor, is restructuring economic frameworks. The two mutually empower each other: AI provides algorithms and computing power for the digital economy, and the digital economy supplies data and scenarios for AI iteration. In this context, scientifically evaluating the level of synergy between them and exploring their spatiotemporal evolution patterns is of significant practical importance for identifying regional disparities and formulating targeted policies. By constructing a Coupling Coordination

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Degree model and applying Grey Relational Analysis, this study aims to reveal the spatiotemporal patterns and influencing factors of AI–digital economy synergistic development at the provincial level in China, providing scientific reference for unleashing the integrated multiplier effect of "AI + Digital Economy."

2 Literature Review

2.1 Research on Digital Economy Development

The core essence of the digital economy is widely recognized as economic activities driven by data as a key factor, information networks as the carrier, and technological innovation as the driving force (China Academy of Information and Communications Technology, 2020). Related research primarily focuses on two main aspects: measurement systems and economic impact. In terms of measurement, a multi-dimensional framework has been established, encompassing macro-level accounting, meso-level indicator systems (Wang Zhixin et al., 2022)^[1], and micro-level enterprise evaluations. In recent years, with the deepening of practice, indicator systems have been continuously optimized, placing greater emphasis on measuring data elements and evaluating digital industrialization to more accurately reflect the dynamic development and structural evolution of the digital economy. At the economic impact level, extensive studies have shown that the digital economy can drive economic growth, promote industrial structure upgrading, and foster new quality productive forces (Wang Zhimao et al., 2025)^[2]. Its social effects, such as contributing to common prosperity, have also garnered attention. However, its development is accompanied by a significant "digital divide," with prominent regional imbalances (Li Zhiguo et al., 2021)^[3]. This spatial heterogeneity provides an important practical basis and theoretical entry point for understanding the regional disparities in the synergistic development of artificial intelligence and the digital economy.

2.2 Research on Artificial Intelligence Development

The measurement of artificial intelligence primarily employs three types of proxy indicators: research and development investment, patent output, and robot adoption. In recent years, with breakthroughs in cutting-edge technologies such as large models, research perspectives have expanded, focusing on the emergence of frontier technology clusters and the evaluation of innovation ecosystems. Its economic effects exhibit a "double-edged sword" characteristic: while promoting employment, enhancing total factor productivity, and fostering new quality productive forces (He Yuanlang et al., 2025)^[4], it may also impose structural shocks on the labor market. Moreover, its impact on economic resilience demonstrates complex nonlinear relationships (Liu Jiaqi et al., 2024)^[5]. Similar to the digital economy, AI innovation activities exhibit significant spatial agglomeration and a "technology divide" (Li Cuini et al., 2022)^[6]. This starting point of regional imbalance profoundly influences the subsequent spatial pattern of the synergistic development between the two.

2.3 Research Review and Innovations

Through a review of existing literature, this study identifies three main shortcomings in current research: first, a fragmented perspective that often treats the two as independent subjects or in a unidirectional relationship; second, insufficient dynamic analysis, lacking in-depth investigation into long-term synergistic evolution and resilience responses to external shocks; and third, methodological limitations, as traditional econometric models face challenges in analyzing such complex nonlinear relationships.

Based on this, the main innovative contributions of this study are reflected in: Perspectively, constructing a coupled system analysis framework for AI and the digital economy at the provincial level; in terms of content, revealing the spatiotemporal evolution patterns of synergistic development and the new characteristic of "gradient solidification, resilience differentiation"; and methodologically, integrating the entropy method, the Coupling Coordination Degree model, and Grey Relational Analysis to form a complete "measurement-evaluation-attribution" research chain. It identifies the regional heterogeneity of driving factors, providing a scientific basis for formulating precise regional synergistic policies.

3 Research Design and Model Construction

3.1 Construction of the Indicator System

(1) Indicator for Artificial Intelligence Development Level

The measurement of artificial intelligence development levels draws on the research of Liu Jiaqi et al. (2024)^[5]. The number of AI patent applications is selected as a proxy indicator, and data is collected from the website of the China National Intellectual Property Administration (CNIPA). For the classification of AI patents, this process specifically references the official Strategic Emerging Industry Classification and International Patent Classification Reference Table (2021) , which provides the corresponding International Patent Classification (IPC) codes for emerging technologies, including those within the AI field.

