

INTEGRATED EVALUATION OF LOW-ALTITUDE ECONOMIC DEVELOPMENT USING AN IMPROVED GRA–TOPSIS METHOD

YongZheng Man¹, Ke Shi^{1*}, JunHui Li²

¹*Institute of Civil Aviation Supervisor Training, Civil Aviation Flight University of China, Guanghan 618307, Sichuan, China.*

²*Shifang Rongbei Logistics Development Service Center, Shifang 618400, Sichuan, China.*

**Corresponding Author: Ke Shi*

Abstract: The low-altitude economy is emerging as an important growth domain in the transition from pilot exploration to large-scale development. However, existing evaluation frameworks often emphasize industrial scale while insufficiently capturing the joint effects of airspace resources, infrastructure, innovation, application scenarios, market demand, and governance capacity. This study integrates indicators from the aerospace industry chain with low-altitude economic development indicators and develops a multidimensional evaluation system comprising six dimensions and 34 tertiary indicators. A group-decision relative-entropy aggregation procedure is used to derive subjective weights, which are combined with entropy-based objective weights. The resulting weights are incorporated into an improved Grey Relational Analysis–Technique for Order Preference by Similarity to an Ideal Solution (GRA–TOPSIS) framework. Using 12 simulated evaluation units, the method produces a transparent chain from expert scoring and the group decision matrix H to the weighted normalized matrix R , the grey-relational optimal indicator set, Euclidean distances from the positive and negative ideal solutions, and the final relative closeness values. The simulated results distinguish different development levels and illustrate how distance-based and structural similarity information can be integrated. Because the dataset is simulated, the numerical rankings should not be interpreted as empirical regional findings; the study instead provides a reproducible methodological template for subsequent research based on official statistics and enterprise-level data.

Keywords: Low-altitude economy; Aerospace industry chain; Comprehensive evaluation; Improved GRA–TOPSIS; Combined weighting; Simulated data

1 INTRODUCTION

Research on the low-altitude economy initially focused primarily on the development of general aviation, the resource characteristics of low-altitude airspace, and reforms in low-altitude airspace management. From the perspective of general aviation development, Qin Xulin and Ma Xiaoxin were among the earliest scholars to examine the institutional, infrastructural, and market-development challenges facing China's general aviation industry, thereby providing an industrial foundation for subsequent studies of the low-altitude economy [1]. From a resource-based perspective, Qin Rui et al. regarded low-altitude airspace as a spatial resource with economic value and emphasized the significance of low-altitude resource development for regional economic growth and industrial organization [2]. Qin Rui subsequently defined the low-altitude economy from the perspectives of conceptual clarification and structural composition, arguing that it is not a single form of general aviation activity, but rather a composite economic system based on low-altitude airspace, aircraft, operational services, and related industries [3]. These studies laid an important foundation for clarifying the concept of the low-altitude economy and developing its theoretical framework.

As the low-altitude economy has increasingly been incorporated into the framework of strategically emerging industries and the cultivation of new quality productive forces, domestic research has gradually shifted from conceptual discussions toward industrial chains, policy support, application scenarios, and regional development pathways. From an industrial-chain perspective, Zhang Jiaxin and Xu Qian examined the constraints on the development of the low-altitude economy and argued that its growth is influenced by multiple factors, including core technologies, infrastructure, industrial coordination, and institutional supply [4]. From the perspective of three-dimensional unmanned flight, Qiao Li et al. explored pathways for modernizing the low-altitude economy and emphasized the need to establish coordination among technological innovation, scenario-based applications, and governance rules [5]. Drawing on the background, connotations, and global landscape of the low-altitude economy, Lü Renli argued that its development depends not only on aircraft manufacturing and operational capabilities, but also on airspace management, infrastructure, and the international competitive environment [6]. Zhuang Zhuo examined the role of artificial intelligence in enabling the low-altitude economy and analyzed the application potential of intelligent technologies in low-altitude logistics, inspection, emergency rescue, and urban governance [7].

Research on measuring the level of low-altitude economic development has expanded in recent years, although the field remains at an early stage. Taking Zhejiang Province as an example, Wang Qianqian, Bai Hongyu, and Gu Sishi constructed an evaluation indicator system from three dimensions: facility provision, demand potential, and industrial innovation. They then applied the analytic hierarchy process and the entropy-weight method to measure the level of low-altitude economic development across cities in Zhejiang Province [8]. Their study highlighted the roles of

infrastructure, market demand, and innovation investment in regional low-altitude economic development and provided an important reference for evaluating low-altitude economic development at the provincial and prefectural levels. Based on panel data from 30 provinces, autonomous regions, and municipalities, Tong Peng and Wang Ke measured China's low-altitude economic development from four dimensions: low-altitude manufacturing, low-altitude flight operations, low-altitude support, and integrated services. They further examined regional disparities and their influencing factors [9]. By adopting an industrial-chain perspective, this study extended the evaluation framework for the low-altitude economy and identified digital new infrastructure as an important factor contributing to regional differences. From the perspective of new quality productive forces, Shan Liang and Liu Yushi examined the coupling and coordination between technological innovation capacity and low-altitude economic development. Their findings suggest that the technological innovation system and the low-altitude economic system interact with each other, while innovation investment, innovation outputs, and the innovation environment provide important support for low-altitude economic development [10].

