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# Evaluation of Differentiated Development Levels in Multi-Airport System

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## Article

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## ABSTRACT

*The growing complexity of air transport systems highlights the rising importance of differentiated development within MAS. A multidimensional indicator system is developed, comprising two hierarchical layers and ten basic indicators encompassing airport attributes and route network characteristics, using a combined subjective–objective weighting approach. To quantify the influence of city characteristics on MAS differentiation, city developed coefficient and city distance coefficient are introduced. Furthermore, complex network theory and the DSC are applied to evaluate overlapping routes differentiation. Empirical analysis of the Beijing–Tianjin–Hebei MAS indicates that PKX and PEK exhibit the lowest level of comprehensive differentiation, whereas PKX and CDE demonstrate the highest. Both route network and comprehensive differentiation exhibit a bipolar distribution. Finally, targeted strategies are proposed for the Beijing–Tianjin–Hebei MAS to promote collaborative operations and coordinated development.*

## KEYWORDS

*differentiated development, MAS, multidimensional indicator system, DSC, complex network theory*

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## INTRODUCTION

With the rapid growth of China's civil aviation industry, a coordinated multi-airport system (MAS) has gradually emerged. Enhancing its operational efficiency and development model has become a pressing priority. However, while MAS expansion has increased aviation capacity, it has also created challenges such as unclear functional positioning, overlapping route networks, and inefficient resource utilization. Differentiated development is therefore essential to achieving efficient and coordinated operations.

Previous studies have explored this issue from various perspectives. Feldman[1] highlighted the need for airport differentiation to meet emerging trends. Adikariwattage[2] classified airports by passenger character-

istics and terminal scale, whereas Mayer[3] emphasized cargo-related functions. Jiang et al.[4] introduced an improved similarity coefficient to assess homogeneity in regional airport development. Guo et al.[5] established a multidimensional framework to evaluate homogeneity among airports within multi-airport regions. Huang[6] examined Shenzhen Airport's differentiated development within the Greater Bay Area. Hong et al.[7] developed indicators for small- and medium-sized airports in Jiangsu Province. Building on this framework, Wang et al.[8] proposed coordinated differentiation strategies for Henan's airports. Guo[9] offered global comparative insights into MAS evolution, and Sun et al.[10] proposed a scale-invariant metric to measure inter-airport similarity.

In summary, existing research largely adopts a single-dimensional approach, with limited attention to the influence of host cities. Therefore, this study adopts a multidimensional perspective, explicitly incorporating urban influences, and constructs a comprehensive evaluation framework that integrates urban characteristics. Combining qualitative and quantitative analyses, it provides both theoretical and empirical support for advancing the differentiated development of MAS.

### **MULTIDIMENSIONAL INDICATOR SYSTEM**

This study develops a three-level evaluation framework based on the core principles of the Analytic Hierarchy Process (AHP) to assess the differentiated development levels of MAS, as shown in Figure 1. The first level, the basic indicator layer, reflects differences in construction scale and operational characteristics among airports within the MAS. This layer comprises ten basic indicators: terminal area; number of aircraft parking bays; runway length; number of runways; passenger throughput; cargo throughput; aircraft movements; number of routes; number of overlapping routes; and the proportion of international to domestic routes. The second level, the guideline layer, aggregates indicators from the basic layer to form higher-level differentiation dimensions. This layer consists mainly of two dimensions: airport attribute, capturing differences in facilities, scale, and operational capacity; and route network, representing variations in route layout, network structure, and route type distribution. The third level, the objective layer, synthesises the comprehensive level of differentiated development. By integrating the results of the basic indicator and criterion layers comprehensively, this framework determines the level of differentiated development among airports within the MAS. This provides a theoretical basis for formulating targeted differentiation and coordinated operation strategies.

