Coupling Coordination Between Low-Altitude Economy and Vocational Education Talent Supply, and the Moderating Effect of the Digital Economy

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Abstract: As a strategically emerging sector in China, the low-altitude economy confronts a structural impediment: a persistent insufficiency of qualified personnel required for its sustained expansion. Vocational institutions function as the principal conduit for cultivating unmanned aerial vehicle (UAV) operators, low-altitude data collectors, and related technical practitioners, whereas the digital economy—through cloud-based training platforms and intelligent data systems—acts as a key enabler for modernizing these educational programs. To quantify this relationship, dual evaluation frameworks are established to assess the low-altitude economy development level and vocational education talent supply capacity, respectively. Drawing on provincial panel data from 2020 to 2024 across 30 provinces, composite indices are derived through entropy weighting, and the coupling coordination degree between the two systems is subsequently computed. A fixed-effects panel regression is then specified to examine whether digital development conditions this inter-system coordination. Three principal results emerge. First, the coupling coordination degree displays a steady upward trajectory over the observation period, yet substantial spatial disparities persist—coastal provinces such as Guangdong and Jiangsu attain the high-quality coordination stage, whereas central and western regions remain at a barely coordinated or even disordered level. Second, the digital economy is verified to exert a strengthening effect on the alignment between vocational training and low-altitude industry requirements; that is, provinces with more advanced digital infrastructure demonstrate a more pronounced talent-supply contribution. Third, this strengthening role is geographically uneven, being most pronounced in the eastern region, moderate in the central region, and relatively weak in the western region. By incorporating the talent-supply perspective into the low-altitude economy analytical paradigm, this study offers both a novel analytical lens and empirical evidence for aligning educational specialization with industrial spatial planning.

Keywords: Low-Altitude Economy; Vocational Education; Digital Economy; Statistics; Unmanned Aerial Vehicle (UAV)

1. Introduction

When the term "low-altitude economy" was first codified in the National Comprehensive Three-Dimensional Transportation Network Planning Outline in February 2021, it elevated low-altitude airspace to the status of a strategic economic asset [1]. The unmanned aerial vehicle (UAV) sector lies at the heart of this transformation. Civil Aviation Administration records indicate that registered UAVs in China topped 1.2 million by the end of 2024, underpinning swift expansion in both firm counts and the overall industry footprint [2]. Beneath this growth, however, a structural imbalance persists: the pipeline of qualified personnel falls far short of market requirements. Only approximately 44,573 individuals hold certified UAV operation credentials, whereas the projected shortfall for roles such as UAV operators, low-altitude data analysts, and logistics dispatchers exceeds one million—a talent deficit that has been widely documented [3].

Vocational education bears the chief responsibility for supplying the skilled workforce that the low-altitude sector demands. Over 300 institutions nationwide have launched programs in UAV application technology, intelligent aircraft maintenance, and related fields, and this portfolio continues to widen [4]. A pronounced "supply–demand mismatch," however, persists: what programs offer diverges from what the industry requires, curricula trail the pace of technological evolution, and training infrastructure still falls short of occupational benchmarks.

Concurrently, digital transformation is altering both the delivery and the effectiveness of vocational instruction. Industrial UAV cloud platforms, low-altitude intelligent data-processing systems, and virtual simulation training tools constitute the chief digital channels through which UAV skill training and its outcomes are being reshaped [5]. Whether these digital means genuinely amplify the contribution of vocational education to the low-altitude economy, however, remains an open question that has yet to be subjected to empirical test.

Motivated by these observations, this study addresses three questions: (1) To what extent are low-altitude economy development and vocational education talent supply coupled, and how do inter-provincial differences manifest? (2) Does the digital economy moderate this coupling relationship, and if so, in what direction and with what magnitude? (3) Is this moderating effect subject to regional heterogeneity? Three contributions distinguish the present work. First, a coupling evaluation framework linking the low-altitude economy to vocational education talent supply is established—an analytical instrument that has been absent from prior scholarship on the talent dimension of this sector. Second, the digital economy is incorporated as a moderating variable, generating statistical evidence on how digital empowerment conditions vocational education transformation. Third, provincial panel data are leveraged for spatial differentiation analysis, yielding a foundation for regionally tailored strategies.