In addition, some studies have begun to examine the effects of digital transformation, policy support, and scenario expansion on the development of the low-altitude economy. From the perspective of enterprise digitalization, Bai Ruihao analyzed the mechanisms through which digitalization enhances the core capabilities of enterprises in the low-altitude economy and argued that digitalization can influence firms' competitive advantages through dynamic capabilities [11]. Zhou Jianzhong proposed that digital empowerment constitutes an important pathway for the new development of the low-altitude economy, emphasizing the need for coordinated progress in policy implementation, standard development, platform construction, and technological innovation [12]. Zhao Fei and Wang Huang highlighted the supporting role of digital and intelligent technologies in low-altitude economic development and argued that the low-altitude industry should promote scenario innovation and industrial upgrading in accordance with the characteristics of the digital economy [13]. Overall, domestic research has gradually expanded from conceptual definition and industrial-chain analysis to the measurement of development levels, digital empowerment, and regional disparity analysis. Nevertheless, further research is needed on the construction of comprehensive indicator systems, the harmonization of statistical standards, the comparability of regional measurements, and the evaluation of governance and safety support.

Although international studies rarely use the term "low-altitude economy" explicitly, a substantial body of research has been developed in the fields of general aviation, urban air mobility, unmanned aircraft operations, airport planning, flight safety, and aviation technology innovation. Using a multi-criteria decision-making approach to examine investment policies for general aviation airports, Caetano et al. found that airport location, spatial coverage, and the prioritization of infrastructure investment are key factors influencing the development of general aviation [14]. This line of research provides useful methodological insights for infrastructure planning and the development of low-altitude airspace resources. Focusing on the preliminary design of hybrid-electric general aviation aircraft, Finger et al. emphasized the importance of new-energy propulsion, aircraft lightweighting, and integrated system design for the future development of general aviation aircraft [15]. Blickensderfer et al. investigated general aviation pilots' comprehension of aviation weather information display systems and found that the ability to interpret weather information directly affects the safety and operational efficiency of low-altitude flight [16]. Fuller and Hook examined the role of automated safety systems in reducing fatal accidents in general aviation and showed that safety technologies and automated systems are important instruments for improving the safety of low-altitude flight operations [17]. Existing domestic and international research has already accumulated a certain body of knowledge in areas such as clarifying the concept of the low-altitude economy, regional measurement, industrial chain synergy, and comprehensive evaluation. However, three shortcomings still remain: First, indicator systems tend to focus excessively on industry scale, making it difficult to simultaneously reflect openness of application scenarios, policy governance, and safety coordination; second, single weighting methods are prone to being influenced by subjectivity or dispersion; third, the expression of the integration between the low-altitude economy and the aerospace industry chain remains relatively weak.

Based on this, this paper focuses on the following issues: First, how to reconstruct a comprehensive evaluation system suitable for integrated development based on existing indicators; second, how to leverage a combined subjective and objective weighting approach along with an improved GRA-TOPSIS method to achieve robust ranking; and third, whether the calculation results under simulated data can reveal hierarchical differences and structural shortcomings among different development units.

2 CONSTRUCTION OF A COMPREHENSIVE EVALUATION INDEX SYSTEM FOR THE DEVELOPMENT LEVEL OF THE LOW-ALTITUDE ECONOMY

2.1 Approach to Indicator Construction

The low-altitude economy is an emerging economic model that leverages low-altitude airspace resources and is driven by low-altitude flight activities involving both manned and unmanned aircraft. It integrates various sectors, including aerospace manufacturing, general aviation, drones, communication and navigation, artificial intelligence, digital platforms, scenario-based operations, and comprehensive services. Compared to traditional industries, the low-altitude economy is characterized by long industrial chains, high levels of technological integration, broad application scenarios, strong spatial dependence, and stringent safety regulatory requirements. Therefore, measuring the development level of

the low-altitude economy cannot rely solely on single dimensions such as industry size or the number of enterprises; rather, a comprehensive evaluation system should be established, covering fundamental conditions, industrial support, flight operations, innovation capabilities, and governance safeguards.

Building on existing research and policy practices, this paper constructs a comprehensive evaluation index system for the development level of the low-altitude economy following the framework of “theoretical logic—industrial chain—scenario applications—governance safeguards.” First, starting from the intrinsic nature of the low-altitude economy, we clarify that its development depends not only on aircraft manufacturing and industrial scale but also on airspace resources, takeoff and landing facilities, digital new infrastructure, application scenarios, technological innovation, safety regulation, and regional coordination. Second, drawing on relevant domestic and international studies that examine dimensions such as facility supply, demand potential, industrial innovation, low-altitude manufacturing, low-altitude flight, low-altitude support, and integrated services, we distill a foundational framework for measuring the development level of the low-altitude economy. Third, we refer to local low-altitude economic policy documents and aviation-related. The development indicators for the Tian industry chain incorporate practical metrics such as leading enterprises in the chain, enterprises above designated size, innovation platforms, industrial investment, demonstration scenarios, professional services, policy implementation, and security incidents. Finally, following the hierarchical principle, a comprehensive evaluation indicator system is constructed, consisting of a goal layer, a criterion layer, and an indicator layer.