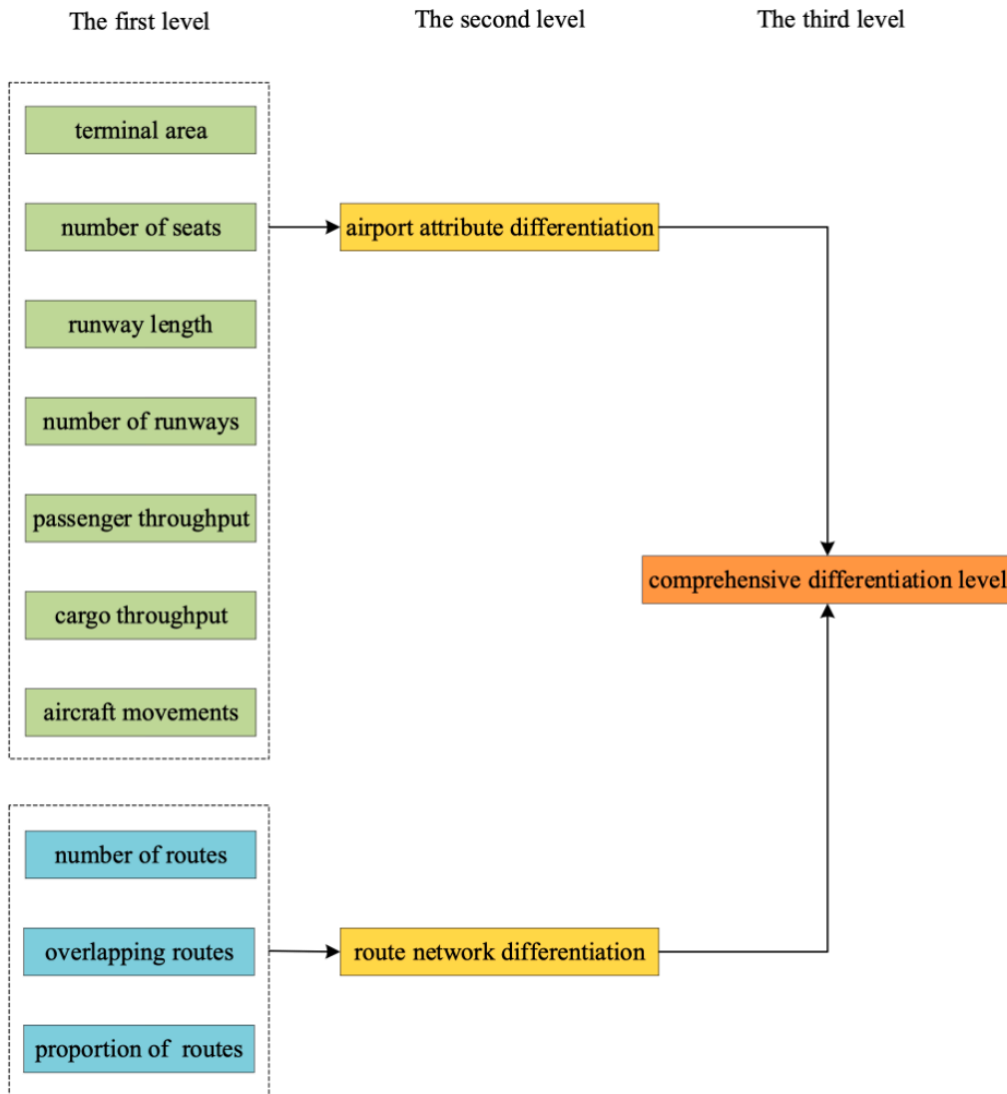


Figure 1. Evaluation system for the level of differentiated development of MAS

**EVALUATION METHODOLOGY**

Evaluating the differentiation levels of MAS involves using multiple indicators measured in different units. Directly conducting multi-indicator evaluations may result in biased or distorted outcomes. Data normalisation can eliminate the influence of differing measurement units. This study applies *Min – Max* normalisation to standardise the required data, as shown in Equation (1).

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{1}$$

**Combined weights**

This study takes an evaluation approach that combines subjective and objective methods. This balances both perspectives and mitigates any biases that could arise from using just one method. This approach improves the scientific rigour and rationality of the evaluation process, as shown in Equation (2).

$$W = \alpha w + (1 - \alpha)\bar{w} \quad (2)$$

Where  $W$  denotes the combined weight,  $w$  is the subjective weight,  $\bar{w}$  is the objective weight, and  $\alpha$  is the subjective weight coefficient, which is set to 0.5 in this study.

The objective weights are determined by the entropy weight method. The specific steps for calculating indicator weights using this method are presented in Equations (3)–(6). Assume there are  $m$  elements to be evaluated and  $n$  corresponding indicators. An evaluation matrix is then constructed based on the evaluation values of each element, denoted as  $R = (r'_{ij})_{m \times n}$ , where  $r'_{ij}$  represents the *Min – Max* normalised value of indicator  $j$  for element  $i$ .

$$R = \begin{pmatrix} r'_{11} & \cdots & r'_{1n} \\ \vdots & \ddots & \vdots \\ r'_{m1} & \cdots & r'_{mn} \end{pmatrix}_{m \times n} \quad (3)$$

$$p_{ij} = \frac{r'_{ij}}{\sum_{i=1}^m r'_{ij}} \quad (4)$$

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

$$\bar{w}_j = \frac{1 - e_j}{\sum_{j=1}^n (1 - e_j)} \quad (6)$$

### The differentiated development level of airport attribute

The level of socioeconomic development of the city in which an airport is located affects how airport attributes are distributed across the MAS. Therefore, this study introduces the city development coefficient  $c_{pq}$ , which is derived from the permanent resident population, regional GDP, per capita disposable income, and total value of imports and exports of the city where each airport is located, as shown in Equation (7)–(10).

$$h = \frac{\sum_{a=1}^A (c'_{ap} \times c'_{aq})}{\sqrt{\sum_{a=1}^A (c'_{ap})^2} \times \sqrt{\sum_{a=1}^A (c'_{aq})^2}} \tag{7}$$

$$c_d = \frac{\arccos(h)}{\pi} \tag{8}$$

$$c_l = \frac{\left| \sqrt{\sum_{a=1}^A (c'_{ap})^2} - \sqrt{\sum_{a=1}^A (c'_{aq})^2} \right|}{\sqrt{\sum_{a=1}^A (c'_{ap})^2} + \sqrt{\sum_{a=1}^A (c'_{aq})^2}} \tag{9}$$

$$c_{pq} = \sqrt{c_d^2 + c_l^2} + \varepsilon \tag{10}$$

Here,  $\varepsilon$  is a small constant introduced to prevent  $c_{pq} = 0$  when two airports are located in the same city. In this study, we set  $\varepsilon = 0.01$ .  $c'_{ap}$  and  $c'_{aq}$  denote the Min–Max normalized values of indicator  $a$  in the city development coefficient for airports  $p$  and  $q$ , respectively.

