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Configurational Paths for Digital Technology Empowering Quality Improvement in Vocational Education: Evidence from China

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Abstract

Systematically revealing the critical factors and differentiated pathways through which digital technology empowers the high-quality development of vocational education is pivotal for decision-making in educational modernization. Grounded in the Technology-Organization-Environment (TOE) framework, this study employs fuzzy-set Qualitative Comparative Analysis (fsQCA) to investigate the configurational paths of digital technology empowerment in vocational education. The results indicate that this empowerment process is driven by the synergistic interaction of multiple factors rather than single conditions. Four distinct configurational paths were identified:Technology-Prominent,Resource-Aggregation, Talent-Cultivation Enhancement and Technology-Improvement with Environmental-Safeguard. Based on these findings, we propose the following policy implications: first, establish a multi-dimensional collaborative policy framework that ensures adaptive fit among factors; second, prioritize technological advancement and environmental infrastructure to activate the kinetic energy of digital-vocational integration; and third, implement region-specific matching strategies to promote balanced and equitable improvements in digital empowerment levels across different regions.

Introduction

As a hallmark of emerging global industries, digital technology is profoundly reshaping the landscape of vocational education and driving its high-quality development. Leveraging digital technology to empower vocational education has become a strategic imperative driven by socio-economic demands and the need to enhance regional economic vitality and talent competitiveness. In recent years, governments worldwide have enacted various policies to provide top-level design and institutional safeguards for this digital transformation.

However, the implementation outcomes of these policies vary significantly across regions. Persistent bottlenecks—such as inadequate digital infrastructure, data silos between enterprises and educational institutions, and insufficient digital literacy among educators—have hindered the full realization of digital technology's empowering potential in vocational education. Given this context, it is critical to systematically identify the key factors influencing high-quality development and to clarify the differentiated pathways generated by various combinations of conditions.

Focusing on empirical data from 31 provincial-level regions in China, this study investigates the determinants of digital technology empowerment in vocational education. By employing a configurational analysis approach, we explore the synergistic mechanisms and multi-factor linkages that drive this empowerment process. Our findings aim to provide an evidence-based reference for policymakers to formulate more effective strategies for advancing digital technology integration in vocational education.

1. Literature Review and Problem Statement

1.1. Current Landscape of Digital Empowerment in Vocational Education

The pathways through which digital technology empowers vocational education (VE) have become increasingly diversified. Existing literature primarily highlights three dimensions of empowerment:

Instructional Resource Empowerment: Digital technology has significantly enhanced instructional efficiency by revolutionizing pedagogical methods, providing personalized learning support, and facilitating resource sharing **(Jiang,C.Y., Sun,M.,2024;van den Bogaart, et al, 2018)**. Cross-institutional and cross-regional sharing platforms have mitigated disparities in resource distribution, promoting equitable access to high-quality educational assets **(Zhou.W.L., Hu.S.,2023)**.

Talent Cultivation Empowerment: The integration of digital technology with specialized curricula addresses critical issues such as homogenized teaching methods and rigid teacher-student interaction patterns **(Bai.L., et al,2025;Aluko, H.A., et al.2026;Zhang.R., Xie Y.P. 2025)**. By constructing learning ecosystems that combine digital knowledge tools, resource utilization, and the synergy between virtual simulation and real-world practice, these initiatives strengthen students' digital application skills and innovative capacities **(Huo, Y., & Zhang, S. 2025)**.

Industry-Education Synergy: Multi-stakeholder collaboration involving schools, government, industry associations, and enterprises has fostered new models of skill development. Mechanisms such as establishing digital industry colleges **(Gan.Y.T., Huang.R.,2025;Oikarinen, M., et al. 2026)**, conducting collaborative technological innovation **(Feng.S.H., Chen.L.,2025;Miao.L., et al,2025)**, and launching VE big data centers **(Su.Y.T., et al.,2025)** effectively integrate corporate technical resources and curriculum expertise with institutional teaching capabilities.

1.2. Research Gaps: Heterogeneity and Methodological Limitations

Despite these advancements, scholars have noted significant heterogeneity in the effectiveness of digital empowerment. Key bottlenecks include:

Infrastructure Disparities: Variations in regional digital infrastructure hinder the effective alignment of VE resources **(Timotheou, S.,.et al,2023;Feng.K.R., Du.J. ,2025;Tzafilkou, K., et al,2023)**.

Resource Sharing Barriers: Insufficient sharing of digital teaching resources exacerbates the urban-rural divide in digital construction**(Ma.L.T. ,2025)**.

Misalignment with Industry Needs: A disconnect often exists between the demand for digital talents in local industries and the strategic direction of regional VE, leading to a mismatch between institutional strengths and industrial development trajectories **(Gong.H.,et al,2024)**.

While previous studies have proposed strategies such as strengthening policy safeguards **(Jing.A.L., Zhu.Y.J. ,2025;Wang.S.S.,2024)**and optimizing talent cultivation schemes based on industry orientation **(Li.Y.,2025)**, critical gaps remain. First, there is a lack of benchmark models or paradigmatic samples that can explain the diversity of outcomes and the distinct driving paths of digital empowerment. Second, predominant methodologies rely on theoretical analysis, traditional regression, or correlation analysis, which focus on the net effect of single factors. These approaches fail to adequately capture the complex interplay and synergistic mechanisms among multiple antecedents.

1.3. The Configurational Perspective and Research Questions

Analyzing the multi-factor mechanisms underlying digital empowerment is not only necessary but also practically urgent for unraveling its complex logic. From the perspective of complexity science, the configurational approach has been widely adopted to understand causal complexity in organizational outcomes. It posits that multiple influencing factors are interdependent and can combine in various permutations to produce the same outcome (equifinality)**(Prasad, K., et al,2026)**.

