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Emerging Technology-Driven Development: The Interactive Relation Among Digital Talent Agglomeration, Industrial Digitalization, and China's Economic Growth

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***Abstract*—The accelerating diffusion of artificial intelligence (AI), the Internet of Things (IoT), big data analytics, and blockchain across manufacturing, logistics, and services is fundamentally reshaping industrial competitiveness and labour-market demands worldwide. Against this backdrop, two intertwined imperatives emerge: cultivating "digital talent"—defined here as the workforce capable of deploying and innovating upon these emerging technologies—and advancing industrial digitalization as a systemic transformation of production processes. The deep integration of the digital and real economies is fundamental to the sound and rapid development of the overall economy, and human capital is a crucial driver of economic growth. Accordingly, this study performs a systematic and empirical examination of digital talent agglomeration and industrial digitalization levels across China's provincial regions and their influences on regional economic growth, clarifying the existing nonlinear relations and conjugate effects. The findings show that the relation among digital talent agglomeration, industrial digitalization, and regional economic growth follows an inverted-U shape, consistent with the Williamson hypothesis. For the country as a whole and for the eastern, central, and western regions, this study observes a deviation from the conjugate state between digital talent agglomeration and industrial digitalization. In the Yangtze River Delta region, however, the two have achieved a positive and interactive relation in terms of collaborative development that promotes regional economic growth. These results carry three technology-policy implications: digital talent agglomeration and industrial digitalization are important drivers of regional economic growth; resource agglomeration should remain at a moderate level and achieve coordinated development; and a regional integration strategy is critical in this process.**

***Index Terms*—Digital talent; Industrial digitalization; Economic growth; Nonlinear relationships; Conjugate effects; Technology-driven development**

I. Problem Formulation

The fourth industrial revolution—characterised by the convergence of artificial intelligence (AI), the Internet of Things (IoT), big data analytics, and blockchain—is no longer a distant prospect but an operational reality reshaping industries across the globe. AI-powered systems are already optimising production scheduling in real time, reducing idle capacity and raising throughput in automotive, electronics, and chemical manufacturing [1]. Industrial IoT sensor networks enable continuous, granular monitoring of equipment health and energy consumption, shifting firms from scheduled to predictive maintenance [2]. Big data platforms aggregate demand signals, supplier performance, and logistics data at a scale that is transforming supply-chain design and inventory management [3]. Blockchain-based traceability is addressing trust deficits in food, pharmaceutical, and financial supply chains while cutting reconciliation costs [4]. The common thread across all four technologies is the critical need for workers who can not only operate but design, integrate, and continuously improve such systems—a workforce that may be termed "digital talent." Understanding how such talent concentrates geographically, how it interacts with the broader industrial digitalization process, and what this interaction implies for regional economic growth is therefore a question of both theoretical and practical urgency.

The digital economy represents the most recent major form of economic organization to emerge after agrarian and industrial economies, constituting a landmark in the current wave of technological revolution. The Chinese government is promulgating a series of multilevel plans to accelerate digital development and to establish a framework that comprehensively integrates digital technology with the digital economy, digital governance, digital culture, digital society, and digital ecological civilization. The *Digital Economy Development and Cooperation Initiative*, adopted at the G20 Hangzhou Summit in 2016, defines the digital economy as "a series of economic activities in which digitalized knowledge and information serve as key production factors, modern information networks

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act as significant carriers, and the effective utilization of information and communication technologies serves as an important impetus for efficiency enhancement and economic structure optimization"— itself a specific manifestation of a new type of productive force. As the digital economy continues to deepen, data has become a new production factor, with digital technology inevitably transcending narrow applications within the digital industry to integrate deeply with the real economy. This enables a broader range of traditional industries to be optimized and entire production processes to be upgraded through digital transformation, enhancing market competitiveness and realizing a regionally integrated industrial structure through the extension of digital platforms, thereby elevating China's socioeconomic development to new levels. From this perspective, industrial digitalization is more practically significant than mere digital industrialization.

Nevertheless, as the saying goes, "Where talents gather, success follows." The development of the digital economy cannot be inseparable from talent support. Economic growth theory posits that human capital is an important determinant of economic growth, and the accumulation of human capital in an area produces clear comparative development advantages. China's *National Medium- and Long-Term Talent Development Plan (2010–2020)* defines talent as "those who possess certain professional knowledge or specific skills, undertake creative work, and contribute to society—workers with higher abilities and qualities in human resources." The agglomeration of talent produces a significant co-evolutionary effect alongside economic growth, forming a virtuous cycle of "talent policy $\rightarrow$ talent gathering $\rightarrow$ environment optimization $\rightarrow$ comprehensive development." In the digital economy era, high-calibre talent and scientific and technological innovation are expected to become core forces in great-power competition; greater efforts must therefore be made to build a strategic layout for digital talent agglomeration, maximize the role of talent in driving socioeconomic development, establish an innovation-driven autonomous development model, optimize the economic structure, and achieve comprehensive digital transformation [5], [6].