The basic logic behind constructing the indicator system in this paper is as follows: Infrastructure and airspace resources are the prerequisite conditions for the development of the low-altitude economy, determining whether low-altitude flight activities can be conducted safely, orderly, and efficiently. The scale of industries and the sophistication of industrial clusters serve as the industrial support for the sustained development of the low-altitude economy, reflecting the region’s manufacturing capabilities, enterprise hierarchies, and level of industrial supporting facilities. Flight operations and scenario demands represent the critical link through which the low-altitude economy shifts from policy-driven to market-driven, reflecting its actual activity and degree of commercialization. Scientific and technological innovation and new-quality productivity constitute the core driving force for the high-quality development of the low-altitude economy, determining its ability to upgrade industries and expand application scenarios. Governance safeguards and regional coordination provide the institutional foundation for the safe operation and standardized development of the low-altitude economy, influencing its sustainability.

2.2 Principles for Constructing the Indicator System

To ensure the scientific validity and operability of the indicator system, this article adheres to the following principles in the process of indicator selection.

First, the principle of scientific rigor. The indicator system should align with the fundamental essence and development patterns of the low-altitude economy and accurately reflect the key components that constitute the level of its development. The low-altitude economy is not a single-industry activity; rather, it is a complex system composed of airspace resources, aircraft manufacturing, flight operations, scenario applications, digital platforms, and governance services. Therefore, the design of indicators should take into account industrial attributes, spatial attributes, technological attributes, and governance attributes simultaneously.

Second, the principle of systematicity. The indicator system should cover the key stages of low-altitude economic development and avoid evaluating it from a single perspective, such as industry size, number of enterprises, or policy support alone. This article takes a five-dimensional approach—infrastructure, industrial chain, flight operations, technological innovation, and governance and regulatory support—aiming to comprehensively reflect the entire chain of the low-altitude economy, from foundational conditions to industrial development, and from scenario applications to institutional safeguards.

Third, the principle of comparability. The indicators should exhibit strong regional comparability, enabling both horizontal comparisons across different regions and longitudinal comparisons within the same region over different years. For indicators with significant differences in statistical definitions, this paper prioritizes those with clear meanings, relatively stable data sources, and relatively standardized calculation methods.

Fourth, the principle of availability. The low-altitude economy is still in its early stages of development, and some indicators have yet to establish mature statistical methodologies. Therefore, when selecting indicators, it is essential to both reflect theoretical completeness and take into account the difficulty of data acquisition. For data that are difficult to obtain directly, supplementary information can be gathered from publicly available government sources, statistics compiled by industry regulators, annual reports from enterprises, materials provided by industry alliances, or questionnaire surveys.

Fifth, the principle of dynamism. The low-altitude economy is developing rapidly, with frequent technological iterations and policy changes. Therefore, the indicator system should possess a certain degree of flexibility, allowing for moderate adjustments based on the stage of development of the low-altitude economy and available data conditions. As for indicators that are not yet mature at present but hold significant future importance—such as eVTOL operations, low-altitude intelligent network coverage, and inter-regional low-altitude air routes—these can be gradually incorporated in subsequent research studies.

2.3 Hierarchical Structure of the Indicator System

The comprehensive evaluation index system for the development level of the low-altitude economy constructed in this paper comprises three hierarchical levels: the goal level, the criterion level, and the indicator level.

The target layer is the comprehensive index of low-altitude economic development level, used to reflect the overall level of low-altitude economic development of the evaluated entity.

The guideline layer comprises five first-level indicators: infrastructure and airspace resources, industrial scale and cluster-level capabilities, flight operations and scenario demands, technological innovation and new-quality productivity, and governance support and regional collaboration.

The indicator layer consists of several secondary and tertiary indicators, which are used to specifically characterize the connotations of each primary indicator. Specifically, infrastructure and airspace resources primarily reflect the spatial and infrastructural foundations for the development of the low-altitude economy; while industry scale and cluster-level capabilities mainly reflect the capacity of the low-altitude economy industry to support growth and development. Level of industrial chain synergy; flight operations and scenario demands primarily reflect the actual operational vitality and market demand foundation of the low-altitude economy; technological innovation and new-quality productivity mainly reflect the level of technological innovation, digital transformation, and talent support in the low-altitude economy; governance safeguards and regional collaboration primarily reflect the capacity for policy systems, safety regulation, financial services, and cross-regional cooperation, see Table 1.