Consequently, this study focuses on the following overarching question: What are the configurational paths that lead to improved levels of digital technology empowerment in vocational education? This inquiry is broken down into two progressive sub-questions:

What are the key antecedent conditions affecting the efficacy of digital empowerment?

How do these diverse antecedents synergistically interact to drive the empowerment process?

To address these questions, this paper integrates the Technology-Organization-Environment (TOE) framework with the fuzzy-set Qualitative Comparative Analysis (fsQCA). we aim to identify which combinations of antecedents lead to high-level empowerment and how they function. Our findings will provide a robust theoretical basis and practical guidance for policymakers to formulate targeted strategies.

2. Research Design and Analytical Framework

2.1 Research Design

The TOE framework posits that the factors influencing technology adoption and innovation are concentrated across three dimensions: technological, organizational, and environmental. By establishing a comprehensive analytical framework, it explains organizational behaviors regarding technology integration and adoption. Since the factors influencing digital technology empowerment in vocational education development largely fall within these technological, organizational, and environmental dimensions, the TOE framework facilitates the integrative analysis of existing factors. Furthermore, previous studies have explored the application of the TOE framework in analyzing how different elements affect vocational education development, such as innovation in vocational education

technology **(Li.M.L., et al,,2024;Yi.X., et al,2025;Xu.ZH., et al,2026; Zhou, K., et al,2025;Liu.W. ,2025)** and pathways for teacher professional development **(Bülbül, A.E., Özelçi, S.Y.,2026)**. These studies demonstrate the strong explanatory power and applicability of the TOE framework, thereby enhancing the scientific rigor and rationality of constructing the configurational analysis framework.

Consequently, from a configurational perspective, this study employs the fsQCA)method to explore the synergistic effects of multiple conditional variables underlying the empowerment of vocational education development by digital technology. To address the research objectives, this paper selects 31 provinces in China as samples and constructs an integrative analytical framework for the factors influencing digital technology empowerment in vocational education development based on the TOE framework. Subsequently, the fsQCA method is utilized to investigate the combinatorial paths and patterns leading to both high and non-high effectiveness.

2.2. Analytical Framework

The analytical framework is grounded in the TOE framework. The technological context pertains to the internal and external technologies relevant to the organization, emphasizing innovation capacity and technological fit. The organizational context encompasses internal structural attributes, including resource endowments, degree of centralization, and institutional pressures, covering aspects such as communication mechanisms and governance systems. The environmental context refers to the external macro-environmental factors influencing organizational operations, such as industry dynamics and regulatory landscapes. A schematic representation of this framework is presented in Figure 1.

2.2.1 Technological Context

This dimension comprises two second-order conditions: Knowledge Innovation and Skilled Talent.Knowledge Innovation: As a primary engine driving digital technology advancement, higher education institutions serve as the core subjects and sources of knowledge innovation. They play a pivotal role in positively facilitating the production, transfer, and integration of knowledge within the regional digital technology innovation ecosystem.Skilled Talent: Skilled professionals constitute the endogenous momentum for empowering vocational education (VE) with digital technology. This operates through a dual mechanism:First, vocational colleges optimize the regional structure of technical human resources, thereby providing critical technical support to digital technology enterprises.Second, a higher level of human capital in digital skills creates a feedback loop that reinforces VE development. Specifically, it enhances curriculum construction, practical teaching, faculty quality, technical standards, and overall talent cultivation within the region **(Fu.C.,et al,2025;Yang.J.F.,et al,2026)**.

2.2.2 Organizational Context

This dimension includes two second-order conditions: Policy Support and Financial Support.Policy Support: A robust policy safeguard system is essential for enhancing the implementation efficacy of

strategies targeting both digital industry and VE development. By establishing an institutionalized guarantee system characterized by "government leadership and social participation," this framework clarifies the collaborative responsibilities of local governments, institutions, and enterprises. Such policies support vocational colleges in optimizing specialized programs in fields like intelligent manufacturing and big data, while incentivizing enterprises to participate in curriculum development and the provision of practical training resources, ultimately elevating the level of digital empowerment in VE.Financial Support: As a key driver of the national strategy for "reinvigorating the country through science and education," fiscal expenditure on education plays a critical role. Through dynamic and precise capital allocation, financial inputs can bridge resource disparities in digital technology and VE across different regions within a province. Furthermore, these funds effectively guide social capital toward constructing digital training bases and innovation incubators for university students, ensuring efficient resource allocation and the tangible implementation of policy support **(Li.M.h., Liu.SH.H. ,2025)**.

2.2.3 Environmental Context

This dimension consists of two second-order conditions: Digital-Intelligent VE Infrastructure and R&D Environment.Digital-Intelligent VE Infrastructure: The construction of digital-intelligent VE infrastructure integrates tools such as virtual simulation and AI-assisted learning. This provides standardized sharing of digital teaching resources and personalized learning support, enabling vocational colleges to cultivate skilled talents who are highly aligned with the demands of the digital technology industry.R&D Environment: Fostering an open and collaborative R&D ecosystem involving "government-enterprise-university" tripartite cooperation promotes the deep integration of corporate technical resources with VE talent cultivation. This synergy not only optimizes the regional digital technology R&D environment but also provides sustainable human capital support for long-term innovation.

3. Data Analysis and Configurational Results

3.1. Variable Selection and Measurement

3.1.1. Outcome Variable

The outcome variable is derived from the ShanghaiRanking’s China Vocational College Ranking (2024), published by the higher education evaluation institution ShanghaiRanking. This ranking system conducts a stratified and classified evaluation of the operational levels of over 1,300 higher vocational colleges in China based on six dimensions: moral education, training conditions, institutional positioning, student development, faculty quality, and social service. By employing a differentiated indicator system for separate rankings, it robustly, objectively, comprehensively, and scientifically reflects the overall operational level of vocational colleges. In this study, the level of vocational education development in each region is measured by the ratio of the number of colleges ranked within the top 500 in the province to the total number of vocational colleges in that province.