(2) Digital Economy Indicator System

The construction of the digital economy indicator system draws on the research framework of Wang Zhixin et al. (2022)^[1] and incorporates the intrinsic logic of the digital economy's "foundation-industry-integration" progression. A comprehensive evaluation indicator system is established from the three dimensions of digital infrastructure, digital industrialization, and industrial digitalization (see Table 1).

Table 1. Comprehensive Evaluation Indicators for the Digital Economy

Primary Dimension	Code	Specific Indicator	Attribute
Digital Infrastructure	D11	Broadband Internet Access Rate	+
	D12	Mobile Phone Penetration Rate	+
	D13	Length of Long-Distance Optical Cable Lines	+

Primary Dimension	Code	Specific Indicator	Attribute
Digital Industrialization	DI4	Per Capita Total Telecommunications Business Volume	+
	DNI1	Number of Legal Entities in Information Transmission, Software, and IT Services	+
	DNI2	Proportion of Employees in Information and Software Industries	+
	DNI3	Number of Web Pages	+
	DNI4	Number of Domain Names	+
Industrial Digitization	ID1	Proportion of Enterprises with E-commerce Transaction Activities	+
	ID2	E-commerce Sales Volume	+
	ID3	Number of Websites per 100 Enterprises	+
	ID4	Express Delivery Volume	+

3.2 Model Construction

(1) Coupling Coordination Degree Model

To scientifically measure the intensity of interaction and the level of coordinated development between the two major systems of artificial intelligence and the digital economy, this study introduces a coupling coordination degree model. First, the entropy method is employed to determine the objective weights of each evaluation indicator for the AI development level and the digital economy development level, respectively, and to calculate the comprehensive evaluation values of the two subsystems: U_1 (Artificial Intelligence) and U_2 (Digital Economy). On this basis, a coupling degree model is constructed to measure the intensity of interaction between the systems:

$$C=2 \times \sqrt{\frac{U_1 \times U_2}{(U_1 + U_2)^2}}$$

Among them, C represents the coupling degree, with a value range of $[0,1]$. However, a high coupling degree only indicates strong interaction between systems but fails to distinguish between "high-level synergy" and "low-level resonance." To address this, the coupling coordination degree model is further introduced:

$$T = \alpha U_1 + \beta U_2, \quad D = \sqrt{C \times T}$$

In the formula, T represents the comprehensive coordination index of the two systems, while α and β are undetermined weights. Given the equal importance of artificial intelligence and the digital economy in this study, $\alpha = \beta = 0.5$ is set. Ultimately, D denotes the coupling coordination degree, where a higher value indicates a more optimal synergistic state between the two systems at a higher development level. Referring to existing research, the D value is divided into 10 levels (Table 2) to facilitate qualitative evaluation of the coordinated development level.

Table 2. Classification criteria for coupling coordination level

Range of coupling coordination degree D value	Coordination level	Coupling coordination degree
[0-0.1)	1	Extreme imbalance
[0.1-0.2)	2	Serious imbalance
[0.2-0.3)	3	Moderate imbalance
[0.3-0.4)	4	Mild imbalance
[0.4-0.5)	5	On the brink of imbalance
[0.5-0.6)	6	Barely out of balance
[0.6-0.7)	7	Primary Coordination
[0.7-0.8)	8	Intermediate coordination
[0.8-0.9)	9	Good coordination
[0.9-1]	10	High quality coordination

(2) Grey Relational Model

To systematically identify and rank the key external factors influencing the coupling coordination degree between artificial intelligence and the digital economy, this study adopts the **Grey Relational Analysis (GRA) method**. Compared to traditional regression models, this method imposes fewer requirements on data distribution and can effectively handle small sample sizes and nonlinear relationships, making it suitable for exploring the strength of associations among multiple factors.