The resource agglomeration mechanism operates as an open system. Both talent and industry within—and beyond—this system are subject to multiple factors that shape their agglomeration levels. Differences in regional geographic, cultural, institutional, and socioeconomic development environments determine the direction of resource flows. The key challenge in studying the resource agglomeration mechanism lies in establishing a virtuous cycle system for regional environmental development. For instance, the effects of talent resource agglomeration are both agglomerative (economic) and dispersive (diseconomic) [5]. When industrial agglomeration exceeds a "threshold value," diseconomic phenomena may occur, such as environmental resource depletion, excess talent supply, and rising institutional transaction costs [6]. Resource agglomeration also involves development interactions across regions: when a single region's development pace exceeds that of its neighbours, talent agglomeration occurs; when agglomeration reaches a certain level, talent spillover may take place, and so on. What development trajectory characterises the relationship between digital talent agglomeration and industrial digitalization? Whether they form complementary interactions and positive effects on economic development, or whether structural imbalances and diseconomic effects prevail, warrants careful examination. Therefore, drawing on the concept of "location entropy" and the four-part decomposition of the digital economy proposed by the China Academy of Information and Communications Technology—namely digital industrialization, industrial digitalization, digital governance, and digital valorization, with the measurement of digital economy scale primarily involving the first two [7]—this study defines and measures digital talent agglomeration and industrial digitalization levels and analyses their relationship with China's regional economic growth and their degree of coordinated development.

Building on existing research, this study makes three main contributions. *First*, studies on digital talent remain scarce, with mainstream scholarship focused on demand analysis and talent training. Cutting-edge research has treated digital talent only as an intermediate variable in digital economic development or regional economic growth, lacking a systematic understanding of the law of digital talent agglomeration. *Second*, the China Academy of Information and Communications Technology defines industrial digitalization as the increase in output and efficiency brought about by applying digital technology in traditional industries, encompassing new industries, new business models, and new commercial forms [7]. Industrial digitalization can be viewed as the result of continuously deepening digital technology and is an important pathway to promoting high-quality socioeconomic growth and developing new productive forces. However, most existing studies on the digital economy are relatively broad and rarely focus on industrial digitalization specifically. *Third*, recognizing the inherent limitations of coupling systems and cointegration tests in examining interactions between different types of resource agglomeration, this study adopts the conjugate-effect framework to measure the degree to which digital talent agglomeration and industrial digitalization are coordinated, and uses an interaction term to verify their specific relationship.

II. Literature Review and Theoretical Hypotheses

Scholars have conducted extensive explorations of talent agglomeration, which can be classified into two broad streams: analyses of the factors influencing talent agglomeration, and analyses of the effects of talent agglomeration—specifically, the study of its interaction with other variables such as economic development, technological innovation, and industrial structure. A large body of empirical work has confirmed the existence of such interactions. However, relatively few studies have examined digital talent specifically, particularly with regard to its definition and disaggregation.

Regarding the effects of talent agglomeration, the extant literature clusters around three mainstream viewpoints. First,

agglomeration produces positive economic effects: it is positively correlated with regional innovation capacity, effectively interacts with industrial agglomeration, optimizes the industrial structure, and promotes economic growth [8], [9]. It can also build complementary mechanisms through the spatial spillover of talent and resources, achieving regional integration and narrowing economic disparities across regions [8], [9]. Second, talent agglomeration can also generate inefficiencies, primarily through negative externalities such as excessive competition and diseconomies of scale caused by over-agglomeration [10]. This can simultaneously induce brain drain in peripheral areas [11], thereby negatively affecting aggregate economic growth. Third, despite talent agglomeration's capacity to improve technological efficiency, promote technological progress, and enhance total factor productivity, over-agglomeration can generate congestion effects and cause efficiency losses. Furthermore, talent agglomeration is highly sensitive to the external environment, and its capacity to form a collaborative development relationship with other factors is closely linked to its ability to generate economic effects [12].

In accordance with new economic geography theory, external economies arising from larger market scale and abundant human resources can initiate the centripetal force that compels industries to concentrate in a given area, further expanding through information spillover effects. Conversely, market contraction and talent outflow form the centrifugal force for industrial transfer. In this context, the Williamson hypothesis holds that the agglomeration of resource factors within a specific regional space exerts an inverted-U-shaped impact on economic growth: agglomeration significantly enhances economic efficiency in its early stages, but once it surpasses a critical threshold, the economic effect turns negative, ultimately hindering growth and producing an outwardly dispersed structure [13]. In terms of human resources, influenced by locational advantages and the natural environment, talent agglomeration in a region—by strengthening the population's educational level and reducing transaction costs—generates innovation, information sharing, knowledge spillover, regional, and incentive effects, thereby enhancing regional innovation capacity, promoting total factor productivity with significant spatial spillover effects, and further driving industrial agglomeration and economic growth [14], [15]. Industrial agglomeration effectively reduces the cost of talent agglomeration, raises talent income levels, creates first-mover advantages, continuously attracts high-calibre talent and resources, optimizes the industrial structure, establishes a regional sharing system, and generates a positive cumulative circular effect [16], [17]. Developing regional talent and industrial agglomeration leads to a Matthew effect, continuously accumulating scale advantages; but when agglomeration exceeds a certain threshold, it produces negative externalities—disorderly competition, resource congestion, and overconsumption—that obstruct regional economic growth and induce talent and resource spillover and diffusion [18]. Thus, the influence of both talent agglomeration and industrial agglomeration on economic growth follows an inverted-U shape, initially positive and then negative. Krugman's "core–periphery" model in new economic geography theory reveals the spatial law of agglomeration and dispersion of economic activities [19]. Based on these discussions, we propose:

Hypothesis 1: Both digital talent agglomeration and industrial digitalization exert a nonlinear, inverted-U-shaped impact on regional economic growth.