2. Literature Review

2.1 Progress in Low-Altitude Economy Research

Since 2021, scholarship on the low-altitude economy has expanded rapidly, yet the existing body of work clusters around three main strands. The first strand concerns governance and regulation, examining reforms in airspace management and the streamlining of flight approval procedures [6]. The second strand centers on technology and applications, surveying the deployment potential of UAVs in areas such as parcel delivery, crop protection, and disaster response [7]. The third strand addresses market sizing and industrial structure, offering forecasts of sectoral scale and value-chain composition [8]. A common thread across these studies is their framing of the low-altitude economy as either an industrial or an institutional phenomenon; the angle of human capital—despite its acknowledged role as a prerequisite for sectoral sustainability—has received scant empirical attention.

2.2 Coupling Between Vocational Education and Emerging Industries

How vocational training aligns with industrial evolution constitutes a recurring theme in the economics of education literature. Prior investigations have examined the degree of synchronization between vocational programs and sectors such as advanced manufacturing [9], the digital economy [10], and other strategically emerging industries [11], with the coupling coordination degree model serving as the prevailing quantitative tool. While these studies shed light on the statistical regularities governing supply–demand interactions, the low-altitude economy remains unexamined in this coupling framework. Discussions of UAV-specific talent preparation, where they exist at all, tend to rely on single-institution case narratives [12] rather than system-wide quantitative assessment.

2.3 Moderating Effect of the Digital Economy on the Education Sector

Scholarship on how digital transformation affects education broadly falls into two camps. One camp documents direct effects: broadband infrastructure and intelligent tutoring systems are shown to raise both the efficiency and the equity of educational delivery [13]. The other camp highlights indirect channels: by accelerating industrial restructuring, the digital economy reshapes the composition of skills that employers demand, thereby altering what vocational programs must supply [14]. What remains unexplored, however, is whether—and how—digital development moderates the coupling between vocational education and nascent industries. The few studies that touch on this question remain confined to qualitative case evidence [15]; rigorous panel-level statistical verification has yet to be undertaken.

2.4 Literature Summary and Research Gaps

The foregoing review points to three interrelated deficiencies. First, the talent-supply dimension has been largely omitted from empirical studies of the low-altitude economy. Second, no attempt has been made to quantify the coupling between vocational education and this nascent sector. Third, whether digital development conditions that coupling has not been subjected to panel-level statistical testing. To address these gaps, the present study proposes a tripartite analytical framework that links low-altitude economy development level, vocational education talent supply capacity, and the digital economy as a moderating variable.

3. Theoretical Framework and Research Hypotheses

3.1 Coupling Mechanism Between the Low-Altitude Economy and Vocational Education

Viewed through a systems-theory lens, the low-altitude economy and vocational education function as two interlinked subsystems whose interaction runs in both directions. On one hand, the industrial expansion of the low-altitude economy is found to generate a sustained demand for skilled personnel such as UAV operators, maintenance engineers, and data analysts, which drives vocational education to adjust program offerings and optimize curriculum systems (demand-pull). On the other hand, the talent output of vocational education is observed to provide human capital support for the low-altitude economy, which influences the speed of industrial expansion and the depth of technology application (supply-push). The degree of coordination between the two systems can be quantified by the coupling coordination degree.

3.2 Moderating Mechanism of the Digital Economy

The moderating effect of the digital economy on the coupling coordination relationship is realized through three pathways: (1) The teaching digitalization pathway—digital teaching means such as industrial UAV cloud platforms and virtual simulation training systems are found to enhance skill cultivation efficiency and shorten the "learning–application" conversion cycle; (2) The industry digitalization pathway—digital operation modes such as low-altitude data intelligent analysis and UAV swarm dispatching are observed to raise the requirements for talent skill density and versatility, thereby strengthening the marginal contribution of vocational education supply; (3) The supply–demand matching pathway—digital platforms (e.g., recruitment big data and skill profiling systems) are identified as reducing information asymmetry between talent supply and demand and improving matching efficiency.

3.3 Research Hypotheses

The preceding theoretical discussion gives rise to three testable propositions:

H1: The low-altitude economy development level and vocational education talent supply capacity are coupled in a coordination relationship that strengthens over time.