The degree of differentiation  $S_k$  of base indicator  $k$  under the airport attribute guideline layer is expressed in Equation (11), whereas the differentiated development level  $d_a$  of the airport attribute is presented in Equation (12).

$$S_k = c'_{pq} \times \frac{|k_p - k_q|}{\max(k_p, k_q)} \tag{11}$$

$$d_a = \sum W_k \times S_k \tag{12}$$

Where  $c'_{pq}$  represents the city development coefficient after *Min – Max* normalization, and  $W_k$  is the composite weight corresponding to indicator  $k$ .

**The differentiated development level of the route network**

This study establishes an airport route network model grounded in complex network theory. The model is represented as an undirected graph, in which each node corresponds to an airport and each edge represents a route connection between two airports. As illustrated in Figure 2, the route network model is defined as

$G = (V, E)$ , where  $V$  is the set of airports denoted as  $V = \{v_1, v_2, \dots, v_n\}$ ,  $E$  denotes the set of edges, represented as  $E = \{e_{pq} \mid v_p, v_q \in V, p \neq q\}$ .

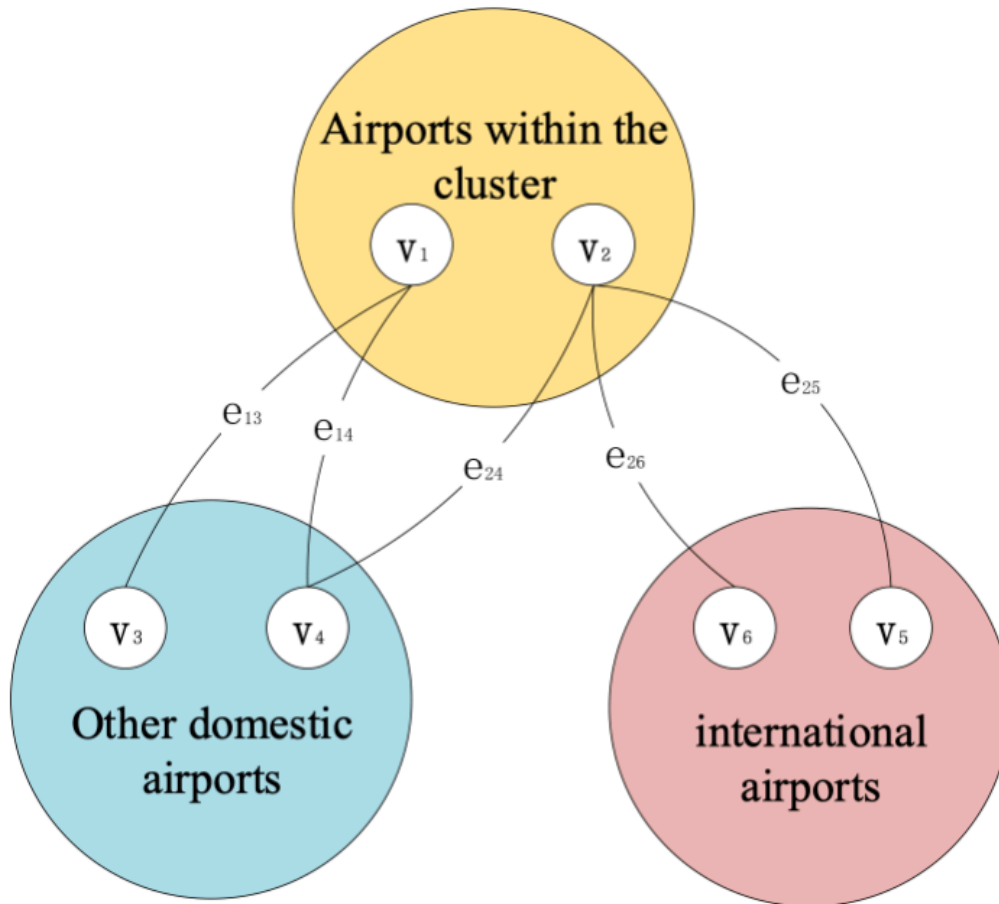


Figure 2. Airport cluster route network model

*City distance coefficient*

The spatial distance between airports affects the differentiated development of route networks. A shorter spatial distance indicates greater competition on identical or overlapping routes. Accordingly, this study introduces the airport–city distance coefficient  $d_{pq}$  to quantify the competitive intensity of route networks, as shown in Equation (13), where  $Dis_{pq}$  denotes the great-circle distance between Airports  $p$  and  $q$ .

$$d_{pq} = \ln(Dis_{pq}) \tag{13}$$

*Overlapping routes*

This study bases on the route network model and adopts the Dice Similarity Coefficient to quantify structural difference in overlapping routes within the network, as expressed in Equation (14).

$$Diff = 1 - Dice = 1 - \frac{2 \times [\Phi(p) \cap \Phi(q)]}{\varphi(p) + \varphi(q)} \quad (14)$$

Here,  $\Phi$  denotes the set of airport routes,  $\Phi(p) \cap \Phi(q)$  represents the set of overlapping routes between airports  $p$  and  $q$ , and  $\varphi(p)$  and  $\varphi(q)$  indicate the respective numbers of routes for airports  $p$  and  $q$ .