First, the reference series and comparative series are determined. The annual coupling coordination degree D of each province is taken as the reference series $X_0=(x_0(1),X_0(2),\dots,X_0(n))$. Six selected external influencing factors—Economic Development Level (EDL), Human Capital Level (HC), Degree of Openness (OPEN), Urbanization Level (URBAN), Technology Market Development Level (TECH), and Transportation Infrastructure Level (TRANS)—are used as the comparative series $X_i=(x_i(1),x_i(2),\dots,x_i(n))$, where $i=1,2,\dots,6$.

Second, the original data is subjected to dimensionless preprocessing to eliminate the effects of different measurement units. This study employs the mean normalization method:

$$\chi'_i(k)=\frac{\chi_i(k)}{\frac{1}{n}\sum_{k=1}^n \chi_i(k)}$$

where $x'_i(k)$ represents the processed sequence value.

Subsequently, the grey relational coefficient $\gamma_{0i}(k)$ between each comparative series and the reference series at each time point k is calculated:

$$\gamma_{0i}(k) = \frac{\min_i \min_k |x'_0(k) - x'_i(k)| + \rho \max_i \max_k |x'_0(k) - x'_i(k)|}{|x'_0(k) - x'_i(k)| + \rho \max_i \max_k |x'_0(k) - x'_i(k)|}$$

In the formula, ρ is the **distinguishing coefficient**, typically set to 0.5, used to adjust the differentiation of the comparison environment.

Finally, by averaging the grey relational coefficients of each comparative series, the **grey relational degree** γ_{0i} between the comparative series and the reference series is obtained:

$$r_{0i} = \frac{1}{n} \sum_{k=1}^n \gamma_{0i}(k)$$

The value of the relational degree γ_{0i} ranges between 0 and 1. A higher value indicates a stronger association between that influencing factor and the coupling coordination degree, signifying a more critical role in the synergistic development. By comparing the magnitudes of the relational degrees for each factor, the ranking and identification of the importance of the influencing factors can be achieved.

3.3 Data Sources

The data for this study comprise panel data from 31 Chinese provinces spanning the period 2011 to 2023. Specifically, the measurement data for the artificial intelligence (AI) development level were sourced from the China Statistical Yearbook on Science and Technology and the Incopat patent database. The 12 indicators constituting the digital economy evaluation system were primarily drawn from the China Statistical Yearbook, the China Statistical Yearbook of the Electronic and Information Industry, and the provincial statistical yearbooks. Data for the external influencing factors were compiled from official publications, including the China Statistical Yearbook, the China Statistical Yearbook on Science and Technology, and the China Statistical Yearbook of Transportation. For occasional missing values, the linear interpolation method was employed for imputation. Chapter 4: Spatio-Temporal Evolution Analysis of the Coupling Coordination Degree.

4 Spatio-Temporal Evolution Analysis of the Coupling Coordination Degree

4.1 Temporal Evolution Characteristics of the Coupling Coordination Degree

Fig. 1 shows the temporal evolution of the coupling coordination degree (CCD) at the national and regional levels from 2011 to 2023. During the study period, the national CCD achieved leapfrog development from disorder to coordination, reaching its peak (0.6854) in 2020. Due to the impact of the COVID-19 pandemic, the coordination degree significantly dropped to 0.6234 in 2021. Although it recovered slightly afterward, it failed to return to the pre-pandemic level, indicating the persistence of the shock's effects.

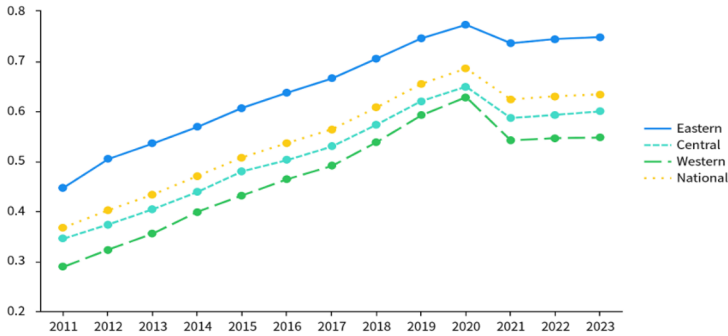


Fig. 1. Temporal Evolution Trend of Coupling Coordination Degree at the National Level and Across the Three Major Regions

Regional evolution exhibits gradient characteristics and heterogeneity. The eastern region, with a higher starting point and leading development, entered the intermediate coordination stage in 2019 and remained within this range in 2023 (0.7481) despite a post-pandemic decline, demonstrating strong resilience. In contrast, the central and western regions peaked in 2020 (0.6489 and 0.6280, respectively), experienced a sharp decline in 2021, with the western region even falling back to the brink of disorder. By 2023, neither region had recovered to its 2020 level, reflecting the relative fragility of their synergistic foundations.