Table 1 Comprehensive Evaluation Index System for the Development Level of the Low-Altitude Economy

First-Level	Second-Level	Third-Level	Indicator Attribute
Infrastructure & Airspace Resources	Airspace & Takeoff/Landing Facilities	Proportion of available low-altitude airspace	Positive
		Number of general aviation airports	Positive
		Number of low-altitude takeoff/landing points/helipads	Positive
		Number of low-altitude air routes opened	Positive
		Coverage level of 5G/BeiDou/low-altitude communication, navigation, and surveillance	Positive
	Digital New Infrastructure	Number of low-altitude flight service stations/regulatory service platforms	Positive
		Adaptability to special terrains such as mountains and islands	Positive
	Terrain & Spatial Adaptability	Coverage rate of low-altitude economy spatial planning	Positive
		Investment in low-altitude infrastructure	Positive
	Facility Investment	Operating revenue of low-altitude economy-related industries	Positive
Industrial Scale & Cluster Capability	Industrial Scale	Value-added/output of low-altitude economy-related industries	Positive
		Tax revenue	Positive
	Chain-Leading Enterprises & Enterprise Echelon	Operating revenue of chain-leading enterprises	Positive
		Number of above-scale/above-limit low-altitude economy enterprises	Positive
		Number of above-scale/above-limit low-altitude economy enterprises	Positive
		Local supporting rate / intra-provincial procurement share	Positive
	Industrial Chain Support	Completeness of key links in low-altitude manufacturing	Positive
		Total investment in low-altitude economy industries	Positive
	Investment & Projects	Number of key projects with investment over 100 million yuan	Positive
		General aviation flight hours	Positive
Flight Operations & Scenario Demand	Flight Activity	Drone flight sorties / flight volume	Positive
		Number of registered aircraft and registered drones	Positive
	Logistics & Transportation Demand	Low-altitude logistics freight volume	Positive
		Low-altitude passenger / short-haul transport volume	Positive
		Number of low-altitude application scenarios	Positive
	Scenario Applications	Operating revenue of demonstration application scenarios	Positive
		Express delivery volume / intensity of instant delivery demand	Positive
Technological Innovation & New Quality Productive Forces	Market Demand Base	Low-altitude logistics freight volume	Positive
		Low-altitude passenger / short-haul transport volume	Positive
	Logistics & Transportation Demand	Number of low-altitude application scenarios	Positive
		Operating revenue of demonstration application scenarios	Positive
	Innovation Input	Enterprise R&D investment intensity	Positive

First-Level	Second-Level	Third-Level	Indicator Attribute
Governance Assurance & Regional Coordination	Innovation Platforms	Government fiscal investment in science, technology, and industrial support	Positive
		Number of innovation platforms and pilot-test platforms for the low-altitude economy	Positive
		Number of industry-leading talents and specialized professionals	Positive
	Talent Support	Number of universities, research institutes, and training institutions related to aerospace/low-altitude fields	Positive
		Completeness of special policies for the low-altitude economy	Positive
	Policy & Institutions	Disbursement rate of government special funds	Positive
		Incidence rate of low-altitude flight safety incidents	Negative
	Safety Regulation	Coverage of surface meteorological observation stations / low-altitude meteorological services	Positive
		Balance of low-altitude economy loans / financing scale	Positive
	Financial & Service Ecosystem	Number of professional service institutions	Positive
		Number of high-level industry exchange and cooperation platforms	Positive
	Openness & Coordination	Number of cross-regional low-altitude coordinated air routes / cooperation projects	Positive

The indicator data in this article are primarily sourced from statistical yearbooks, publicly available government documents, data from industry regulators, annual reports of enterprises, materials from industrial alliances, and survey questionnaire data. Infrastructure-related indicators can be mainly obtained from the civil aviation, transportation, development and reform, natural resources, and local low-altitude economy authorities; industry-scale indicators can be sourced from statistical agencies, departments of industry and information technology, tax authorities, and enterprise annual reports; flight-operation indicators can be derived from civil aviation regulators, low-altitude flight service platforms, postal administration authorities, and operating enterprises; science-and-technology innovation indicators can be sourced from science and technology agencies, intellectual property offices, the technical contract registration system, and data from universities and research institutes; and governance and safeguarding indicators can be obtained from policy documents, fiscal authorities, financial regulatory agencies, meteorological departments, and emergency management agencies.

In the data processing procedure, the first step is to verify the scope and consistency of the raw data to ensure that the same indicators are comparable across different regions. Next, the indicators need to be standardized according to their respective attributes. For positively oriented indicators, a higher value indicates a higher level of development; for negatively oriented indicators—such as the incidence rate of low-altitude flight safety incidents—a higher value signifies greater risk and thus requires reverse standardization. Furthermore, given that the units and dimensions of various indicators differ, it is necessary to apply range normalization or other dimensionless transformation methods. Finally, for individual missing values, interpolation, mean substitution, or supplementation using data from adjacent years may be employed, depending on the nature of the data; however, the specific handling approach should be clearly documented in the empirical analysis.

3 RESEARCH METHODS AND DESIGN

The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is a method developed in 1981 by Hwang and Yoon to address single-type or mixed-type multi-attribute decision-making problems. It ranks alternatives based on their proximity to the ideal solution, taking into account the range of each attribute's parameter values. Grey Relation Analysis (GRA), on the other hand, reflects the degree of closeness among alternatives from the perspective of curve shape similarity. By combining these two approaches, we can overcome the limitation of solely calculating relative distances while neglecting curve trends, which may lead to an inaccurate representation of real-world situations.