The differentiated development levels of overlapping routes should also account for intensity variations, as illustrated in Equation (15). Here,  $r_p$  denotes the proportion of passenger traffic on overlapping routes between Airports  $p$  and  $q$  relative to the total passenger traffic at Airport  $p$ , while  $r_q$  represents the corresponding proportion for Airport  $q$ .

$$T_{p \cap q} = \frac{|r_p - r_q|}{r_p + r_q} \quad (15)$$

The differentiated development levels of overlapping routes is presented in Equation (16).

$$S = d'_{pq} \times Diff \times T_{p \cap q} \quad (16)$$

The degree of differentiation  $S_v$  of basic indicator  $v$  under the route network guideline layer is expressed in Equation (17), whereas the differentiated development level  $d_h$  of the route network is presented in Equation (18).

$$S_v = \begin{cases} d'_{pq} \times \frac{|v_p - v_q|}{\max(v_p, v_q)} & \text{number of routes, proportion of routes} \\ d'_{pq} \times Diff \times T_{p \cap q} & \text{overlapping routes} \end{cases} \quad (17)$$

$$d_h = \sum W_v \times S_v \quad (18)$$

Where  $d'_{pq}$  represents the city distance coefficient after *Min – Max* normalization, and  $W_v$  is the composite weight corresponding to indicator  $v$ .

### Comprehensive differentiated development level

The comprehensive differentiation development level of the MAS is given by Equation (19), where  $W_a$  and  $W_h$  are the combined weights of the airport attribute and the route network guideline layer, respectively.

$$d = W_a \times d_a + W_h \times d_h \tag{19}$$

MAS should exhibit a hierarchical and functionally differentiated structure. Accordingly, they are categorized into hub and feeder airport layers, and a tiered classification scheme is developed based on the evaluation results to elucidate their operational characteristics, as presented in Table 1.

Table 1. Classification of Differentiated Development Levels

Differentiated development levels	Classification	Operational interpretation	
		Intra-layer	Inter-layer
0	No differentiation	No functional division within the layer; functions are completely homogeneous	No division between layers; the system is entirely homogeneous
(0,0.2]	Low differentiation	Airports within the layer tend to converge, with highly overlapping functions	Inter-layer division is indistinct; the system exhibits high redundancy
(0.2,0.4]	Relatively low differentiation	Limited differences exist within the layer, but overall similarity remains high	The system is transitioning from homogeneous competition to functional specialization
(0.4,0.6]	Moderate differentiation	Moderate intra-layer differentiation, balancing functional specialization and operational resilience	The system exhibits a relatively clear division of roles, though further improvement is needed
(0.6,0.8]	Relatively high differentiation	Intra-layer functional specialization is strengthened, but with potential risks to resilience	The system shows a clear division of roles, with moderate inter-layer differentiation
(0.8,1)	High differentiation	Excessive intra-layer differentiation leads to reduced risk resistance	Inter-layer division is further strengthened, but overall system resilience may decline
1	Complete differentiation	Airports within the layer operate independently, lacking risk-sharing capacity	Layers are fully decoupled, resulting in a fragile system

### RESULTS

To validate the applicability of the proposed evaluation framework, an empirical analysis is conducted using the Beijing–Tianjin–Hebei multi-airport system. By integrating the constructed indicator system and evaluation methodology, the differentiation levels of airport attributes, route networks, and overall system performance are systematically assessed.

The Beijing-Tianjin-Hebei region is a major political, economic, and cultural hub of China. The region contains nine airports, namely Capital International (PEK), Beijing Daxing International (PKX), Tianjin Binhai Interna-

tional (TSN), Zhengding (SJW), Beidaihe (BPE), Handan (HDG), Ningyuan (ZQZ), San'anhe (TVS), and Puning (CDE). As a result of the coordinated development strategy of the Beijing–Tianjin–Hebei region, this MAS plays a crucial role in China’s national civil aviation system.

This study collates data on the Beijing–Tianjin–Hebei MAS from 2019 to 2024, sourced from official platforms including NBSC and OAG, as shown in Table 2. The airport classification of the Beijing–Tianjin–Hebei MAS is shown in Table 3.

Table 2. Relevant Data of the MAS (Average from 2019 to 2024)

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
terminal area(10000m2)	78	141	36.4	20.9	1.1	2	1.9	0.6	0.5
number of aircraft parking bays	314	223	59	69	8	14	11	8	5
runway length(m)	3800	3800	3600	3400	2600	2600	3000	2700	2800
number of runways	3	4	2	1	1	1	1	1	1
passenger throughput(10000 passengers)	5722.8	4821.4	1793.9	1020.6	26.8	74.6	33.4	59.1	20.2
cargo throughput(tons)	1272007	296452	122407	57122	215	1128	121	451	100
aircraft movements	385266	306939	135761	77251	23906	11265	2956	6079	2244
number of routes	219	185	117	86	9	17	7	16	4

Table 3. The airport classification of the MAS

Layer	Airport
Hub airport	PEK
	PKX
	TSN
	SJW
Feeder airport	BPE
	HDG
	ZQZ
	TVS
	CDE

**Evaluation of differentiated development levels of airport attribute**

This study assumes that the subjective weights of the basic indicators within the airport attribute guideline layer are equal. The composite weights are shown in Table 4.