The continuous deepening of new technologies—including big data, AI, IoT, and blockchain—at the real-economy level has vigorously promoted the agglomeration of digital talent and the digital transformation of traditional industries. Dependence on digital industrialization alone cannot promote sound and rapid economic development; only by integrating it with industrial digitalization, enabling digital talent to cluster within regions and diffuse across industries, and further optimizing production relations through digital governance and data valorization, can qualitative improvements be achieved in overall economic development [20], [21]. Accordingly, we propose:

Hypothesis 2: Digital talent agglomeration and industrial digitalization primarily promote regional economic growth by enhancing the digital economy's overall development level.

Meanwhile, the specific effects of talent and industry agglomeration—and the stage at which they act on economic growth—are closely associated with the development environment, geographical location, and talent policies. Interaction patterns within talent groups also significantly influence the "threshold" for diseconomic effects. Within the digital talent agglomeration and industrial digitalization domains explored here, the digital economy primarily shapes the industrial and social structure through two channels: digital industrialization and industrial digitalization [22], [23]. Resource agglomeration studies in this field should therefore commence from these two directions. Moreover, in accordance with the "centre–periphery" model, resource agglomeration within a region must be commensurate with the economic development stage. As agglomeration generates rapid development, the growth-driving force gradually shifts from being resource-driven to being total-factor-productivity-driven, requiring digital technology to fully assert its optimizing role, making both digital industrialization and industrial digitalization indispensable. A particularly significant element is the talent–industrialization ecological chain: a resilient human resource system is the core element of digital economic development and the most potent endogenous force driving competitiveness in regional economic and industrial development. Supported by favourable industrial digitalization policies, a virtuous digital talent–industrialization ecological chain can be built, achieving resource sharing and complementarity and effectively countering the diseconomic effects of resource over-agglomeration [24]–[26]. Relevant research further confirms that only when talent agglomeration and industrial agglomeration are in a collaborative development state can they mutually reinforce each other and adapt to the economic development stage [27], [28]. Thus, the interaction between digital talent agglomeration and industrial digitalization, and its influence on regional economic development, is complex and uncertain. Sound and

rapid economic growth requires the formation of a mutually collaborative development state between the two. Hence:

Hypothesis 3: Only when digital talent agglomeration and industrial digitalization are in a conjugated state of collaborative development can they positively affect regional economic growth.

A. Emerging Technologies as Drivers of Industrial Transformation

The Industry 4.0 literature has established AI, IoT, big data, and blockchain as the four foundational enabling technologies of contemporary industrial transformation [1]. In intelligent manufacturing, machine-learning algorithms perform dynamic scheduling of job-shop production floors, outperforming traditional operations-research heuristics by dynamically rebalancing workloads in response to equipment failures and demand fluctuations. Empirical studies in Chinese industrial clusters document throughput gains of 12–18% following AI scheduling deployment, while labour-productivity improvements have been traced to increased demand for system-integration and data-science competencies—precisely the profile of "digital talent" as defined in this study [1].

Industrial IoT enables dense, real-time telemetry across production assets that was previously infeasible at scale. Wang et al. (2023) review 187 IIoT deployments in Chinese manufacturing provinces and find that provinces with higher IoT adoption intensity exhibit faster convergence between their industrial digitalization index and their share of technically skilled workers, suggesting a co-evolutionary dynamic between technology infrastructure and talent demand [2]. Big data analytics further compounds this effect at the supply-chain level: Zhang et al. (2024) demonstrate, using a panel of 238 Chinese listed manufacturing firms from 2018 to 2022, that big-data-driven demand forecasting significantly reduces inventory holding costs and supply disruptions while simultaneously raising the firm-level wage premium for data engineers and AI specialists [3]. Blockchain-based traceability has emerged as a trust infrastructure for multi-tier supply chains: Xu and Duan (2023) analyse blockchain pilot programmes in nine Chinese provinces and document that participating firms reduce inter-organisational transaction costs by 8–14%, while creating a new category of blockchain-governance roles drawing on both coding and regulatory compliance expertise [4].

Taken together, these technology-specific findings converge on a structural insight directly relevant to the present study: each enabling technology creates a distinct demand profile for digital talent, and the geographic concentration of such talent, in turn, accelerates industrial digitalization. This positive feedback loop mirrors the theoretical mechanism underlying Hypotheses 1 and 3, but grounds it explicitly in a technology-driven rather than a purely economic-geographic logic. It also underscores a tension that has received insufficient empirical attention: the pace of technology diffusion may outstrip the rate at which regional labour markets can supply appropriately skilled workers, producing the structural mismatch between digital talent agglomeration and industrial digitalization that this study is designed to examine.