3.1 Data and Preprocessing

Suppose there are n regions whose low-altitude economic levels are to be evaluated, involving m evaluation indicators. We construct a decision matrix $X=[x_{ij}]_{n \times m}$, $x_{ij} \geq 0 (i=1,2,\dots,n; j=1,2,\dots,m)$. Due to the differences in the meanings, measurement units, and dimensions of the low-altitude economic metrics, we perform normalization on these indicators. (1) Benefit-type indicators—i.e., indicators where higher attribute values are better—have the following normalization formula:

$$y_{ij} = \frac{x_{ij} - \min_{1 \leq i \leq n} x_{ij}}{\max_{1 \leq i \leq n} x_{ij} - \min_{1 \leq i \leq n} x_{ij}} \quad (1)$$

(2) Cost-type indicators—i.e., indicators where lower attribute values are better—have the following normalization formula:

$$y_{ij} = \frac{\max_{1 \leq i \leq n} x_{ij} - x_{ij}}{\max_{1 \leq i \leq n} x_{ij} - \min_{1 \leq i \leq n} x_{ij}} \quad (2)$$

3.2 Group Decision and Combined Weighting

(1) Calculating subjective weights of indicators using the relative entropy aggregation method for group decision-making.

This method is a subjective approach for evaluating and making decisions on multiple objectives. It overcomes the shortcomings of the eigenvalue method in group decision-making and features simple steps, as detailed below:

Construct the group decision matrix $H=(h_{ij})_{n \times m}$.

A 5-point scale is used, where h_{ij} represents the expert's evaluation rule for indicator j , and $i=1,2,\dots,n; j=1,2,\dots,m$.

Calculate the standardized decision matrix $C=(c_{ij})_{n \times m}$.

$$c_{ij} = \frac{h_{ij}}{\sum_{j=1}^m h_{ij}} \quad (3)$$

Calculate the group preference vector $\alpha=(\alpha_1, \alpha_2, \dots, \alpha_m)$, which represents the subjective weights of each indicator.

$$\alpha_j = \frac{\prod_{i=1}^n (c_{ij})^{\delta_j}}{\sum_{j=1}^m \prod_{i=1}^n (c_{ij})^{\delta_j}} \quad (4)$$

Among them, δ_j represents the decision weight assigned by the expert to indicator j , and is set to $\delta_j=1/n$.

(2) Calculating objective weights of indicators using the entropy weighting method

The entropy weighting method is an objective approach for multi-objective decision-making that derives weights based on the data itself. When using this method to evaluate indicators with significant divergence, it can yield more accurate weights. The specific steps are as follows:

Calculate the information entropy weight of the j th indicator in the system. The traditional entropy weighting method stipulates that when $p_{ij}=0$ and $p_{ij}=1$, $p_{ij}\ln(p_{ij})$ both equal 0. To address this drawback, the method has been improved as follows.

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^n p_{ij} \ln(p_{ij}) \quad (5)$$

Calculate the entropy weight for the j indicator, which is the objective weight.

$$v_j = \frac{1-e_j}{\sum_{j=1}^m (1-e_j)} \quad (6)$$

Determine the combined weights

This paper adopts a combined approach of group decision-making relative entropy aggregation and entropy weighting to integrate subjective and objective weights. Let β_j denote the combined indicator weight, defined as follows:

$$\beta_j = \frac{\alpha_j v_j}{\sum_{j=1}^m \alpha_j v_j} \quad (7)$$

3.3 Improved GRA-TOPSIS

(1) Traditional TOPSIS Method

Construct the weighted normalized matrix R . Based on matrix arithmetic methods, combine the standardized decision matrix Y with the combined weights β_j according to the following formula:

$$R = (r_{ij})_{n \times m} = (\beta_j y_{ij})_{n \times m} \quad (8)$$

Construct the positive ideal solution $R^+=(R^+_1, R^+_2, \dots, R^+_m)$ and the negative ideal solution $R^-=(R^-_1, R^-_2, \dots, R^-_m)$. Among these, the benefit-type positive and negative ideal solutions are defined as follows: $R^+=(\max\{r_{i1}\}, \max\{r_{i2}\}, \dots, \max\{r_{im}\})$, $R^-=(\min\{r_{i1}\}, \min\{r_{i2}\}, \dots, \min\{r_{im}\})$. The cost-type positive and negative ideal solutions are the opposite of those for benefit-type criteria.

The distances from the positive and negative ideal solutions, calculated using the Euclidean distance, are denoted as D^+_i and D^-_i , respectively, where $i=1,2,\dots,n$, and:

$$D^+_i = \sqrt{\sum_{j=1}^m (r_{ij} - R^+_j)^2} \quad (9)$$

$$D^-_i = \sqrt{\sum_{j=1}^m (r_{ij} - R^-_j)^2} \quad (10)$$

Calculate the proximity degree and sort it.

$$B_i = \frac{D^-_i}{D^+_i + D^-_i} \quad (11)$$

The higher the progress value posted, the higher the ranking of the region in terms of its low-altitude economic level—and vice versa.