3.1.2. Condition Variables

The three dimensions of technology, organization, and environment encompass six key variables.

(1) Technological Context Variables

Knowledge Innovation: Measured by the number of valid patents in the electronic communication and computer equipment manufacturing sectors, which objectively reflects the intensity of technological input in digital technology. Following a two-year policy utility lag, this variable is calculated as the mean value over the preceding two years (2022–2023).Skilled Talent: Measured by the proportion of vocational colleges participating in the national "Double High Plan" (construction of high-level schools and professional groups) relative to the total number of vocational colleges in the province. This reflects the level of talent cultivation in vocational education aligned with the manufacturing sector.

(2) Organizational Context Variables

Policy Support: Comprehensive policy support from administrative departments exerts a positive impact on economic and social development. This variable is measured by the policy attention paid to "vocational education" and "digital technology" in each province. Based on official government websites of all provinces (including municipalities and autonomous regions), we retrieved policy texts (such as notices, opinions, and measures) closely related to the themes of "digital technology" and "vocational education" using these keywords. Following a two-year policy utility lag, this variable is calculated as the mean count of such documents issued by each province over the preceding two years (2022–2023).Financial Support: Measured by the mean proportion of education expenditure in the general public budget expenditure of each province from 2022 to 2023.

(3) Environmental Context Variables

Digital-Intelligent VE Infrastructure: Pilot projects for digital campus construction accurately measure the practical depth of digital transformation in vocational education. This variable is measured by the proportion of vocational colleges in each province designated as National Pilot Colleges for Digital Campus Construction relative to the total number of vocational colleges.R&D Environment: The full-time equivalent of R&D personnel precisely measures the guarantee status of digital technology research and development. Thus, this variable is measured by the mean total number of R&D personnel in the electronic & communication equipment manufacturing and computer & office equipment manufacturing sectors from 2022 to 2023.

3.1.3 Sample and Data Sources

The research sample comprises 31 provincial-level regions in China (including provinces, municipalities, and autonomous regions). Data for the Xinjiang Production and Construction Corps, Hong Kong, and Macau were excluded due to missing values. Statistical data were sourced from the China Statistical Yearbook, the China High-Tech Industry Statistical Yearbook, provincial statistical yearbooks, and official

government websites of respective provinces. The descriptive statistics for all variables are presented in **Table 1**.

Table 1. Variable Definitions and Descriptive Statistics

Category	Dimension	Variable Name	Mean	Std. Dev.	Max	Min
Outcome	—	Regional Vocational Education Development Level	0.333	0.102	0.617	0.143
Condition	Technical	Knowledge Innovation	21487.790	62592.491	347996.5	0
		Skilled Talent	5.645	4.491	19	0
	Organizational	Policy Support	155.258	126.956	523	18
		Financial Support	0.159	0.033	0.216	0.085
	Environmental	Digital-Intelligent VE Infrastructure	9.903	6.231	27	1
		R&D Environment	38971.016	83507.026	441404	0

Note：1. “VE” = Vocational Education; “R&D” = Research and Development.

2. The "Double High Plan" refers to the Plan for Building High-Level Vocational Schools and Majors with Chinese Characteristics, a national initiative to develop world-class vocational institutions and major clusters in China.
3. The Academic Ranking of World Universities (ARWU), commonly known as the "Shanghai Ranking," was first published in 2003 by the Center for World-Class Universities at Shanghai Jiao Tong University. It is widely recognized as one of the most authoritative and comprehensive global university ranking systems.

3.2. Data Calibration

Following the standard analytical procedure of Qualitative Comparative Analysis (QCA), condition variables that are not inherently crisp sets must be calibrated. Adopting the approach proposed by Tan Haibo, Du Yunzhou, et al. **(Du.Y.Z., Jia.L.D. , 2017)**, we employed **the direct calibration method** to transform the raw data. The three calibration anchors were defined based on the descriptive statistics of the case data: the **90th percentile** (threshold for full membership), the **median** (crossover point), and the **10th percentile** (threshold for full non-membership). The calibration anchors and descriptive statistics for each condition are presented in **Table 2**.

Table 2. Calibration of Data

Condition	Fuzzy Set Calibration Anchors		
	Full Membership	Crossover Point	Full Non-membership
Regional Vocational Education Development Level	0.458	0.311	0.211
Knowledge Innovation	38985.5	4246.5	101.3
Skilled Talent	12.6	5	1
Policy Support	354.8	117	33
Financial Support	0.209	0.161	0.111
Digital-Intelligent VE Infrastructure	19.8	8	2.2
R&D Environment	99033.4	12057	209.3

3.3 Necessity and Sufficiency Analysis of Individual Conditions

Within the QCA framework, necessity analysis tests whether an outcome is dependent on a specific condition, evaluated via consistency and coverage scores. A condition is deemed necessary when its consistency exceeds the conventional threshold of 0.9, while coverage reflects the condition's explanatory power regarding the outcome. Using fsQCA 3.0, we performed separate necessity analyses for both the presence (high performance) and absence (non-high performance) of the outcome variable. The results for individual conditions are summarized in Table 3.

Table 3: Results of Necessity and Sufficiency Analysis for Individual Conditions

Condition Variables	High Performance		Non-High Performance	
	Consistency	Coverage	Consistency	coverage
Knowledge Innovation	0.710	0.871	0.886	0.739
Skilled Talent	0.738	0.821	0.826	0.745
Policy Support	0.600	0.665	0.674	0.610
Financial Support	0.652	0.688	0.681	0.645
Digital Intelligence in VE	0.739	0.746	0.728	0.721
R&D Environment	0.710	0.863	0.878	0.737

Note: VE = Vocational Education. Data calculated using fsQCA 3.0 software.