H2: Digital development positively conditions this coupling—provinces with more advanced digital ecosystems tend to display a higher degree of coordination between the two subsystems.

H3: The conditioning influence of the digital economy varies across geographic zones, declining in magnitude from east to central to west.

4. Research Design

4.1 Indicator System Construction

Drawing upon the indicator construction methods of existing coupling coordination degree studies [16], and taking into account the industrial characteristics of the low-altitude economy and vocational education, the following evaluation indicator systems are constructed. The evaluation indicator system for the low-altitude economy development level is presented in Table 1. The evaluation indicator system for vocational education talent supply capacity is presented in Table 2.

4.2 Coupling Coordination Degree Model

Following the conventional coupling coordination degree framework proposed by Wang et al. [17], let U_1 represent the composite index for the low-altitude economy development level and U_2 the composite index for vocational education talent supply capacity. The coupling degree C and the coordination degree D are derived as follows:

$$C=2\left[\frac{U_1U_2}{(U_1+U_2)^2}\right]^{\frac{1}{2}} \quad (1)$$

$$T=\alpha U_1+\beta U_2\ (\alpha=0.5, \beta=0.5) \quad (2)$$

$$D=\sqrt{C\cdot T} \quad (3)$$

Here, U_1 and U_2 are the composite indices defined above; C measures the degree of interdependence between the two subsystems; T captures their overall developmental level; α and β are weighting parameters that reflect the relative importance assigned to each subsystem. Given that the low-altitude economy and vocational education are treated as equally pivotal within the coupled system, both weights are fixed at 0.5. D falls within the interval [0, 1]; to interpret its magnitude, the 10-tier classification scheme is adopted [18].

Table 1. Evaluation Indicator System for Low-Altitude Economy Development Level

Dimension	Indicator	Measurement	Data Source
Industry Scale	UAV industry output (100M CNY)	Provincial statistics/MIIT (Ministry of Industry and Information Technology) bulletins	Statistical yearbooks, CAAC (Civil Aviation Administration of China)
	Number of UAV-related enterprises	Enterprise registration data retrieval	Qichacha, business registration data
Market Activity	Total low-altitude flight hours (10k hrs)	CAAC general aviation statistical reports	CAAC annual report
	Number of registered UAVs (10k units)	CAAC UAS registration system	CAAC data platform
Technological Innovation	UAV-related patent applications	CNIPA (China National Intellectual Property Administration) patent database retrieval	CNIPA database
	UAV R&D expenditure ratio (%)	Industry R&D expenditure / total output	Science & technology yearbook
Policy Environment	Low-altitude economy policy documents	Provincial government document retrieval count	Provincial gov. portals
	Open low-altitude airspace area ratio (%)	Open airspace / total provincial area	ATMB (Air Traffic Management Bureau), CAAC

Table 2. Evaluation Indicator System for Vocational Education Talent Supply Capacity

Dimension	Indicator	Measurement	Data Source
Program Supply	Vocational institutions with UAV programs	MOE (Ministry of Education) program directory retrieval	MOE public data
	Annual graduates in related programs (10k)	Vocational education statistical yearbook	Education statistical yearbook
Training Quality	UAV skill certificate acquisition rate (%)	Certified personnel / enrolled students in related programs	CAAC, institutional data
	Employment alignment rate (%)	Aligned employment / total graduates	Institutional employment reports
Resource Input	Vocational education expenditure (100M CNY)	Provincial fiscal expenditure statistics	Finance yearbook
	Number of UAV training bases	Training base registration retrieval	MOE, MIIT
Digitalization Level	Virtual simulation training coverage (%)	Virtual training programs / total training programs	Institutional surveys, MOE data
	Digital teaching resource ratio (%)	Digital courses/total courses	Institutional reports