In summary, the temporal evolution indicates that: the synergistic relationship between artificial intelligence and the digital economy has achieved a qualitative leap; however, its development process is significantly disrupted by external major events and exhibits non-linear characteristics. There are clear resilience disparities across regions, with the east showing greater stability, while the central and western regions display a "fast rise, fast fall" vulnerability when facing shocks.

4.2 Spatial Evolution Characteristics of Coupling Coordination

Table 3. Spatial Evolution of Regional Average Coupling Coordination Degree

year	2011	2015	2019	2023
Eastern	0.4469	0.6066	0.7456	0.7481
Central	0.3451	0.4798	0.6202	0.5995
Western	0.2887	0.4316	0.5916	0.5471
National	0.3673	0.5077	0.6545	0.6336

Based on the data in Table 3, the evolution of the spatial pattern of coupling coordination between artificial intelligence and the digital economy exhibits characteristics of "gradient solidification and shock reshaping." First, the "high in the east, low in the west" gradient pattern remained stable throughout the study period. In 2011, the coordination degree in the eastern region (0.4469) was 1.55 times that of the western region (0.2887), and by 2023, this disparity ratio still reached 1.37 times (0.7481 vs. 0.5471), indicating the persistence of relative regional gaps.

Second, the evolutionary paths of the three major regions showed significant differences before and after the COVID-19 pandemic. From 2011 to 2019, all regions maintained synchronous growth, with the western region leading in average annual growth rate (10.5%), reflecting a "latecomer catch-up" effect. However, the pandemic shock created a differentiation effect: between 2019 and 2023, the coordination degree in the eastern region stabilized at a high level (0.7456 \rightarrow 0.7481), demonstrating strong resilience, while both the central and western regions experienced declines (central: 0.6202 \rightarrow 0.5995; western: 0.5916 \rightarrow 0.5471), with the western region showing the largest decline, leading to a short-term widening of regional disparities.

Finally, the spatial distribution of coordination levels exhibits an "east stable, central-west volatile" pattern: the eastern region has remained stably at the "intermediate coordination" level since 2019; the central region declined from the threshold of "primary coordination" to the "barely coordinated" range; and the western region fluctuated near the "verging on disorder" threshold. This indicates systematic differences in regional resilience. The spatial evolution is not a simple process of diffusion or convergence but rather a complex dynamic response to external shocks, moderated by regional development stages and resilience.

5 Empirical Study on Influencing Factors of Coupling Coordination Degree

5.1 Overall Association Analysis

Table 4. Results of Grey Relational Model Calculation

Evaluation Item	Relevance	Ranking
EDL	0.548	4
HC	0.694	2
OPEN	0.539	5
URBAN	0.813	1
TECH	0.499	6
TRANS	0.651	3

The results of the Grey Relational Model in Table 4 show that the correlation between each external factor and the AI-digital economy coupling coordination degree is greater than 0.499, indicating a moderate to strong association. Among them, the urbanization level (URBAN) has the highest correlation (0.813), making it the primary influencing factor. Its role as a "spatial carrier" provides the foundation for infrastructure deployment, technology application, and talent agglomeration.

Human capital level (HC) and transportation infrastructure level (TRANS) rank second and third with correlation values of 0.694 and 0.651, respectively, forming the "dual pillars of software and hardware." They determine the capacity for technology absorption and innovation, as well as the efficiency of factor mobility and supply chain support.

In contrast, the economic development level (EDL), openness (OPEN), and technology market development level (TECH) show lower correlations (0.548, 0.539, and 0.499, respectively). This indicates that, at the current stage, promoting synergistic development depends more on foundational and network-oriented factors such as the agglomeration of "human resources" and the connectivity of "physical infrastructure," rather than economic scale or external technology inputs.