The results indicate that the consistency scores for all individual environmental conditions regarding both high and non-high performance fall below the 0.9 threshold. This implies that no single condition is necessary for achieving either outcome. Consequently, it is essential to proceed with a configurational analysis to examine how combinations of conditions jointly influence vocational education development.

3.4 Configurational Analysis

Configurational analysis reveals how specific combinations of multiple conditions jointly influence the outcome. Following standard QCA procedures, we set the frequency threshold to 1 and the consistency threshold to 0.8. In interpreting the solutions, conditions appearing in the parsimonious solution were classified as core conditions, while those present in the intermediate solution but absent in the parsimonious solution were designated as peripheral (or auxiliary) conditions (Li.M.h., Liu.SH.H. ,2025;Ding.L.,et al.2026).The results were organized by core conditions and presented in tabular form. Initially, four distinct pathways were identified for high performance (labeled S1, S2a, S2b, S3a, S3b, and S4) and three for non-high performance (NS1, NS2, and NS3). To enhance clarity, configurations sharing identical core conditions were integrated into equivalent groups. The final configurational profiles and their corresponding empirical cases are presented in Table 4 and Table 5, respectively.

To ensure the robustness of these findings, we conducted sensitivity analyses following the protocols established by Zhang**(Zhang.M., Du.Y.ZH. ,2019)**and Fiss **(Fiss P.C.2011)**. First, we excluded the municipality of Tianjin from the sample. The re-estimated model yielded an overall coverage of 0.676 and an overall consistency of 0.884, which are substantially consistent with the original high-performance results in terms of both metrics and configurational structure. Second, we lowered the PRI consistency threshold from 0.8 to 0.75. The resulting configurations remained largely unchanged. These tests confirm that the identified configurational solutions are robust and reliable.

Table 4: Configurational Solutions for High and Non-High Performance Cases

Condition Variables	High Performance Configurations					Non-High Performance Configurations		
	S1	S2a	S2b	S3a	S4	NS1	NS2	NS3
Knowledge Innovation	●	●		⊗	●	⊗	⊗	⊗
Skilled Talent	●	●	●	●	⊗	⊗	⊗	●
Policy Support	⊗	●	●	●	●	●	●	●
Financial Support	●		●	⊗	⊗		⊗	●
Digital Intelligence in VE		●	●	●	⊗	●	⊗	⊗
R&D Environment	⊗	●	●	⊗	●	⊗	⊗	⊗
Raw Coverage	0.372	0.345	0.249	0.191	0.372	0.412	0.534	0.225
Unique Coverage	0.134	0.105	0.022	0.039	0.134	0.039	0.123	0.034
Consistency	0.925	0.916	0.899	0.831	0.925	0.977	0.941	0.881
Overall Coverage	0.666					0.614		
Overall Consistency	0.873					0.857		

Note: ● indicates the presence of a core condition.

⊗ indicates the absence of a core condition.

● indicates the presence of a peripheral (auxiliary) condition.

⊗ indicates the absence of a peripheral condition.

Blank spaces indicate that the condition may be either present or absent .

Table 5: Representative Cases Corresponding to Configurational Paths

Outcome	No.	Configurational Paths and Representative Cases		
		Configuration Label	**Combination of Conditions**	**Representative Cases**
High Performance	1	Technology-Driven	Knowledge Innovation * Skilled Talent *Financial Support	Guangdong, Shandong, Tianjin
	2	Resource-Agglomeration	Skilled Talent * Financial Support *Digital Intelligence in VE *R&D Environment*Digital Intelligence in VE	Zhejiang, Jiangsu, Hubei, Hunan, Henan Hebei
	3	Tech-Env Assurance	Knowledge Innovation *Policy Support *R&D Environment	Shanghai
Non-High Performance	1	Technology-Inhibited	~Knowledge Innovation *~Skilled Talent *~R&D Environment	Guangxi, Guizhou
	2	Tech-Env Inhibited	~Knowledge Innovation*~Skilled Talent*~Financial Support*~Digital Intelligence in VE *~R&D Environment	Inner Mongolia, Jilin, Tibet
	3	Innovation-Env Inhibited	Knowledge Innovation *~Digital Intelligence in VE *~ R&D Environment	Liaoning

Note:

VE = Vocational Education.

For High Performance paths, only the presence of conditions is listed; for Non-High Performance paths, only the absence of conditions is listed.

Bold text indicates core conditions; regular text indicates peripheral (auxiliary) conditions.

The symbol *represents the logical "AND" (conjunction).

The symbol ~indicates the absence of a condition (logical negation).

3.4.1 Analysis of High-Performance Configurations

Based on the results presented in Table 4, four distinct configurational paths leading to high performance were identified. The overall consistency of the solution is 0.873, indicating that 87.3% of the cases (provinces) satisfying these four configurations exhibit high levels of vocational education development effectiveness. The overall coverage is 0.666, suggesting that these four configurations collectively explain 66.6% of the observed instances of high performance. Specifically:

(1) The Technology-Driven Configuration

This configuration corresponds to solution path S1, characterized by the presence of **Knowledge Innovation** (core condition), **Skilled Talent** (core condition), and **Financial Support**. Path S1 underscores a strategy centered on technological empowerment. It suggests that fostering innovation vitality in the digital technology sector, accelerating the structural upgrading of regional digital industries, and strengthening the construction of "Double High Plan" institutions and professional clusters within the province—alongside measures to improve the operating conditions of vocational colleges—can effectively promote high-performance development in digital technology-enabled vocational education. Given that the core conditions of this path are predominantly technology-oriented factors, we label it the "**Technology-Driven Configuration.**"