Table 4. Weights of indicators within the airport attribute

Basic indicator	Subjective weight	Objective weights	Combined weight
terminal area	1/7	0.15	0.14
number of seats	1/7	0.13	0.14
runway length	1/7	0.07	0.11
number of runways	1/7	0.18	0.16
passenger throughput	1/7	0.14	0.14
cargo throughput	1/7	0.21	0.18
aircraft movements	1/7	0.12	0.13

The urban development coefficients are presented in Table 5, from which the differentiation levels of each fundamental indicator for airport attributes can be derived, as shown in Tables6-12.

Table 5. City development coefficient

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.00	0.01	0.48	0.65	0.97	0.76	0.98	0.69	1.05
PKX	0.01	0.00	0.48	0.65	0.97	0.76	0.98	0.69	1.05
TSN	0.48	0.48	0.00	0.26	0.85	0.43	0.87	0.34	1.01
SJW	0.65	0.65	0.26	0.00	0.78	0.20	0.79	0.18	0.98
BPE	0.97	0.97	0.85	0.78	0.00	0.71	0.37	0.67	0.95
HDG	0.76	0.76	0.43	0.20	0.71	0.00	0.71	0.21	0.95
ZQZ	0.98	0.98	0.87	0.79	0.37	0.71	0.00	0.75	0.75
TVS	0.69	0.69	0.34	0.18	0.67	0.21	0.75	0.00	1.00
CDE	1.05	1.05	1.01	0.98	0.95	0.95	0.75	1.00	0.00

Table 6. Terminal area

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.004	0.242	0.453	0.910	0.708	0.908	0.654	0.994
PKX	0.004	0.000	0.336	0.528	0.915	0.717	0.919	0.656	0.996
TSN	0.242	0.336	0.000	0.106	0.788	0.390	0.787	0.321	0.949
SJW	0.453	0.528	0.106	0.000	0.707	0.172	0.683	0.168	0.909
BPE	0.910	0.915	0.788	0.707	0.000	0.316	0.159	0.266	0.479
HDG	0.708	0.717	0.390	0.172	0.316	0.000	0.020	0.140	0.681
ZQZ	0.908	0.919	0.787	0.683	0.159	0.020	0.000	0.486	0.532
TVS	0.654	0.656	0.321	0.168	0.266	0.140	0.486	0.000	0.184
CDE	0.994	0.996	0.949	0.909	0.479	0.681	0.532	0.184	0.000

Table 7. Number of seats

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.003	0.368	0.483	0.899	0.694	0.899	0.642	0.984
PKX	0.003	0.000	0.333	0.428	0.889	0.681	0.886	0.635	0.978
TSN	0.368	0.333	0.000	0.036	0.701	0.314	0.676	0.282	0.881
SJW	0.483	0.428	0.036	0.000	0.658	0.152	0.633	0.153	0.863
BPE	0.899	0.889	0.701	0.658	0.000	0.288	0.096	0.000	0.340
HDG	0.694	0.681	0.314	0.152	0.288	0.000	0.144	0.087	0.584
ZQZ	0.899	0.886	0.676	0.633	0.096	0.144	0.000	0.195	0.391
TVS	0.642	0.635	0.282	0.153	0.000	0.087	0.195	0.000	0.356
CDE	0.000	0.003	0.368	0.483	0.899	0.694	0.899	0.642	0.984

Table 8. Runway length

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.000	0.024	0.065	0.291	0.230	0.196	0.191	0.263
PKX	0.000	0.000	0.024	0.065	0.291	0.230	0.196	0.191	0.263
TSN	0.024	0.024	0.000	0.014	0.225	0.115	0.139	0.082	0.214
SJW	0.065	0.065	0.014	0.000	0.175	0.045	0.089	0.036	0.164
BPE	0.291	0.291	0.225	0.175	0.000	0.000	0.047	0.024	0.065
HDG	0.230	0.230	0.115	0.045	0.000	0.000	0.090	0.008	0.065
ZQZ	0.196	0.196	0.139	0.089	0.047	0.090	0.000	0.071	0.048
TVS	0.191	0.191	0.082	0.036	0.024	0.008	0.071	0.000	0.034
CDE	0.263	0.263	0.214	0.164	0.065	0.065	0.048	0.034	0.000

Table 9. Number of runways

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.002	0.151	0.413	0.615	0.485	0.621	0.439	0.667
PKX	0.002	0.000	0.226	0.465	0.692	0.545	0.699	0.494	0.750
TSN	0.151	0.226	0.000	0.124	0.406	0.206	0.416	0.163	0.481
SJW	0.413	0.465	0.124	0.000	0.000	0.000	0.000	0.000	0.000
BPE	0.615	0.692	0.406	0.000	0.000	0.000	0.000	0.000	0.000
HDG	0.485	0.545	0.206	0.000	0.000	0.000	0.000	0.000	0.000
ZQZ	0.621	0.699	0.416	0.000	0.000	0.000	0.000	0.000	0.000
TVS	0.439	0.494	0.163	0.000	0.000	0.000	0.000	0.000	0.000
CDE	0.667	0.750	0.481	0.000	0.000	0.000	0.000	0.000	0.000