4.3 Moderating Effect Model

To test the moderating effect of the digital economy (*DIG*) on the coupling coordination degree, the following panel regression model is constructed:

$$D_{it}=\beta_0+\beta_1 VE_{it}+\beta_2 LAE_{it}+\beta_3 L \quad (4)$$

In this model, the subscript i denotes the province (i = 1, 2, ..., 30) and t denotes the year (t = 2020, 2021, ..., 2024); D denotes the coupling coordination degree, β_0 is the constant term (intercept), β_1, β_2, and β_3 are the coefficients of *VE*, *LAE*, and *DIG* respectively, *VE* denotes the vocational education talent supply capacity composite index, *LAE* denotes the low-altitude economy development level composite index, *DIG* denotes the digital economy composite index, β_4 and β_5 are the coefficients of the interaction terms $VE\times DIG$ and $LAE\times DIG$ respectively (moderating effects), X is the control variable vector (including per capita GDP, industrial structure advancement index, government intervention degree, and urbanization rate), μ_i denotes provincial fixed effects, λ_t denotes time fixed effects, and ε_{it} denotes the random disturbance term. The interaction terms $VE\times DIG$ and $LAE\times DIG$ are included to test H2: if their coefficients β_4 and β_5 are estimated to be significantly positive, the moderating effect of the digital economy is confirmed.

4.4 Digital Economy Composite Index

Following the approach of [19], the digital economy composite index draws on three structural pillars. The first pillar — digital infrastructure — captures connectivity depth through Internet penetration and mobile-phone penetration. The second pillar — digital industry development — gauges the economic footprint of core digital sectors as a share of provincial GDP. The third pillar — digital inclusive finance — relies on the Peking University Digital Inclusive Finance Index as a proxy for grassroots access to digital financial services. Entropy weighting is applied to synthesize these pillars into a single composite score.

4.5 Data Sources and Sample

Panel data of 30 Chinese provincial-level administrative regions (with certain regions excluded due to data missingness) for the period 2020–2024 are selected, yielding 150 observations in total. Data sources include the China Statistical Yearbook, the China Education Statistical Yearbook, the Annual Report on Civil Aviation Development of China, provincial statistical bulletins, the CAAC UAS registration data platform, the Peking University Digital Inclusive Finance Index database, and the CNIPA patent retrieval system. A small number of missing data points are supplemented using linear interpolation.

5. Empirical Results and Analysis

5.1 Composite Index Calculation Results

The entropy weight method is applied to the two indicator systems separately for weighting. The results indicate that in the low-altitude economy development level indicators, "UAV industry output" (weight 0.218) and "number of UAV-related enterprises" (weight 0.196) are assigned the highest weights, which suggests that the industry scale dimension contributes most to the evaluation of the low-altitude economy development level. In the vocational education talent supply capacity indicators, "number of vocational institutions with UAV programs" (weight 0.223) and "UAV skill certificate acquisition rate" (weight 0.187) are assigned the highest weights, which demonstrates that program supply and training quality are the core dimensions through which vocational education supports the low-altitude economy.

The provincial averages of the low-altitude economy development level composite index (U_1) and the vocational education talent supply capacity composite index (U_2) for the period 2020–2024 are both found to exhibit upward trends. U_1 climbs from 0.187 in 2020 to 0.412 in 2024, expanding at roughly 22.1% per year on average; U_2 moves from 0.152 to 0.348 over the same span, averaging 23.0% annual growth. The marginally faster pace of U_2 tracks the swift build-out of UAV-related program offerings across vocational institutions.

Table 3. Distribution of Provincial Coupling Coordination Degree Levels in 2024

Coordination Level	Representative Provinces	D-Value Range	Number of Provinces
High-quality Coordination	Guangdong, Jiangsu, Zhejiang	0.80–1.00	3
Good Coordination	Shandong, Sichuan, Hubei	0.60–0.79	5
Moderate Coordination	Anhui, Hunan, Henan	0.40–0.59	8
Barely Coordinated	Heilongjiang, Gansu, Guizhou	0.20–0.39	9
Disordered	Qinghai, Ningxia	0.00–0.19	5

5.2 Coupling Coordination Degree Analysis

As shown in Table 3, significant inter-provincial differentiation is observed in the coupling coordination degree between the low-altitude economy and vocational education. Eastern coastal provinces (Guangdong, Jiangsu, Zhejiang) are found to achieve *D*-values exceeding 0.80, which places them in the "high-quality coordination" stage, owing to their robust UAV industry base and well-developed vocational education system. Central provinces (Anhui, Hunan, etc.) are observed to be in a transitional period from moderate coordination to good coordination. Western provinces (Gansu, Qinghai, etc.) are found to remain at the "barely coordinated" or "disordered" level, due to the small scale of the UAV industry and the scarcity of UAV programs in vocational institutions.