(2) Improved TOPSIS Method

As shown by the traditional TOPSIS method, it has advantages such as simple computation and reliable results; however, it also has certain shortcomings: (1) When two or more evaluation objects lie on the vertical midline of the ideal solution, the Euclidean distances from these objects to the positive and negative ideal solutions will be equal, making it impossible to distinguish between their relative merits, as illustrated in Figure 1. (2) The method neglects the correlation among evaluation indicators, treating all indicators as independently existing factors, thereby introducing bias into the assessment results.

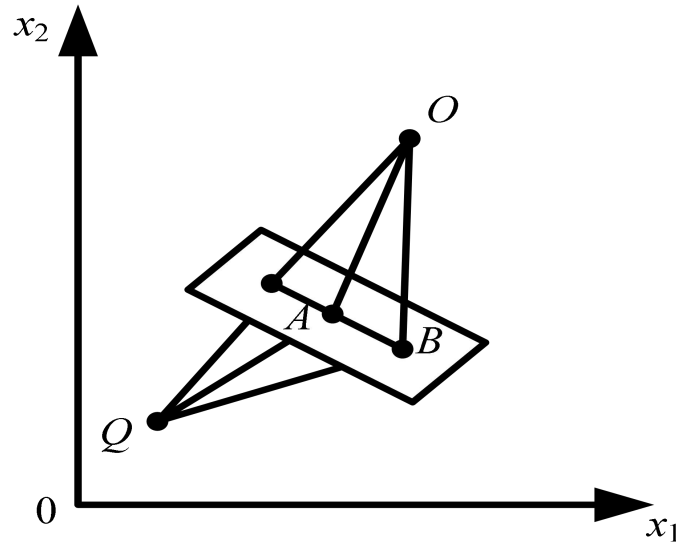


Figure 1 Defects of Traditional TOPSIS Method

Based on the aforementioned shortcomings, we propose an improved approach to the traditional TOPSIS method by leveraging the grey relational analysis method and constructing a new method for calculating proximity. This approach introduces the grey relational analysis, which can better address the issue of interdependence among indicators. Furthermore, it refines the evaluation formulas for the best and worst solutions, thereby overcoming the limitations inherent in the conventional calculation process. The specific steps are as follows:

Calculate the weighted normalized matrix, as shown in Formula (7). Then, identify the optimal index set U_j^* , and use it as the reference sequence in the improved GRA-TOPSIS method:

$$U_j^* = (R_0(1)^*, R_0(2)^*, \dots, R_0(m)^*) \quad (12)$$

Calculate the gray relational coefficients s_{ij} for each indicator, and obtain the gray relational matrix $S=(s_{ij})_{n \times m}$.

$$S_{ik} = \frac{\min_j \min_i \Delta_i(j) + \zeta \max_j \max_i \Delta_i(k)}{\Delta_i(j) + \zeta \max_j \max_i \Delta_i(k)} \quad (13)$$

Among them, $\Delta_i(j)$ is $|R_0(j)^* - r_i(j)|$, and ζ is the resolution coefficient, which takes a value in the interval $[0,1]$; typically, $\zeta = 0.5$ is chosen.

Determine the positive ideal solution s_0^+ and the negative ideal solution s_0^- of matrix S . Referring to the traditional construction approach mentioned above and combining it with grey relational theory, the calculation formulas are as follows:

$$s_0^+ = \max_{1 \leq i \leq n} s_i(j) = (s_0^+(1), s_0^+(2), \dots, s_0^+(m)) \quad (14)$$

$$s_0^- = \min_{1 \leq i \leq n} s_i(j) = (s_0^-(1), s_0^-(2), \dots, s_0^-(m)) \quad (15)$$

Among them, $s_i(j)$ represents the s_{ij} value calculated for each region.

Improve Formulas (9) and (10), and separately calculate the Euclidean distances from the low-altitude economic level of the i -th region to the positive ideal solution s_0^+ and the negative ideal solution s_0^- :

$$d_i^+ = \sqrt{\sum_{j=1}^m (s_i(j) - s_0^+(j))^2} \quad (16)$$

$$d_i^- = \sqrt{\sum_{j=1}^m (s_i(j) - s_0^-(j))^2} \quad (17)$$

Gray relational closeness degree of the low-altitude economic level in the calculation area:

$$G_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (18)$$

Based on the above calculations, we rank the low-altitude economic levels of this region; the region with the largest G_i has the highest level of low-altitude economic development.

4 SIMULATED DATA ANALYSIS AND RESULTS

4.1 Group Decision Matrix and Combined Weights

To evaluate the development level of the low-altitude economy in 12 regions (represented by S1, S2, S3, S4, S5, S6, S7, S8, S9, S10, S11, and S12, respectively).