III. Research Design

A. Benchmark Model and Variable Selection

Based on panel data from 30 provinces and municipalities in China (excluding Tibet, Hong Kong, Macao, and Taiwan) from 2007 to 2022, this study performs an empirical analysis of the interactive relation among digital talent agglomeration, industrial digitalization, and regional economic growth. To examine the inverted-U-shaped nonlinear relation, this study constructs the following benchmark model for Hypothesis 1:

$$\begin{aligned} \mathrm{gdp}_{it} = \alpha_{it} + \delta_1 \mathrm{det}_{it} + \delta_2 \mathrm{idl}_{it} + \delta_3 \mathrm{det}_{it}^2 \\ + \delta_4 \mathrm{idl}_{it}^2 + \mathrm{del}_{it} + \delta_5 \mathbf{X}_{it} + \varepsilon_{it} \end{aligned} \tag{1}$$

Here, i denotes the province and t the year. The dependent variable gdp_{it} represents the regional economic growth level; because nominal gross domestic product (GDP) is used in constructing the core explanatory variables via the location entropy method, this study takes the logarithm of nominal regional GDP as the measure of local economic growth. The core explanatory variables are the digital talent agglomeration index (det) and the industrial digitalization index (idl), both constructed using the location entropy method. The digital talent agglomeration level is measured by computing the location entropy of employees in (i) information transmission, software, and information technology services, and (ii) computer, communication, and other electronic equipment manufacturing industries [29], [30]. Following Zhao et al. (2024) [31], who compiled input–output tables for 42 sectors across provinces and municipalities for 2012, 2015, and 2017, the missing-year tables are estimated using the RAS (Ratio Adjusted Squares) method [32], [33]. Digital core industries are then identified according to the National Bureau of Statistics' *Statistical Classification of Digital Economy and Its Core Industries*, matched to the relevant product sectors in the input–output tables. The direct consumption coefficient of traditional industries for digital core industry products is measured and multiplied by the added value of traditional industries to obtain the industrial digitalization added-value scale, from which the location entropy is computed.

Furthermore, the development of digital infrastructure, digital industries, and the external digital environment is a significant factor influencing both digital talent agglomeration and industrial digitalization. Drawing on He et al. (2023) [34], this study constructs corresponding evaluation indicators and computes scores to measure each province's and municipality's digital economic development level (del) from 2007 to 2022 as a mediating variable. $\mathbf{X}_{it}$ represents the set of control variables and ε_{it} is the random disturbance term.

The control variables are selected based on their degree of influence on regional economic growth: (1) *Unemployment rate* (unemp): the urban unemployment rate of each region. Inadequate employment and insufficient labour productivity exert a clearly negative impact on economic development.

(2) *Urbanization rate* (urban): the proportion of the urban population to the total regional population. Increases in the urban population share are an important indicator of development, and national policies are primarily implemented at the municipal level. Talent and industries also concentrate around cities. However, excessive urbanization can generate congestion, resulting in unequal opportunities, higher living costs, resource waste, and a wider wealth gap, thereby hindering economic growth [35]. (3) *Built-up area rate* (built): reflects urban infrastructure completion. The expansion of built-up areas represents effective land utilization and an optimized urban structure, conducive to improving regional economic growth. (4) *Economic structure* (estr): measured by the share of tertiary industry output in regional GDP. A higher tertiary-sector share can effectively meet society's development needs; however, the hollowing-out of manufacturing through industrial relocation remains an important development challenge. (5) *Financial development level* (fin): measured by the ratio of the loan balance of regional financial institutions to total industrial output. Regions with higher financial development provide sufficient funds to modernize industries and accelerate resource distribution, though avoiding excessive economic financialization is equally important for stable regional development.

The analytical sample uses panel data from 30 provinces and municipalities in China (excluding Tibet, Hong Kong, Macao, and Taiwan) from 2007 to 2022. The input–output tables for 42 departments, which serve as the basis for computing the industrial digitalization index, are drawn from the CEADS database. Remaining variable data are derived from the annual regional data of the National Bureau of Statistics of China, the *China Statistical Yearbook*, and the *China Labour Statistical Yearbook*. Missing observations for urban unemployment rate and built-up area are filled via linear interpolation. Table I presents the variable descriptions and descriptive statistics.

TABLE I
VARIABLE EXPLANATION AND DESCRIPTIVE STATISTICS

Variable	Symbol	*N*	Mean	Std. Dev.	Min / Max
Economic growth	gdp	480	9.625	0.975	6.579 / 11.754
Digital talent agglo.	det	480	0.658	0.516	0.141 / 2.640
Industrial digit. level	idl	480	0.699	1.172	0.020 / 6.971
Digital econ. dev.	del	480	0.857	0.411	0.315 / 2.343
Unemployment rate	unemp	480	0.903	0.977	0.099 / 5.489
Urbanization rate	urban	480	3.335	0.690	1.200 / 5.200
Built-up area rate	built	480	0.575	0.134	0.282 / 0.896
Economic structure	estr	480	0.321	0.143	0.075 / 0.710
Financial dev. level	fin	480	0.479	0.093	0.298 / 0.838

B. Examination of the Conjugate Effect

As discussed above, substantial uncertainty surrounds the interaction between digital talent agglomeration and industrial digitalization and their influence on regional economic development. Adjustments in national policy, changes in the international environment, enhancements to the industrial structure, and improvements in transportation conditions all shape resource mobility, resulting in structural imbalances and mismatches between the two. Only when they are in a state of collaborative development can they generate a positive and sustained effect on economic growth.

"Conjugation" is a term drawn from the natural sciences—mathematics, physics, and chemistry—referring to a pair of entities that interact and match in a certain pattern. In the social sciences, it is generally treated as a systemic concept emphasising symmetry, synergy, and coupling among elements. Resource agglomeration characterised by a conjugation effect can achieve orderly complementarity, reduce internal friction, and promote harmonious and mutually reinforcing economic development. After reviewing coupled-systems analysis and cointegration tests, this study concludes that the former exhibits considerable subjectivity and lacks unified standards in index system construction, while the latter is designed primarily to test whether a linear combination of non-stationary sequences possesses a stable long-run equilibrium—a framework that is not directly applicable here. This study therefore adopts a Wald test to examine correlations among variables and infer the conjugate state between digital talent agglomeration and industrial digitalization, supplemented by lagged variable analysis and interaction terms to verify the robustness of the specific linkage between the two.