This configuration explains 37.2% of the cases exhibiting high performance. The representative cases include Guangdong, Shandong, and Tianjin, all of which are economically developed coastal regions in eastern China with robust foundations for digital technology development. Empirical data supports this classification. Guangdong ranks 1st among China's 31 provinces in the total number of R&D personnel in the digital technology industry, while Shandong and Tianjin rank 8th and 13th, respectively.In terms of the core digital technology industry structure, Guangdong leads the nation in both the scale of digital product manufacturing and digital product services. Shandong ranks within the top three for digital product services, and Tianjin holds the 1st position in the growth rate of digital technology application scale.Furthermore, all three provinces demonstrate strong commitment to cultivating technical and skilled talent. In the assessment of skilled talent cultivation factors, Shandong, Guangdong, and Tianjin rank 2nd, 4th, and 8th, respectively. Guangdong and Shandong: Leveraging their complete industrial systems and large populations of high-tech enterprises, these provinces have introduced policies to support the joint construction and management of modern industrial colleges by vocational colleges and industry enterprises. These measures have deeply integrated industry with education and schools with enterprises.Tianjin: As a National Demonstration Zone for Vocational Education Reform and Innovation, Tianjin has enacted policies such as the "Tianjin Municipal Regulations on Promoting the Integration of Vocational Education and Industry" (since 2022). These initiatives explore reforms in building a modern vocational education system and further deepen industry-education integration.For regions possessing a solid foundation in digital technology industries and a favorable environment for skilled talent cultivation, these findings suggest that policymakers should leverage their existing technological advantages. Strategies should focus on reinforcing knowledge innovation and optimizing the ecosystem for skilled talent cultivation to sustain high-performance outcomes.

(2) The Resource-Agglomeration Configuration

This configuration corresponds to solution paths S2a and S2b. It is characterized by a robust resource foundation that facilitates balanced development across the technology, organization, and environment dimensions. With the exception of a few conditions exhibiting an ambiguous state , all other dimensions are supported by the presence of either core or peripheral conditions. Reflecting this comprehensive convergence of favorable factors, we label this the "Resource-Agglomeration Configuration."This configuration explains 59.4% of the cases exhibiting high performance, representing the most prevalent

path. The representative cases include Zhejiang, Jiangsu, Hubei, Hunan, and Henan.Jiangsu exemplifies this balance, ranking 1st nationally in both skilled talent cultivation and the environmental guarantee for digital-intelligent vocational education, while securing the 2nd position in knowledge innovation. This indicates a high level of prominence and equilibrium across all key elements.Hubei has achieved strong factor guarantees across all three dimensions. Leveraging its strategic advantages as China's first national pilot province for education informatization and a provincial-level pilot for the National Smart Education Platform, Hubei has strengthened institutional frameworks and increased fiscal investment in education. By constructing a digital education "new infrastructure" based on a "digital foundation + public platforms + educational applications" architecture, the province has secured a leading position nationally in the total volume of digital vocational education resources. For regions possessing a solid foundation in both digital technology industries and vocational education infrastructure, these findings suggest a strategy of resource integration. Policymakers should aim to forge an "ecosystem community" for high-quality development by integrating resources from vocational colleges, industry enterprises, and research institutions within the region. This approach fosters a sustainable, long-term development pattern characterized by mutual reinforcement between digital technology and vocational education.

(3) The Talent-Cultivation-Driven Configuration

This configuration corresponds to solution paths S3a and S3b, characterized by the presence of Technical and Skilled Talent Cultivation as a core condition, alongside Digital-Intelligent Vocational Education. The results indicate that even in contexts where resources such as industrial development and organizational support are not dominant, a strategic focus on cultivating digital technical skills and elevating the level of digital-intelligent vocational education can still yield high performance in digital technology-enabled vocational development. By enhancing the public visibility and influence of both digital technology and vocational education, this pathway effectively compensates for resource deficits. Consequently, we label this the "Talent-Cultivation-Driven Configuration."

This configuration explains 40.6% of the cases, with Hebei Province serving as a representative example. Empirical measurements reveal that Hebei lags behind the national average in knowledge innovation and R&D environment, indicating a relatively weak industrial foundation for digital technology development. However, the province benefits significantly from regional synergistic development: it receives spillover effects and assistance from the Beijing-Tianjin metropolitan region and leverages the industrial momentum generated by the construction of the Xiong'an New Area.

In recent years, Hebei has implemented targeted policies, such as the "Action Plan for Accelerating Digital Talent Cultivation to Support Digital Technology Development (2024–2026)." These initiatives focus on aligning with developed regions like Beijing and Tianjin to launch special campaigns for the training, attraction, retention, and utilization of digital talent. Furthermore, the province is fostering "Digital+" interdisciplinary majors and advancing the upgrading and digital transformation of vocational education programs.

Implications: For regions with a nascent digital technology industrial base, these findings suggest a strategy of focusing on digital skill cultivation. Policymakers should proactively facilitate the transfer of digital industries from developed regions and construct a supportive ecosystem that integrates "talent cultivation with employment security," thereby creating a sustainable environment for digital workforce development.

(4) The Technology-Enhancement and Environmental-Guarantee Configuration

This configuration corresponds to solution path S4, characterized by the presence of Knowledge Innovation (core condition), Policy Support, and R&D Environment (core condition). Path S4 indicates that in regions with a solid foundation in digital technology industries and a superior R&D environment, providing targeted policy support and institutional guarantees for digital technology-enabled vocational education can effectively promote the deep integration of industrial development and vocational training. Consequently, we label this the "Technology-Enhancement and Environmental-Guarantee Configuration."This configuration explains 37.2% of the high-performance cases, with Shanghai Municipality as the representative sample. Shanghai ranks among the top nationally in both knowledge innovation and R&D environment, and holds the 1st position in policy support, reflecting the municipal government’s exceptional commitment to leveraging digital technology for vocational education. The "*Shanghai Vocational Education Development 14th Five-Year Plan*" explicitly outlines the in-depth implementation of the National Education Digitalization Strategy. It has introduced a series of measures focusing on "application, sharing, and innovation" to elevate the digital empowerment level of regional vocational colleges.