Based on the comprehensive scores assigned by five simulation experts regarding the importance of evaluation indicators, an aggregated decision matrix H is formed within the first-level dimensions by taking the average. Matrix H is a 5×6 matrix, with columns corresponding sequentially to A1—Infrastructure and Airspace Resources, A2—Industry Scale and Supply Chain Collaboration, A3—Innovation Investment and Technology Transfer, A4—Talent and Service Support, A5—Open Scenarios and Market Demand, and A6—Policy Governance and Security Coordination. Using Formulas (1) through (7), the 5×34 third-level indicator score matrix is subjected to row normalization and relative entropy aggregation to obtain subjective weights. Combined with the entropy weighting method, objective weights are derived, and finally, the combined weights are obtained, see Table 2.

Table 2 First-Level Indicator Weights for Low-Altitude Economy Measurement

Expert	A1	A2	A3	A4	A5	A6
E1	4.683	3.833	4.171	3.58	4.04	4.54
E2	3.733	3.4	3.771	4.22	4.84	4.16
E3	4.05	3.767	3.986	4.48	3.5	3.9
E4	4.15	4.033	4.643	4.22	4.72	4.82
E5	3.617	3.9	4.6	4.06	3.92	4.0

The combined weights for the first-level dimensions are as follows: A1 = 0.180232, A2 = 0.142141, A3 = 0.225449, A4 = 0.161134, A5 = 0.130043, A6 = 0.161001, with a total of 1.000000. The results indicate that the composite weight of the innovation input and technology transfer dimensions is the highest, while the weights of the scenario openness and market demand dimensions are relatively lower.

4.2 Weighted Normalized Matrix and Optimal Indicator Set

Based on Formula (8) and the ranking according to the average grey relational degree of each indicator, we selected eight indicators to form the optimal grey relational indicator set $U_j^* = \{I9, I28, I18, I26, I12, I5, I8, I3\}$, which correspond respectively to tax contribution, operating revenue from demonstration scenarios, number of low-altitude economy patents granted, number of drone flights, local supporting rate, digital infrastructure coverage, value-added of the low-altitude economy industry, and number of low-altitude takeoff and landing sites. The corresponding reference sequence is $R = (0.013832, 0.020304, 0.019012, 0.024181, 0.016042, 0.025648, 0.026313, 0.029094)$, see Table 3.

Table 3 Selected Columns of the Weighted Normalized Matrix R

Unit	I09	I28	I18	I26	I12	I05	I08	I03
S01	0	0.003849	0.002923	0	0	0	0	0.002006
S02	0.003038	0.005187	0.006071	0.001832	0.002417	0.004815	0.006979	0.00301
S03	0.002226	0	0	0.001466	0.001046	0.002218	0.001852	0
S04	0.005757	0.01072	0.006463	0.010991	0.005319	0.008624	0.005809	0.006019
S05	0.002909	0.007063	0.007098	0.008793	0.003124	0.007986	0.008922	0.012039
S06	0.007171	0.011054	0.009781	0.016853	0.005503	0.015829	0.015844	0.019062
S07	0.008656	0.011283	0.01076	0.013922	0.005862	0.019357	0.017647	0.017055
S08	0.010039	0.011546	0.014112	0.019418	0.008101	0.021178	0.024911	0.025081
S09	0.01136	0.017374	0.014253	0.020884	0.008211	0.024407	0.019635	0.029094
S10	0.009864	0.014141	0.010422	0.016487	0.010101	0.020253	0.023399	0.022071
S11	0.013832	0.020304	0.019012	0.024181	0.016042	0.021488	0.026313	0.029094
S12	0.012105	0.01933	0.016161	0.024181	0.010357	0.025648	0.02344	0.028091

The table above shows the 8-column submatrix of R on U_j^* . The full R remains a 12×34 matrix. Taking S12 as an example, its corresponding row vector is (0.012105, 0.019330, 0.016161, 0.024181, 0.010357, 0.025648, 0.023440, 0.028091).

Euclidean distance between the positive and negative ideal solutions. According to Formulas (13) through (17), calculate the Euclidean distances d_i^+ and d_i^- from the evaluation unit to the positive ideal solution A^+ and the negative ideal solution A^- , respectively. Finally, use Formula (18) to determine the grey relational closeness degree, which is equivalent to the TOPSIS relative closeness degree, see Table 4.

Table 4 Simulated Distances, TOPSIS Relative Closeness, Grey-Relational Grade, and Final Score

Unit	D i+	D i-	C i	G i	F i
S01	0.166736	0.015151	0.0833	0.439789	0.261545
S02	0.161281	0.020238	0.111494	0.451987	0.281741
S03	0.168899	0.01018	0.056844	0.434166	0.245505

Unit	D i+	D i-	C i	G i	F i
S04	0.130761	0.050516	0.278668	0.50972	0.394194
S05	0.130019	0.051215	0.282592	0.507111	0.394852
S06	0.099995	0.078399	0.43947	0.571856	0.505663
S07	0.087829	0.09148	0.510179	0.608561	0.55937
S08	0.063881	0.117442	0.647696	0.69384	0.670768
S09	0.04027	0.14111	0.77798	0.790419	0.784199
S10	0.0422	0.138873	0.766944	0.771951	0.769447
S11	0.018814	0.16466	0.897456	0.92648	0.911968
S12	0.013381	0.167991	0.926225	0.943364	0.934795

5 DISCUSSION AND CONCLUSION

The findings of this study indicate that the level of development of the low-altitude economy depends not only on the size of the industry itself, but more importantly on whether a closed-loop system has been established in terms of airspace resources, application scenarios, innovation investment, talent services, and policy coordination. In other words, the comparative advantage of the low-altitude economy does not stem from isolated breakthroughs, but rather from the synergistic interplay of “supply capacity—demand-driven forces—institutional safeguards.”