Table 10. Passenger throughput

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.001	0.311	0.509	0.918	0.717	0.926	0.652	0.996
PKX	0.001	0.000	0.284	0.488	0.917	0.716	0.925	0.651	0.996
TSN	0.311	0.284	0.000	0.107	0.799	0.395	0.816	0.316	0.952
SJW	0.509	0.488	0.107	0.000	0.725	0.177	0.728	0.163	0.913
BPE	0.918	0.917	0.799	0.725	0.000	0.431	0.069	0.350	0.224
HDG	0.717	0.716	0.395	0.177	0.431	0.000	0.372	0.042	0.662
ZQZ	0.926	0.925	0.816	0.728	0.069	0.372	0.000	0.310	0.283
TVS	0.652	0.651	0.316	0.163	0.350	0.042	0.310	0.000	0.625
CDE	0.996	0.996	0.952	0.913	0.224	0.662	0.283	0.625	0.000

Table 11. Cargo throughput

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.007	0.409	0.592	0.922	0.726	0.931	0.659	1.000
PKX	0.007	0.000	0.266	0.500	0.921	0.724	0.931	0.658	1.000
TSN	0.409	0.266	0.000	0.132	0.810	0.409	0.830	0.325	0.962
SJW	0.592	0.500	0.132	0.000	0.742	0.187	0.751	0.172	0.929
BPE	0.922	0.921	0.810	0.742	0.000	0.544	0.154	0.335	0.488
HDG	0.726	0.724	0.409	0.187	0.544	0.000	0.602	0.122	0.828
ZQZ	0.931	0.931	0.830	0.751	0.154	0.602	0.000	0.522	0.126
TVS	0.659	0.658	0.325	0.172	0.335	0.122	0.522	0.000	0.740
CDE	1.000	1.000	0.962	0.929	0.488	0.828	0.126	0.740	0.000

Table 12. Aircraft movements

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.002	0.293	0.495	0.865	0.706	0.924	0.648	0.994
PKX	0.002	0.000	0.253	0.464	0.850	0.700	0.922	0.646	0.993
TSN	0.293	0.253	0.000	0.107	0.669	0.378	0.813	0.312	0.947
SJW	0.495	0.464	0.107	0.000	0.514	0.163	0.724	0.159	0.904
BPE	0.865	0.850	0.669	0.514	0.000	0.356	0.307	0.479	0.822
HDG	0.706	0.700	0.378	0.163	0.356	0.000	0.497	0.093	0.727
ZQZ	0.924	0.922	0.813	0.724	0.307	0.497	0.000	0.367	0.172
TVS	0.648	0.646	0.312	0.159	0.479	0.093	0.367	0.000	0.599
CDE	0.994	0.993	0.947	0.904	0.822	0.727	0.172	0.599	0.000

By integrating the differentiated development levels of basic indicators with their corresponding weights, the level of the airport attribute guideline layer is obtained, as shown in Table 13 and Figure 3. The results

indicate that the intra-layer differentiation levels of both the hub airport layer and the feeder airport layer are mainly concentrated in the relatively low differentiation, suggesting that a preliminary form of functional division has begun to emerge within each layer, but the overall division remains unclear and the degree of differentiation is still limited. Specifically, the score between PEK and PKX is as low as 0.003, which may be attributed to their shared location in Beijing and their roles as hub airports, resulting in highly similar airport attribute indicators and thus low differentiation. In contrast, TSN and SJW, with a score of 0.094, as well as HDG and TVS, with a score of 0.118, exhibit a high degree of functional convergence, indicating that their roles are highly similar. This highlights the urgent need to further clarify functional positioning and promote differentiated development paths among these airports. Meanwhile, the differentiation between hub and feeder airports is relatively high overall, indicating that the airport system has preliminarily established a relatively clear hierarchical division of roles, with well-defined cross-layer functional differentiation. Overall, at the airport attribute, the MAS has exhibited a certain degree of hierarchical specialization, while intra-layer differentiation still needs to be further strengthened.

Table 13. Airport attribute

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.003	0.267	0.447	0.790	0.622	0.791	0.567	0.861
PKX	0.003	0.000	0.253	0.434	0.800	0.630	0.803	0.574	0.874
TSN	0.267	0.253	0.000	0.094	0.643	0.322	0.656	0.263	0.786
SJW	0.447	0.434	0.094	0.000	0.512	0.130	0.525	0.123	0.679
BPE	0.790	0.800	0.643	0.512	0.000	0.289	0.118	0.212	0.348
HDG	0.622	0.630	0.322	0.130	0.289	0.000	0.258	0.072	0.520
ZQZ	0.791	0.803	0.656	0.525	0.118	0.258	0.000	0.288	0.219
TVS	0.567	0.574	0.263	0.123	0.212	0.072	0.288	0.000	0.378
CDE	0.861	0.874	0.786	0.679	0.348	0.520	0.219	0.378	0.000