IV. EMPIRICAL ANALYSIS

A. Nonlinear Relation Analysis

To address heteroscedasticity and serial correlation in the panel regressions, this study employs the Generalized Least Squares (GLS) model. The results are presented in Table II. Columns (1)–(2) examine the influence of digital talent agglomeration on regional economic growth; columns (3)–(4) examine the effect of industrial digitalization; and columns (5)–(8) consider their joint influence along with control variables.

The results show that when only digital talent agglomeration is examined, the first-order term carries a positive coefficient and the second-order term a negative coefficient, both significant at the 1% level, revealing a significant inverted-U-shaped relation between the two. Similarly, when only industrial digitalization is examined, the first-order term is significantly positive and the second-order term significantly negative, also exhibiting an inverted-U-shaped pattern. When both variables are included simultaneously in columns (5)–(8), introducing control variables does not alter their inverted-U-shaped relationship with regional economic growth. This implies that regional digital talent agglomeration and industrial digitalization are consistent with the Williamson hypothesis: in the early stages, spatial concentration of resources generates positive agglomeration and promotes economic growth, but once concentration exceeds a certain level, excessive congestion effects emerge and negatively affect growth. Hence, **Hypothesis 1 is supported**.

Subsequently, to analyse the interaction mechanism between digital talent agglomeration and industrial digitalization, this study introduces the digital economic development level (del)

TABLE II
BENCHMARK REGRESSION RESULTS

	(1) gdp	(2) gdp	(3) gdp	(4) gdp	(5) gdp	(6) gdp	(7) gdp	(8) gdp
det	0.7964***	2.0070***			1.3676***	0.9257***	2.9879***	1.8470***
	(0.0119)	(0.0405)			(0.0144)	(0.0268)	(0.0381)	(0.0510)
det^2	−0.5076***	−0.7043***				−0.4023***		
	(0.0146)	(0.0152)				(0.0167)		
idl			0.3367***	3.9794***	−0.4776***	−0.3993***	0.9106***	1.9989***
			(0.0151)	(0.0747)	(0.0150)	(0.0203)	(0.0424)	(0.1011)
idl^2			−1.5874***	−0.6698***			−1.0623***	
			(0.0319)	(0.0209)			(0.0448)	
unemp		−0.2066***		−0.2165***		−0.2899***	−0.3400***	−0.1863***
		(0.0050)		(0.0043)		(0.0053)	(0.0071)	(0.0069)
								−0.2384***
								(0.0104)
urban		3.0857***		2.2352***		4.5159***	3.5644***	3.3632***
		(0.0543)		(0.0501)		(0.0321)	(0.0572)	(0.0639)
								2.3658***
								(0.0798)
built		1.0955***		1.1113***		1.0640***	1.4302***	0.9337***
		(0.0297)		(0.0300)		(0.0369)	(0.0298)	(0.0304)
								1.2435***
								(0.0443)
estr		0.0233		−0.1720***		0.3145***	2.5231***	0.2529***
		(0.0588)		(0.0599)		(0.0809)	(0.0937)	(0.0908)
								1.7064***
								(0.1017)
fin		−0.9066***		−0.7348***		−1.0537***	−1.0898***	−0.8467***
		(0.0155)		(0.0166)		(0.0234)	(0.0193)	(0.0219)
								−0.7692***
								(0.0199)
_cons	8.9370***	8.8760***	8.7512***	6.6095***	9.1472***	8.8963***	7.9983***	7.2923***
	(0.0455)	(0.0305)	(0.0535)	(0.0464)	(0.0151)	(0.0439)	(0.0400)	(0.0795)
N	480	480	480	480	480	480	480	480

***, **, * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors in parentheses.
The same convention applies to all subsequent tables.

as the mediating variable. The GLS results are presented in Table III.

TABLE III
REGRESSION RESULTS OF MEDIATION EFFECTS

	(1) gdp	(2) del	(3) gdp
det	1.8470***	0.0027	1.6751***
	(0.0510)	(0.0070)	(0.0560)
det^2	−0.4023***	0.0450***	−0.6057***
	(0.0167)	(0.0030)	(0.0263)
idl	1.9989***	0.1461***	1.0602***
	(0.1011)	(0.0089)	(0.0582)
idl^2	−1.0623***	−0.0773***	−0.5756***
	(0.0448)	(0.0038)	(0.0232)
del			5.4383***
			(0.1625)
unemp	−0.2384***	−0.0226***	−0.0940***
	(0.0104)	(0.0008)	(0.0063)
urban	2.3658***	0.1055***	1.7455***
	(0.0798)	(0.0095)	(0.0544)
built	1.2435***	0.0511***	0.8834***
	(0.0443)	(0.0034)	(0.0417)
estr	1.7064***	0.3295***	−0.2001***
	(0.1017)	(0.0078)	(0.0746)
fin	−0.7692***	−0.0280***	−0.5832***
	(0.0199)	(0.0025)	(0.0182)
_cons	7.2923***	−0.1226***	8.0787***
	(0.0795)	(0.0047)	(0.0714)
N	480	480	480

The second column shows that digital talent agglomeration enhances digital economic development, while industrial digitalization's effect on digital economic development is initially positive and then inhibitory—the main source of the inverted-U-shaped relationship between digital economic development and the core explanatory variables. The third column reveals that a higher digital economic development level is associated with more pronounced regional economic growth, and the inverted-U-shaped relationship between digital talent agglomeration and industrial digitalization and regional economic growth persists, confirming the significant mediating role of digital economic development. Hence, **Hypothesis 2 is supported**.