Resource Integration: Shanghai has integrated resources from the government, industry associations, schools, and enterprises to establish China’s first Digital Technology Collaborative Innovation Platform dedicated to industry-education integration. By leading initiatives such as the Symposium on Digital Technology Collaborative Innovation and the Forum on Vocational Education Digital Transformation, Shanghai has cultivated a robust policy environment and developmental guarantee system that facilitates the convergence of digital technology and vocational education.

3.4.2 Analysis of Non-High-Performance Configurations

Acknowledging the principle of causal asymmetry, this study further identifies three distinct configurations that inhibit high-performance outcomes in digital technology-enabled vocational education: the Technology-Inhibited Configuration, the Technology-Environment Inhibited Configuration, and the Industrial-Innovation-Environment Inhibited Configuration (see Tables 4 and 5).

The Technology-Inhibited Configuration corresponds to solution NS1 and indicates that the absence (or low level) of both Knowledge Innovation and Skilled Talent jointly constrains the improvement of empowerment effectiveness. Representative cases include the Guangxi Zhuang Autonomous Region and Guizhou Province.Guangxi and Guizhou rank 19th and 21st in knowledge innovation, and 24th and 25th in skilled talent cultivation, respectively. Both indicators fall significantly below the national average.

These findings suggest that under the dual constraints of a weak digital technology industrial base and suboptimal quality and efficiency in vocational talent cultivation, these regions struggle to generate high levels of digital empowerment.

The Technology-Environment Inhibited Configuration corresponds to solution NS2, indicating that a lack of support in Knowledge Innovation, Skilled Talent, and Digital-Intelligent Vocational Education hinders development. Representative cases include the Inner Mongolia Autonomous Region, Jilin Province, and the Tibet Autonomous Region. In addition to sharing the same absent conditions as the Technology-Inhibited Configuration (NS1), these three regions also exhibit an absence of environmental guarantees. Consequently, they fail to secure adequate factor endowments in both organizational technology and organizational environment, leading to a systemic inability to support high-performance outcomes.

The Industrial-Innovation-Environment Inhibited Configuration corresponds to solution NS3, suggesting that the absence of resource support in the dimensions of Industrial Innovation and Digital-Intelligent Vocational Education suppresses empowerment effectiveness. The representative case is Liaoning Province.Although Liaoning demonstrates certain achievements in technical and skilled talent cultivation, its weak digital technology industrial base and insufficient integration of digital technology into vocational construction prevent the formation of a synergistic "Talent Cultivation–Industrial Development" model. As a result, despite isolated strengths in talent, the overall effectiveness of empowering vocational education remains limited due to the lack of industrial synergy and digital integration.

4. Conclusions and Policy Implications

4.1 Research Conclusions

4.1.1 Digital technology-enabled vocational education is driven by the synergistic interplay of multiple factors

- The findings reveal that no single dimensional factor serves as a necessary condition for either achieving high performance or encountering inhibition in empowerment outcomes. Instead, effectiveness emerges from the collaborative interaction of diverse factors across the technology, organization, and environment dimensions.Specifically, four distinct configurations leading to high-performance outcomes have been identified:
- The Technology-Prominent Configuration;
- The Resource-Agglomeration Configuration;
- The Talent-Cultivation-Driven Configuration;
- The Technology-Enhancement and Environmental-Guarantee Configuration.
- Conversely, the analysis of low-performance cases uncovers three inhibitory configurations that constrain development:

- The Technology-Inhibited Configuration;
- The Technology-Environment Inhibited Configuration;
- The Industrial-Innovation-Environment Inhibited Configuration.
- Crucially, the collaboration of factors within each configuration represents not a simple additive sum but rather a complex, conjunctural interaction. Therefore, in policy formulation and implementation, it is imperative to accurately grasp the interactive relationships among technology, organization, and environment. These interactions function as the primary drivers and critical elements propelling the high-quality development of digital technology-enabled vocational education. Conversely, neglecting or mismanaging these synergistic relationships can constitute a significant bottleneck, actively inhibiting development effectiveness.

4.1.2 The Pivotal Role of Technological Factors in Driving Digital Technology-Enabled Vocational Education

- The results demonstrate that technological factors serve as the core driving force behind the development of digital technology-enabled vocational education. This pivotal role is manifested across two distinct dimensions: providing structural support within high-performance configurations and offering inhibitory validation within non-high-performance configurations.
- In the high-performance configurations, conditions related to technological factors—specifically Knowledge Innovation and Skilled Talent—are consistently present across all four identified paths. Representative provinces have leveraged technology-oriented strategies, such as enhancing innovation vitality within the digital technology industry and strengthening talent cultivation systems in higher vocational colleges. These initiatives have fostered a positive feedback loop that integrates technology R&D, talent development, and industrial growth, thereby driving bidirectional empowerment between vocational education and digital technology.
- Consequently, technological factors function dually as the core substrate for generating high performance and the critical variable for overcoming development bottlenecks. Therefore, strategic investment and optimization across key dimensions—specifically industrial innovation, talent cultivation, and the R&D environment—constitute the essential guarantee for realizing the high-quality development of digital technology-enabled vocational education.
- **4.1.3 Environmental Factors as the Stabilizer and Binder for High-Quality Development of Digital Technology-Enabled Vocational Education**
- Digital-intelligent vocational education ecosystems and R&D environments constitute the foundational support for empowering vocational education through digital technology. In high-performance configurations, environmental factors are embedded across multiple pathways as either core or auxiliary conditions, facilitating a balanced synergy among technology, organization, and environment.
- A robust digital-intelligent vocational education ecosystem and a supportive R&D environment act as critical magnets, attracting industrial transfer and facilitating capability absorption from regions

with advanced digital technology industries. This mechanism effectively compensates for local deficiencies in digital industrial foundations, thereby catalyzing the deep integration of digital technologies with vocational education resources.Conversely, configurational analysis reveals that two out of the three non-high-performance paths lack environmental factors as core conditions. This absence disrupts the formation of a closed-loop bidirectional interaction between talent cultivation and industrial development, causing the digital empowerment system to fail in achieving synergistic outcomes.