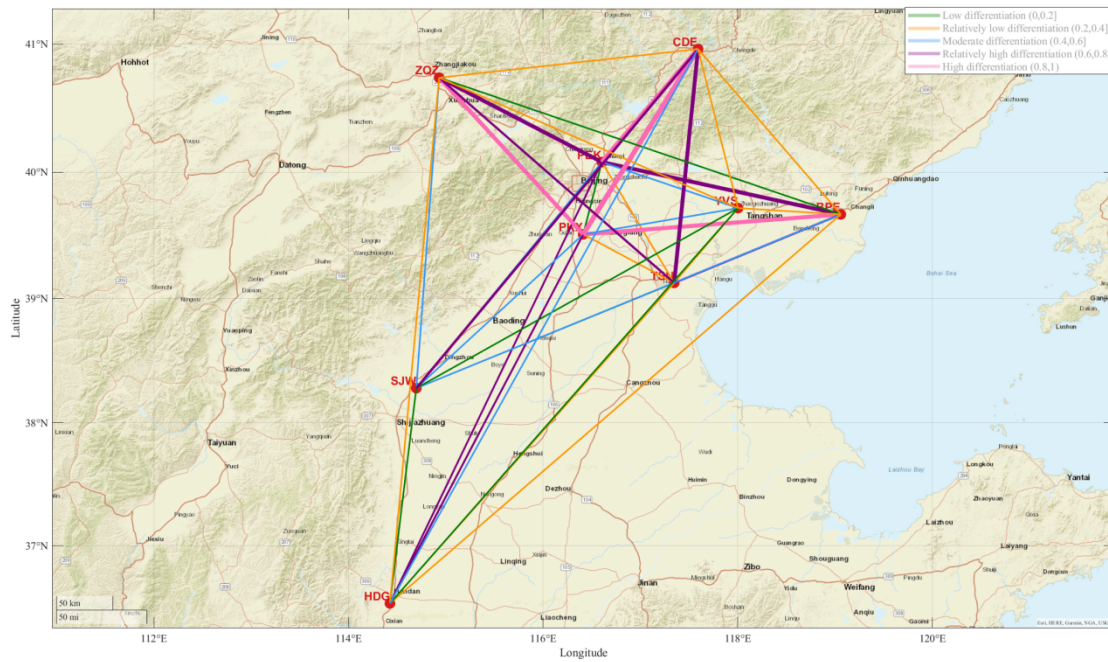


Figure 3. Airport attribute

Source: Figure was generated using MATLAB version.

**Evaluation of differentiated development levels of route network**

This study assumes that the subjective weights of the basic indicators within the route network guideline layer are equal. The composite weights are shown in Table 14.

Table 14. Weights of indicators within route network

Basic indicator	Subjective weight	Objective weights	Combined weight
number of routes	1/3	0.13	0.23
overlapping routes	1/3	0.46	0.4
proportion of routes	1/3	0.41	0.37

Table 15 presents the city distance coefficients. Figure 4 illustrates the route network of the Beijing–Tianjin–Hebei MAS, while Table 16-17 detail the structural and intensity differences in overlapping routes. Consequently, the differentiated development levels of each basic indicator can be derived, as shown in Tables 18-20.

Table 15. City distance coefficient

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.00	4.18	4.83	5.55	5.38	6.08	5.06	4.85	5.14
PKX	4.18	0.00	4.51	5.31	5.43	5.93	5.22	4.93	5.43
TSN	4.83	4.51	0.00	5.51	5.07	5.96	5.61	4.46	5.44
SJW	5.55	5.31	5.51	0.00	6.01	5.28	5.61	5.79	6.06
BPE	5.38	5.43	5.07	6.01	0.00	6.28	5.91	4.51	5.20
HDG	6.08	5.93	5.96	5.28	6.28	0.00	6.15	6.16	6.40
ZQZ	5.06	5.22	5.61	5.61	5.91	6.15	0.00	5.65	5.59
TVS	4.85	4.93	4.46	5.79	4.51	6.16	5.65	0.00	5.05
CDE	5.14	5.43	5.44	6.06	5.20	6.40	5.59	5.05	0.00



Figure 4. The route network of MAS

Source: Figure was sourced from the OAG <https://analytics.oag.com/analyser-client/home>.

Table 16. The structural differentiation

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.381	0.440	0.534	0.930	0.856	0.956	0.881	0.973
PKX	0.381	0.000	0.424	0.506	0.918	0.842	0.948	0.861	0.968
TSN	0.440	0.424	0.000	0.340	0.873	0.746	0.919	0.774	0.967
SJW	0.534	0.506	0.340	0.000	0.874	0.670	0.892	0.765	0.978
BPE	0.930	0.918	0.873	0.874	0.000	0.769	0.625	0.600	0.692
HDG	0.856	0.842	0.746	0.670	0.769	0.000	0.750	0.455	1.000
ZQZ	0.956	0.948	0.919	0.892	0.625	0.750	0.000	0.652	0.636
TVS	0.881	0.861	0.774	0.765	0.600	0.455	0.652	0.000	0.800
CDE	0.973	0.968	0.967	0.978	0.692	1.000	0.636	0.800	0.000