B. Analysis of Conjugate Effects

This section discusses the conjugate effect between digital talent agglomeration and industrial digitalization, examining their conjugate coefficients through the Wald test. The Wald test results indicate that the variable coefficients are all significant, with a consistent sign direction and significant Wald statistics, indicating a conjugate state. Coefficients with inconsistent signs indicate a non-conjugate state.

1) Wald Test: Table IV presents the Wald test results. In China overall, digital talent agglomeration and industrial digitalization are not in a conjugate state and cannot effectively promote each other, failing to maximize their joint driving effect on economic growth.

The subsample analysis in columns (1)–(4) indicates that digital talent agglomeration and industrial digitalization have

TABLE IV
WALD TEST RESULTS (CONJUGATE EFFECT)

	(1) Entire	(2) Eastern	(3) Central	(4) Western	(5) Jing-Jin-Ji	(6) YRD
det	0.9257***	0.8426***	0.5967***	1.7668***	0.9904***	0.3665***
	(0.0268)	(0.0195)	(0.0771)	(0.0820)	(0.1791)	(0.1246)
idl	−0.3993***	−0.3098***	−0.5091***	−0.6247***	−0.8107***	0.7562***
	(0.0203)	(0.0171)	(0.1240)	(0.0705)	(0.2324)	(0.1800)
unemp	−0.1863***	−0.2037***	−0.1518***	−0.0405***	−0.0065	−0.2033***
	(0.0069)	(0.0082)	(0.0321)	(0.0111)	(0.0483)	(0.0721)
urban	3.3632***	2.2361***	4.5376***	2.6753***	−6.9682***	0.3925
	(0.0639)	(0.0542)	(0.5048)	(0.1486)	(0.9363)	(0.5107)
built	0.9337***	−0.0274	0.9791***	1.5721***	4.8717***	7.2075***
	(0.0304)	(0.0426)	(0.1374)	(0.0500)	(0.8219)	(0.8298)
estr	0.2529***	−2.4468***	5.1874***	5.5471***	8.5629***	−3.7639***
	(0.0908)	(0.0703)	(0.5291)	(0.3596)	(0.6417)	(0.5160)
fin	−0.8467***	−0.1772***	−1.5898***	−0.8820***	0.0663	1.2605***
	(0.0219)	(0.0119)	(0.0643)	(0.0505)	(0.1755)	(0.1674)
_cons	8.8963***	10.2367***	7.2058***	5.6836***	8.5585***	7.7747***
	(0.0439)	(0.0474)	(0.2496)	(0.1162)	(0.4523)	(0.5987)
N	480	208	96	176	48	64
Wald	1211.82**	2159.59***	88.26***	565.58***	39.45***	95.70***

YRD: Yangtze River Delta (Shanghai, Jiangsu, Zhejiang, Anhui, per the 2019 Integrated Development Plan).
Jing-Jin-Ji: Beijing–Tianjin–Hebei region.

not formed a conjugate state in China as a whole nor in its eastern, central, or western regions. Ranked by the degree of deviation from conjugacy, the order is: western $>$ central $>$ eastern. Nationally, while digital talent agglomeration has a significantly positive effect on economic growth, industrial digitalization has a significantly negative impact at the 1% level, suggesting that the main reason for non-conjugacy lies in the mismatch between industrial digitalization and the current economic development stage. Given China's overall industrial development advantages, this negative effect may stem more from structural misalignment than from fundamental incompatibility. In the eastern region, the absence of a conjugate effect suggests that development cannot rely solely on the concentration of a single resource factor, but requires the coordination and mutual reinforcement of internal regional resources. In the western region, brain drain is the primary reason for the more pronounced deviation from conjugacy between digital talent and industrial digitalization, as well as for the failure to jointly promote economic growth.

However, columns (5) and (6) show that at the sub-national level, while the Beijing–Tianjin–Hebei region has yet to form a conjugate state, the Yangtze River Delta has constituted a conjugate driving force for economic growth. This implies that under the regional integrated development strategy, while digital talent agglomeration and industrial digitalization in the Yangtze River Delta are not necessarily the highest in absolute terms, they have reached a state of mutual matching and coordinated development. In this way, the "threshold" for the diseconomic effects of resource agglomeration is effectively raised, maximizing the stimulus on the regional economy. Intuitively, the Yangtze River Delta, with Shanghai as its "hub," features a first-class domestic financial system, a superior natural environment, and significant socioeconomic development advantages; it is also a traditional agricultural and industrial heartland with well-developed primary, secondary, and tertiary industries and convenient transportation. It is therefore not unexpected that digital talent agglomeration and industrial digitalization have achieved a conjugate state there. **Hypothesis 3 is thus also supported.**

2) Robustness Test: This study corroborates the baseline findings by lagging the core explanatory variables by one period. Table V presents the results.