This paper constructs a comprehensive evaluation framework for the development level of the low-altitude economy based on an improved GRA-TOPSIS method. It integrates and restructures aerospace industry chain indicators with low-altitude economy indicators, forming a comprehensive evaluation system comprising six first-level dimensions and 34 third-level indicators. The calculation results show that this system can effectively distinguish between different samples' development levels, and its overall scores demonstrate high consistency with the results obtained from TOPSIS and grey relational analysis.

The main contributions of this study are as follows: First, it expands the scope of indicators used to measure the low-altitude economy; second, it combines subjective and objective weighting with an improved GRA-TOPSIS approach, enhancing the stability and interpretability of the evaluation results; third, it provides a methodological template for future studies that use real-world data to conduct regional comparisons, policy evaluations, and evolutionary analyses.

COMPETING INTERESTS

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

FUNDING

This work was supported by the Chengdu Low-Altitude Economy High-Quality Development Research Center under the project titled "Research on the Measurement of Low-Altitude Economy Development Level and the Evaluation Index System for Regional Differentiation" (Grant No. CDDK200509).

REFERENCES

- [1] Qin X, Ma X. Several Issues Requiring Priority Attention in the Development of General Aviation in China. *China Civil Aviation*, 2009(11): 28-29.
- [2] Qin R, Li W, Jin J, et al. Low-Altitude Airspace and the Low-Altitude Economy from a Resource-Based Perspective. *Journal of Civil Aviation University of China*, 2011, 29(4): 56-60.
- [3] Qin R. Reconsidering the Low-Altitude Economy: Conceptual Definition and Structural Analysis. *Journal of Civil Aviation University of China*, 2023, 41(6): 59-64.
- [4] Zhang J, Xu Q. Constraints and Optimization Pathways for the Development of the Low-Altitude Economic Industry Chain. *Economic Review*, 2024(1): 67-74.
- [5] Qiao L, Huo D, Gu W, et al. Optimizing the Pathways for the Modernization of the Low-Altitude Economy: A Three-Dimensional Unmanned Flight Perspective. *Scientific Management Research*, 2025, 43(2): 29-38.
- [6] Lü R. The Background, Connotations, and Global Landscape of the Low-Altitude Economy. *People's Tribune: Academic Frontiers*, 2024(15): 45-56.
- [7] Zhuang Z. Artificial Intelligence-Enabled Low-Altitude Economy: Application Scenarios and Future Directions. *People's Tribune: Academic Frontiers*, 2024(15): 38-44.
- [8] Wang Q, Bai H, Gu S. Construction and Measurement of an Evaluation Indicator System for the Development Level of the Low-Altitude Economy in Zhejiang Province. *Statistics and Practice*, 2025(6): 27-30.
- [9] Tong P, Wang K. Measuring China's Low-Altitude Economic Development Level, Regional Disparities, and Influencing Factors. *Journal of Beijing Union University: Humanities and Social Sciences*, 2025: 1-15.
- [10] Shan L, Liu Y. A Study on the Coupling and Coordination Mechanism between Scientific and Technological Innovation Capability and the Development Level of the Low-Altitude Economy from the Perspective of New Quality Productive Forces. *Journal of Xi'an Aeronautical University*, 2024, 42(6): 1-11.
- [11] Bai R. The Impact of Enterprise Digitalization on Core Capabilities in the Low-Altitude Economy. *Shijiazhuang: Hebei Normal University*, 2025.

- [12] Zhou J. Digital Empowerment and the New Development of the Low-Altitude Economy. *Civil Aviation Management*, 2024(9): 35-37.
- [13] Zhao F, Wang H. Empowering the Rise of the Low-Altitude Economy through Digital and Intelligent Technologies. *Communication Enterprise Management*, 2024(3): 76-77.
- [14] Caetano M, Silva E J, Vieira D J, et al. Criteria Prioritization for Investment Policies in General Aviation Aerodromes. *Regional Science Policy & Practice*, 2022, 14(6): 211-233. DOI: 10.1111/rsp3.12538.
- [15] Finger D F, Bil C, Braun C. Initial Sizing Methodology for Hybrid-Electric General Aviation Aircraft. *Journal of Aircraft*, 2020, 57(2): 245-255. DOI: 10.2514/1.C035428.
- [16] Blickensderfer B L, Guinn T A, Lanicci J M, et al. Interpretability of Aviation Weather Information Displays for General Aviation. *Aerospace Medicine and Human Performance*, 2020, 91(4): 318-325.
- [17] Fuller J G, Hook L R. Effectiveness of Automatic Safety Systems in Reducing General Aviation Fatalities. *Journal of Aerospace Information Systems*, 2023, 20(5): 240-250.