- Consequently, environmental factors function dually as the stabilizer for high-performance pathways and the integrative binder that orchestrates multi-factor synergy. Therefore, strategic investment and optimization by policy actors in key dimensions—specifically digital-intelligent infrastructure construction and R&D support—constitute the fundamental prerequisite for ensuring the high-quality development of digital technology-enabled vocational education.

4.1.4 Aligning Industrial Development Disparities with Tailored Empowerment Strategies for Vocational Education

- Significant regional heterogeneity exists across China's eastern, central, and western regions regarding the development level of the digital technology industry and resource endowments.
- Empirical results reveal a pronounced geographical disparity in configurational outcomes. The distribution of typical samples reveals a stark contrast: 6 out of 10 high-performance configurations are located in the eastern region, 4 in the central region, and none in the western region. Conversely, the western region accounts for 4 out of 6 non-high-performance configurations. This distribution underscores the structural superiority of the eastern and central regions across all key factors compared to the west.
- Despite relatively weak initial endowments in digital technology and vocational education, the western region possesses immense latent potential. Driven by the deepening implementation of national strategies—specifically the Western Development Strategy, the Belt and Road Initiative (BRI), and the New International Land-Sea Trade Corridor—the western digital industrial structure is undergoing a critical transition from primary to advanced stages.This industrial upgrading creates a synergistic feedback loop with the developmental trajectory of vocational education, generating an urgent demand for digital skills talent. Consequently, it is imperative to intensify efforts in absorbing industrial transfers and cultivate a favorable ecosystem encompassing both the business climate and educational environment. Such measures will provide diversified pathways for empowering vocational education through digital technology, tailored to the unique context of the western region.

4.2 Policy Recommendations

4.2.1 Systematically Construct a Multi-Dimensional Collaborative and Adaptive Policy Framework

- This requires a government-led mechanism mobilizing vocational colleges, enterprises, and industry associations to promote a policy system aligned with the TOE framework. Specifically, local governments should form a cross-departmental mechanism integrating education, science/tech, industry/IT, and finance sectors to coordinate resources across digital industry development, institutional safeguards, and business/educational ecosystems. By eliminating silos, this approach assigns complementary roles: education oversees digital transformation; science/industry align tech with vocational demands; finance secures funding for digital-intelligent infrastructure. This fosters a collaborative network for joint policy, resource sharing, and problem-solving, maximizing integration efficiency of digital tech and vocational education. Furthermore, as digital-tech and vocational education synergy is dynamic and multi-stakeholder, ensure policy continuity and strengthen governance via differentiated strategies tailored to regional endowments. In regions with strong digital tech capabilities, prioritize knowledge innovation and skilled talent cultivation by establishing "Modern Industrial Colleges" via tripartite partnerships (colleges, industries, enterprises). This creates a closed loop linking "tech application, talent cultivation, industrial development" to convert technological outcomes into educational assets**(Zhu.H.P., Feng.X.F,2025;Huang.J.CH., et al,2026)**. In regions with a favorable digital-intelligent vocational education environment, continue deepening infrastructure and industry-education integration while facilitating industrial transfer from robust digital hubs. By strengthening demand-side talent attraction to draw investment, these regions can cultivate composite digital skills, fostering bidirectional tech-education fusion. Finally, in regions with strong digital industrial foundations and R&D environments, enhance policy attention and institutional safeguards by building platforms bridging industrial demands with vocational major construction, ensuring precise matching of digital technologies and educational resources.
- **4.2.2 Prioritizing Technological Advancement and Environmental Optimization to Catalyze the Synergistic Integration of Digital Technology and Vocational Education**
- At the technological level, bridge the talent-industry gap via an industry-education integration consortium. Mobilize government, vocational colleges, and enterprises to link 'core digital tech industries' with 'vocational clusters.' Transform frontier R&D (e.g., blockchain, VR) into teaching case repositories, ensuring curricula sync with digital tech advances, shortening student adaptation cycles. Implement customized technical skills training through 'order-based' classes co-established by colleges and partners: enterprises provide real production scenarios and standards; institutions develop integrated courses, ensuring graduates are job-ready for digital roles. Also integrate vocational resources into industrial R&D. Governments use tax cuts and equipment subsidies to incentivize enterprises to open R&D facilities, supporting faculty and master studios in technical breakthroughs. Rapidly convert research outcomes into teaching projects, course designs, and training modules, boosting teaching workforce's digital proficiency.
- At the environmental level, accelerate a digital-intelligent vocational education ecosystem. Integrate digital resource repositories and virtual simulation systems across institutions to offer a 'one-stop' digital teaching platform, enabling digital campuses and smart pedagogy. Foster complementarity

between digital tech and superior vocational resources. Organize leading provincial digital tech enterprises to define technical standards, collaborate with vocational colleges to customize 'Digital Tech + Discipline' curricula, creating a virtuous loop: 'enterprise project → talent cultivation → industrial upgrading.' Driven by industrial transfer and supported by vocational education, this strategy cultivates a regional ecosystem where digital tech and vocational resources reinforce each other, yielding a sustainable innovation cycle.