When digital talent agglomeration and industrial digitalization are considered jointly, the first-order term coefficients are 1.8090 and 2.0039, respectively, both significantly positive at the 1% level; the second-order term coefficients are −0.3823 and −1.0368, both significantly negative at the 1% level. These results further support the inverted-U-shaped relationship between digital talent agglomeration, industrial digitalization, and local economic growth, confirming the strong robustness of the baseline results.

Table VI presents interaction-term regression results for the full sample, the eastern, central, and western regions, and the Beijing–Tianjin–Hebei and Yangtze River Delta sub-regions.

In columns (1)–(4), the only positive interaction term is in the central region, suggesting a positive contribution of the digital talent–industrial digitalization interaction to economic growth there. In the full sample and the eastern and western subsamples, the interaction term is significantly negative, indicating a deviation from conjugacy: the two variables mutually restrict each other and do not form a positive interaction, consistent with the Wald test results. In columns (5) and (6), the interaction coefficient is positive in the Beijing–Tianjin–Hebei region, but the individual variable coefficients are significantly negative; in the Yangtze River Delta, both variable and interaction coefficients are positive, though only the industrial digitalization coefficient is significant. After introducing the interaction term, the relationship between the original and target variables becomes more complex and susceptible to other variable values. The conjugate-effect test results therefore exhibit strong overall robustness but become less stable at the regional level.

TABLE V
ROBUSTNESS TEST: LAGGED CORE EXPLANATORY VARIABLES

	(1) gdp	(2) gdp	(3) gdp	(4) gdp	(5) gdp	(6) gdp
L.det	0.8156***	1.9635***		0.9832***	1.8090***	
	(0.0123)	(0.0617)		(0.0191)	(0.0671)	
L.det^2	−0.4840***			−0.3823***		
	(0.0210)			(0.0229)		
L.idl		0.3751***	3.9113***	−0.3907***	2.0039***	
		(0.0157)	(0.0766)	(0.0173)	(0.0830)	
L.idl^2		−1.5291***		−1.0368***		
		(0.0391)		(0.0436)		
unemp	−0.1967***	−0.2034***	−0.2572***	−0.2976***	−0.1841***	−0.2190***
	(0.0055)	(0.0072)	(0.0056)	(0.0080)	(0.0062)	(0.0105)
urban	2.8948***	2.1604***	4.3262***	3.3233***	3.2338***	2.2034***
	(0.0693)	(0.0701)	(0.0322)	(0.0697)	(0.0786)	(0.1280)
built	0.9080***	0.9714***	0.9279***	1.3091***	0.8123***	1.0351***
	(0.0348)	(0.0425)	(0.0265)	(0.0278)	(0.0442)	(0.0454)
estr	0.1862***	−0.1141	0.5112***	2.8287***	0.2668***	1.6776***
	(0.0710)	(0.1016)	(0.0722)	(0.0861)	(0.0610)	(0.1532)
fin	−0.9731***	−0.8171***	−1.1161***	−1.1388***	−0.9514***	−0.8604***
	(0.0176)	(0.0237)	(0.0231)	(0.0201)	(0.0248)	(0.0313)
_cons	9.1359***	9.0835***	8.7856***	6.6401***	9.0917***	7.5444***
	(0.0389)	(0.0798)	(0.0329)	(0.0824)	(0.0299)	(0.1098)
N	450	450	450	450	450	450

TABLE VI
ROBUSTNESS TEST OF CONJUGATE EFFECTS: INTERACTION TERM TEST

	(1) Entire	(2) Eastern	(3) Central	(4) Western	(5) Jing-Jin-Ji	(6) YRD
det	2.6884***	3.2570***	0.3186	3.0947***	−2.7251***	0.3345
	(0.0473)	(0.0611)	(0.3830)	(0.1749)	(0.5310)	(0.4648)
idl	0.7925***	1.5013***	−0.6564***	−0.0127	−2.9077***	0.7391**
	(0.0262)	(0.0442)	(0.2413)	(0.0964)	(0.3019)	(0.3127)
idl×det	−1.4304***	−1.8223***	0.3723	−1.6676***	2.0454***	0.0213
	(0.0273)	(0.0437)	(0.5070)	(0.2056)	(0.2496)	(0.3021)
unemp	−0.2216***	−0.2409***	−0.1454***	−0.0357***	−0.0844**	−0.2035***
	(0.0128)	(0.0073)	(0.0327)	(0.0118)	(0.0350)	(0.0727)
urban	2.5860***	−0.7910***	4.5735***	2.6102***	−0.7770	0.4047
	(0.1207)	(0.0817)	(0.5064)	(0.1634)	(1.1953)	(0.5419)
built	1.0174***	0.9859***	1.0134***	1.5365***	4.3635***	7.1990***
	(0.0437)	(0.0585)	(0.1426)	(0.0642)	(0.6244)	(0.8307)
estr	1.5950***	1.4808***	5.1615***	5.4341***	4.7870***	−3.7646***
	(0.1030)	(0.1036)	(0.5271)	(0.4230)	(0.6470)	(0.5160)
fin	−0.8295***	−0.4354***	−1.5748***	−0.8494***	0.0546	1.2614***
	(0.0186)	(0.0315)	(0.0657)	(0.0525)	(0.1410)	(0.1677)
_cons	7.6057***	8.5187***	7.2610***	5.2631***	9.9229***	7.7934***
	(0.0966)	(0.0536)	(0.2672)	(0.1580)	(0.3510)	(0.6511)
N	480	208	96	176	48	64

V. CONCLUSIONS AND POLICY IMPLICATIONS

This study examines panel data from 30 provinces and municipalities in China from 2007 to 2022 to determine how digital talent agglomeration and industrial digitalization influence regional economic growth, and investigates the nonlinear relation and synergistic development state brought about by their joint effect. The principal conclusions are as follows.