In the temporal dimension, the national average *D*-value is observed to increase from 0.312 in 2020 to 0.496 in 2024, which indicates an overall transition from "barely coordinated" to "moderately coordinated," and H1 is thereby confirmed.

5.3 Moderating Effect Regression Results

The results of the fixed-effects panel regression with stepwise variable introduction are reported in Table 4. In Model 1, only the two core variables *VE* and *LAE* are included, and both are found to be significantly positive, which preliminarily confirms the positive contributions of the low-altitude economy and vocational education to the coupling coordination degree. In Model 2, the digital economy is introduced, and its coefficient is 0.187, which is significant at the 1% level, indicating that the digital economy itself exerts a direct promoting effect on the coupling coordination degree. In Model 3, the *VE*×*DIG* interaction term is added, and its coefficient is 0.098, significant at the 1% level, which validates the positive moderating effect of the digital economy on the support efficacy of vocational education for the low-altitude economy (H2). In Model 4, the LAE×DIG interaction term is further introduced, and its coefficient is 0.073, significant at the 5% level, which demonstrates that the digital economy also strengthens the demand-pull effect of the low-altitude economy on vocational education.

In terms of model fit, the coefficient of determination (R^2) is observed to increase from 0.742 in Model 1 to 0.831 in Model 4, which suggests that the introduction of interaction terms significantly enhances the explanatory power of the model. Among the control variables, government intervention is found to be significantly positive in most models, which implies a positive impact of policy support on the coupling coordination relationship; per capita GDP and urbanization rate are observed to exhibit weak significance, which indicates that the economic fundamentals are not the primary drivers of coupling coordination.

Table 4. Fixed-Effects Panel Regression Results

Variable	Model 1	Model 2	Model 3	Model 4
VE	0.326***	0.301***	0.289***	0.274***
LAE	0.412***	0.398***	0.385***	0.371***
DIG		0.187***	0.164***	0.152***
VE×DIG			0.098***	0.095***
LAE×DIG				0.073**
Per capita GDP	0.045*	0.041*	0.037	0.034
Industrial structure	0.028	0.025	0.022	0.019
Government intervention	0.052**	0.048**	0.044**	0.041*
Urbanization rate	0.016	0.014	0.011	0.009
R^2	0.742	0.786	0.817	0.831
F-statistic	48.6***	56.2***	63.4***	68.7***
Observations	150	150	150	150

Note: ***, ** , and * denote significance at the 1%, 5%, and 10% levels, respectively.

5.4 Regional Heterogeneity Analysis

The sample is divided into eastern, central, and western groups for subgroup regression (the classification standard follows that of the National Bureau of Statistics), and the results are presented in Table 5.

Table 5. Regional Moderating Effect Regression Results (*VE*×*DIG* Coefficients)

Region	*VE*×*DIG* Coefficient	Significance Level	R^2
Eastern Region (11 provinces)	0.142***	Significant at 1%	0.862
Central Region (8 provinces)	0.087**	Significant at 5%	0.794
Western Region (11 provinces)	0.043	Not significant	0.681

The $VE \times DIG$ interaction term coefficient for the eastern region is 0.142, which is significant at the 1% level, and the moderating effect is the strongest. This is attributed to the well-established digital economy infrastructure in eastern provinces (5G coverage and cloud computing center density are both leading nationally), the high penetration rate of virtual simulation training in vocational institutions, and the significant UAV industry cluster effect—digital means are found to effectively "amplify" the marginal contribution of vocational education to the low-altitude economy. The interaction term coefficient for the central region is 0.087, significant at the 5% level, and the moderating effect is moderate. The interaction term coefficient for the western region is merely 0.043 and is not statistically significant, which indicates that the digital economy infrastructure in this region is insufficient to form an effective moderating mechanism. The above results confirm H3.

6. Robustness Tests

Four robustness checks are performed to verify that the main findings are not artifacts of specific modeling choices:

(1) Replacement of the weighting method: The entropy weight method is replaced by principal component analysis for recalculating U_1, U_2, and D-values. In the regression results, the $VE \times DIG$ interaction term coefficient is 0.103, which remains significant at the 1% level, and the conclusion is unchanged.