5.2 Regional Heterogeneity Analysis

Table 5. Zoning Calculation Results of Grey Relational Model

Influencing Factors	East	Ranking	Central	Ranking	West	Ranking
EDL	0.606	4	0.453	4	0.476	4
HC	0.614	3	0.745	2	0.663	2
OPEN	0.589	5	0.444	5	0.475	5
URBAN	0.793	1	0.815	1	0.779	1
TECH	0.492	6	0.437	6	0.465	6
TRANS	0.699	2	0.543	3	0.606	3

Based on the sub-regional grey relational analysis results in Table 5, the factors influencing the coupling coordination between artificial intelligence and the digital economy exhibit significant regional heterogeneity characterized by "universal foundations and specific cores." Urbanization level (URBAN) shows the strongest correlation across all three regions (East: 0.793, Central: 0.816, West: 0.775), serving as a universal foundational driver. However, the core driving combinations display distinct regional variations: the eastern region primarily relies on "URBAN + transportation infrastructure (TRANS, 0.699)," highlighting its dependence on efficient physical networks; the central region adopts a dual-driver model of "URBAN + human capital (HC, 0.745)," making human capital the key leverage for transformation; while the western region exhibits a pattern of "URBAN + HC (0.663) + TRANS (0.606)," facing dual constraints in both human resources and infrastructure. Furthermore, economic development level (EDL) plays a more prominent role in the east, whereas technology market activity (TECH) has the weakest impact across all regions. In conclusion, this analysis indicates that regional synergistic strategies must be tailored to local conditions: the east should optimize high-end spaces and networks, the center needs to break through human capital bottlenecks, and the west requires a dual approach simultaneously enhancing both human capital and infrastructure.

6 Conclusion and Policy Suggestions

6.1 Main Conclusions

This study mainly draws three conclusions: firstly, the level of collaboration has improved significantly, but the process has been significantly disrupted by external shocks. During the study period, the coupling and coordination achieved a leap from

"maladjustment" to "coordination", but the impact of the COVID-19 epidemic led to a callback and entered the platform period, revealing the vulnerability of development. Secondly, the spatial pattern exhibits characteristics of "gradient solidification and toughness differentiation". The pattern of "high in the east and low in the west" continues to exist, and the east shows "high-level stability", while the central and western regions show "fast climb and fast fall". The impact of the epidemic has exacerbated regional disparities. Thirdly, the influencing factors have both "universal basis" and "stage specific" attributes. Urbanization is a universal foundation, but the core drivers have regional heterogeneity: the eastern region relies on "Urban+Transportation Network", the central region urgently needs "breakthroughs in human capital", and the western region faces "dual shortcomings in human resources and infrastructure". The role of exogenous technological factors is relatively limited.

6.2 Policy Recommendations

Based on the findings, the following policy recommendations are proposed:

First, implement an overall strategy of "tiered advancement and resilience cultivation." At the national level, a risk monitoring and emergency response system for "AI + digital economy" synergistic development should be established. At the regional level, differentiated policies are essential: the eastern region should focus on "promoting deepening" to build a globally competitive innovation hub; the central and western regions should emphasize "strengthening foundations and addressing weaknesses," with targeted recovery support during risk impact periods to prevent further widening of disparities.

Second, advance an "adapting measures to local conditions, precisely driven" approach to factor allocation. In the eastern region, optimize smart city planning and promote intelligent coordination between digital infrastructure and transportation/energy networks (TRANS+). In the central region, implement a "digital talent agglomeration project" by strengthening local education in digital and AI-related fields and attracting talent from the east through preferential policies (HC+). In the western region, synchronize "hardware" (new infrastructure like 5G and computing centers) with "software" (digital literacy training and vocational education) development (TRANS+, HC+).

Third, construct a "data-enabled, scenario-driven" synergistic ecosystem. Encourage regions to leverage their industrial strengths (e.g., agriculture, tourism, energy) by opening government data and creating distinctive "AI + industry" demonstration scenarios. This approach can drive iterative improvements in AI algorithms and innovations in digital economic models, forming a positive cycle of "technology-data-scenario-industry" and ultimately achieving high-level, deeply integrated, and characteristic development.

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