1) A significant nonlinear relation exists among digital talent agglomeration, industrial digitalization, and regional economic growth in China. Both variables exert an inverted-U-shaped influence on economic growth—initially positive, then negative—consistent with the Williamson hypothesis. In the early stage of agglomeration, resource concentration significantly promotes efficiency and facilitates economic development; once a threshold is reached, however, congestion effects, diseconomies of scale, and negative externalities emerge, ultimately hindering growth.
2) Strengthening the foundation and overall level of digital economic development is crucial for empowering digital technology to transform traditional industries, create industrial systems with new business models, and continuously promote sound and rapid economic development.
3) The test of the interaction between digital talent agglomeration and industrial digitalization reveals that, nationally and in most regions, the two are in a state of deviation and non-conjugacy, failing to form a collaborative development trend conducive to sustained economic growth. However, from a regional integration perspective, the Yangtze River Delta has emerged as a region that has initially achieved a conjugated state of digital talent agglomeration and industrial digitalization, carrying important implications for policy design.

A. Technology Deployment Strategy Recommendations

First, regional governments and industry associations should adopt a phased IoT and AI deployment roadmap calibrated to the existing digital talent base. The inverted-U-shaped findings imply that technology deployment outpacing talent supply generates congestion and diminishing returns; conversely, talent accumulation without adequate technology infrastructure produces underutilisation. A phased approach—beginning with IoT sensor deployment in capital-intensive subsectors (e.g., energy, chemicals, heavy machinery) where the initial skills threshold is lower, and progressively advancing to AI-driven process optimisation as the local talent pool deepens—can keep the two variables within the conjugate zone identified for the Yangtze River Delta. Provincial governments should use the industrial digitalization index developed in this study as a real-time dashboard to monitor whether talent and technology co-evolve within sustainable bounds, triggering policy interventions (targeted recruitment incentives, upskilling subsidies) whenever a structural gap is detected.

Second, university–industry technology bridges should be institutionalised as a structural mechanism—not merely a supplementary programme—for translating technology investments into sustained talent supply. The evidence reviewed in Section II consistently identifies a lag between technology adoption at the firm level and the availability of workers trained to deploy those technologies. Co-designed degree tracks and joint research centres linking universities in central and western regions directly to industrial digitalization pilot zones would shorten this lag. Importantly, such bridges must be technology-specific: AI production-scheduling competencies are distinct from IoT network architecture or blockchain smart-contract auditing, and curriculum design should reflect this granularity. The successful model in the Yangtze River Delta—where Shanghai's research universities anchor a talent pipeline spanning Jiangsu, Zhejiang, and Anhui—demonstrates that inter-city academic collaboration within an integrated regional economy can sustain conjugate development even as technology complexity increases.

Third, the Yangtze River Delta technology ecosystem should be treated as a replicable governance model, not merely a geographic success story. The key policy architecture enabling conjugate development in the Delta includes: (a) a unified regional talent-recognition and inter-provincial social-benefit portability system that reduces the transaction costs of inter-city talent mobility; (b) shared digital infrastructure platforms (cloud, edge-computing, and data-exchange protocols) that lower technology deployment costs for smaller firms in peripheral cities; and (c) coordinated industrial policy that deliberately sequences technology adoption across sub-regions to avoid intra-regional congestion. Policymakers in the Chengdu–Chongqing Economic Circle and the Harbin–Changchun Urban Agglomeration should assess how this three-element architecture can be adapted to their own institutional and industrial contexts, transforming the Yangtze River Delta from an exceptional outlier into the first node of a broader network of technology–talent conjugate development zones—a systemic outcome that this study's findings suggest is both feasible and necessary for achieving balanced, high-quality growth across China's diverse regional economies.

Drawing on the foregoing literature and empirical analysis, this study identifies policy implications in three further aspects. *First*, digital talent agglomeration and industrial digitalization are significant drivers of regional economic growth. Regional talent and industrial policies must encompass multiple dimensions: strengthening university–enterprise cooperation, cultivating local talent, and offering preferential policies to attract high-calibre digital talent both domestically and internationally; establishing policy systems that encourage entrepreneurial incubation and accelerated growth while driving industrial advancement through digital-transformation demonstration projects; and integrating urban digital transformation to enhance digital infrastructure and public service management. *Second*, resource agglomeration should proceed to an appropriate degree, and digital talent agglomeration and industrial digitalization must be coordinated. Compared with the absolute scales of talent agglomeration and industrial digitalization, regional governments should prioritize policies aligned with factor-market allocation rules and the actual demands of the regional development stage, rationally guiding talent and industry agglomeration toward structural synergy. *Third*, regional integration strategy is critical throughout the digital talent agglomeration and industrial digitalization process. The Yangtze River Delta results show that regional integration can effectively develop digital talent agglomeration and industrial digitalization in a coordinated manner through resource integration, innovation promotion, infrastructure optimization, and policy coordination, thereby producing greater socioeconomic benefits.

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