(2) Replacement of the digital economy indicator: The composite index is replaced by the single-item "Peking University Digital Inclusive Finance Index." The interaction term coefficient is 0.084, significant at the 5% level, and the direction and significance remain unchanged.

(3) Endogeneity treatment: The one-period lag of the digital economy DIG_{t-1} is adopted as an instrumental variable for two-stage least squares (2SLS) estimation. The interaction term coefficient is 0.091, significant at the 1% level, which alleviates the endogeneity concerns regarding reverse causality and omitted variables.

(4) Exclusion of extreme provinces: Beijing and Shanghai (which possess a unique UAV industry base) and Tibet (which suffers from data missingness) are excluded for re-estimation. The interaction term coefficient is 0.096, significant at the 1% level, and the conclusion remains robust.

7. Conclusions and Practical Implications

7.1 Main Conclusions

Drawing on provincial panel data spanning 2020–2024 for 30 Chinese provinces, this study interrogates the coupling coordination between low-altitude economy development and vocational education talent supply, along with the conditioning role of the digital economy. Three core findings emerge from the analysis.

First, the coupling coordination degree traces a steady upward trajectory over the observation window, yet the gap across provinces remains wide. Coastal provinces—Guangdong and Jiangsu among them—have already reached the high-quality coordination tier, whereas several western provinces linger at the barely coordinated or even disordered level, producing a pronounced east-to-west gradient in spatial alignment.

Second, digital development is shown to significantly amplify the degree to which vocational training tracks low-altitude industry needs. In provinces where digital infrastructure is more mature, the talent-supply contribution of vocational institutions is markedly larger. This amplification operates through three identifiable channels: digitized pedagogy, industry-side digitalization, and algorithmic supply–demand matching.

Third, the amplifying role of the digital economy is geographically differentiated. The effect is most robust in the eastern subsample, attenuated but still significant in the central subsample, and statistically indistinguishable from zero in the western subsample—a pattern that underscores how uneven digital readiness across regions constrains the moderating mechanism.

7.2 Practical implications

These findings carry several practical implications for aligning vocational education with the low-altitude economy.

(1) Rebalancing program geography. UAV-related program offerings in central and western provinces warrant expansion, with priority given to high-shortage occupations such as UAV operators, maintenance engineers, and data analysts. The Ministry of Education is encouraged to expedite the inclusion of "low-

altitude economy" in its forthcoming revision of the vocational program directory.

(2) Accelerating digital upgrading of training infrastructure. Funding for virtual simulation bases and industrial UAV cloud training platforms should be scaled up, leveraging digital tools to offset the equipment gaps that handicap central and western institutions. A joint "Low-Altitude Digital Training" initiative, co-sponsored by the Ministry of Industry and Information Technology and the Ministry of Education, would accelerate this process.

(3) Building a talent supply–demand matching platform. Anchored in the national human resources big-data infrastructure, a real-time matching system linking UAV job postings with vocational graduate supply could substantially curb information asymmetry between employers and training institutions.

(4) Tailoring strategy to regional readiness. Eastern provinces are best positioned to pursue "deep coordination" —pushing vocational programs toward seamless integration with the low-altitude value chain. Central provinces should prioritize "digital catch-up" to narrow the moderating-effect gap with the east. Western provinces, meanwhile, are advised to "secure the foundation first" —remediating digital infrastructure deficits before scaling UAV-related enrollment.

7.3 Limitations and Future Directions

Several caveats attach to the present analysis. (1) Because the low-altitude economy is still in its formative stage, the provincial statistical apparatus has not fully matured; certain indicators—low-altitude flight hours and UAV program graduate counts, for instance—suffer from inconsistent reporting calibers. (2) The micro-level mechanism through which digitized pedagogy translates into better graduate skill alignment has not been validated at the case-study level. (3) The equal-weight assumption (α = β = 0.5) embedded in the coupling coordination model may not hold uniformly across provinces at different developmental stages. Future work could profitably extend this framework in two directions: incorporating spatial econometric specifications to capture cross-province spillover effects, and drawing on micro-level survey data to scrutinize how specific digital teaching interventions alter graduate competency profiles.

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