4.2.3 Implementing Region-Specific Differentiated Strategies to Promote Equitable Digital Empowerment in Vocational Education

- economically developed regions: leverage advanced digital industrial foundations to integrate frontier tech with innovative talent cultivation. Vocational institutions must align with industry leaders and SRDI firms to design market-driven professional clusters, cultivating mid-to-high-level technical talents for industrial upgrading and innovation.
- regions with average economic development: leverage geographical advantages for industrial relocation and a robust vocational ecosystem to enable 'Industrial Relocation + Vocational Synergy' bidirectional empowerment. Accepting digital manufacturing transfers (e.g., semiconductor packaging, smart terminal assembly) from the east, local vocational colleges must develop targeted curricula for equipment operation and maintenance, ensuring talent supply matches incoming enterprises' demands, creating a regionally distinctive modern vocational model tightly coupled with local economic development.
- Relatively underdeveloped regions: strengthen inter-regional collaboration with eastern and central counterparts via paired assistance. Implement faculty pairing to import advanced pedagogical concepts and establish platforms for sharing high-quality digital resources and technical standards from developed regions to mitigate resource scarcity. Use fiscal incentives (tax reductions, land policies) to attract eastern digital manufacturing firms to set up production bases. Mandating 'targeted talent cultivation agreements' between these enterprises and local colleges builds a sustainable ecosystem of 'enterprise investment, institutional education, local talent retention,' gradually nurturing the digital industry and elevating vocational education quality.

Declarations

Conflict of Interest

All authors declare that there are no financial or non-financial interests directly or indirectly related to the submitted work. The disclosure covers the last three years of conducting and preparing the research, and no older interests that could reasonably be perceived as influencing the work exist.The datasets

generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Author Contribution

M.X. collected research data and completed data analysis.wrote the main manuscript text.L.B.H. sorted literature and polished the manuscript language.C.L. (Corresponding Author) conceived the research framework, guided the whole study and revised the paper.L.Z.Z. drew research figures and checked the manuscript format.All authors read and approved the final manuscript.

Data Availability

Data Availability StatementAll quantitative data and materials supporting the conclusions of this paper are sourced from publicly released official Chinese government documents, public industrial statistical reports and open-access academic databases. No original experimental data generated by the authors is included. All data and documents are permanently published on the official statistical websites of the Chinese government, and full texts are freely accessible to all readers without access restrictions. This study involves no confidential or restricted data. Full disclosure of all supporting materials can completely reproduce all analytical findings presented in the manuscript.

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Figures

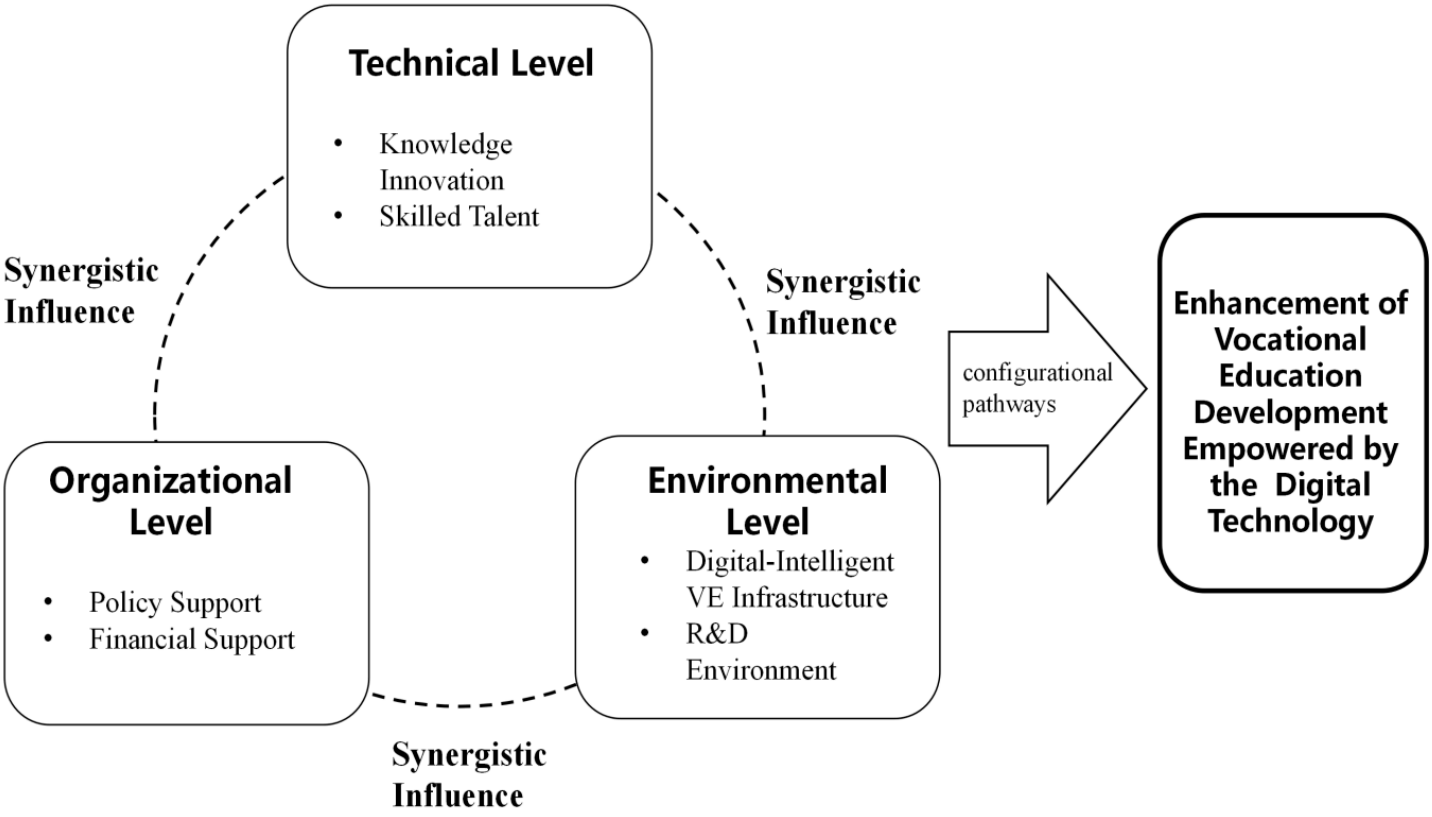


Figure 1

Analytical Framework