Table 17. The intensity differentiation

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.034	0.101	0.118	0.687	0.465	0.301	0.640	0.851
PKX	0.034	0.000	0.059	0.078	0.587	0.427	0.434	0.565	0.808
TSN	0.101	0.059	0.000	0.051	0.526	0.412	0.207	0.444	0.600
SJW	0.118	0.078	0.051	0.000	0.624	0.317	0.338	0.388	0.954
BPE	0.687	0.587	0.526	0.624	0.000	0.197	0.167	0.035	0.225
HDG	0.465	0.427	0.412	0.317	0.197	0.000	0.039	0.029	0.000
ZQZ	0.301	0.434	0.207	0.338	0.167	0.039	0.000	0.191	0.036
TVS	0.640	0.565	0.444	0.388	0.035	0.029	0.191	0.000	0.543
CDE	0.851	0.808	0.600	0.954	0.225	0.000	0.036	0.543	0.000

Table 18. Overlapping flight route

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.008	0.034	0.055	0.537	0.378	0.228	0.427	0.665
PKX	0.008	0.000	0.018	0.033	0.457	0.333	0.336	0.374	0.664
TSN	0.034	0.018	0.000	0.015	0.364	0.286	0.167	0.240	0.493
SJW	0.055	0.033	0.015	0.000	0.512	0.175	0.265	0.269	0.883
BPE	0.537	0.457	0.364	0.512	0.000	0.149	0.096	0.015	0.127
HDG	0.378	0.333	0.286	0.175	0.149	0.000	0.028	0.013	0.000
ZQZ	0.228	0.336	0.167	0.265	0.096	0.028	0.000	0.110	0.020
TVS	0.427	0.374	0.240	0.269	0.015	0.013	0.110	0.000	0.343
CDE	0.665	0.664	0.493	0.883	0.127	0.000	0.020	0.343	0.000

Table 19. Number of routes

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.101	0.351	0.527	0.806	0.877	0.766	0.702	0.789
PKX	0.101	0.000	0.259	0.444	0.807	0.841	0.786	0.704	0.830
TSN	0.351	0.259	0.000	0.228	0.731	0.796	0.824	0.602	0.821
SJW	0.527	0.444	0.228	0.000	0.841	0.662	0.806	0.737	0.903
BPE	0.806	0.807	0.731	0.841	0.000	0.462	0.205	0.308	0.452
HDG	0.877	0.841	0.796	0.662	0.462	0.000	0.566	0.057	0.765
ZQZ	0.766	0.786	0.824	0.806	0.205	0.566	0.000	0.497	0.374
TVS	0.702	0.704	0.602	0.737	0.308	0.057	0.497	0.000	0.592
CDE	0.789	0.830	0.821	0.903	0.452	0.765	0.374	0.592	0.000

Table 20. Proportion of routes

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.322	0.630	0.687	0.840	0.951	0.791	0.758	0.804
PKX	0.322	0.000	0.477	0.488	0.848	0.926	0.817	0.770	0.849
TSN	0.630	0.477	0.000	0.183	0.792	0.931	0.877	0.698	0.850
SJW	0.687	0.488	0.183	0.000	0.939	0.825	0.877	0.905	0.947
BPE	0.840	0.848	0.792	0.939	0.000	0.000	0.000	0.000	0.000
HDG	0.951	0.926	0.931	0.825	0.000	0.000	0.000	0.000	0.000
ZQZ	0.791	0.817	0.877	0.877	0.000	0.000	0.000	0.000	0.000
TVS	0.758	0.770	0.698	0.905	0.000	0.000	0.000	0.000	0.000
CDE	0.804	0.849	0.850	0.947	0.000	0.000	0.000	0.000	0.000

By integrating the differentiated development levels of basic indicators with their corresponding weights, the levels of the route network guideline layer is obtained, as shown in Table 21 and Figure 5. The results indicate that the average score of hub airports is approximately 0.26, suggesting that a preliminary form of functional division has emerged in their route networks, while the overall level of differentiation remains limited. Specifically, the differentiation value between PEK and PKX is only 0.146, which is significantly lower than the average level among hub airports, indicating a high degree of similarity and highlighting the need to further promote differentiated route network development. In contrast, the average score of feeder airports is approximately 0.13, reflecting a high degree of redundancy in their route networks. For example, the score between HDG and TVS is only 0.018, indicating highly similar route network characteristics and potential issues such as convergent route layouts and overlapping service markets. Meanwhile, the average score between hub and feeder airports is approximately 0.61, indicating that the multi-airport system has established a relatively clear hierarchical division of roles at the route network level, with distinct functional differentiation between hub and feeder airports. However, some airport pairs exhibit excessively high differentiation levels, such as SJW and CDE with a score of 0.911, which may weaken overall system resilience and is not conducive to risk sharing and coordinated operations.

Table 21. Route network

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.146	0.327	0.397	0.711	0.705	0.560	0.613	0.745
PKX	0.146	0.000	0.243	0.296	0.682	0.669	0.617	0.597	0.770
TSN	0.327	0.243	0.000	0.126	0.607	0.642	0.581	0.493	0.701
SJW	0.397	0.296	0.126	0.000	0.746	0.528	0.616	0.612	0.911
BPE	0.711	0.682	0.607	0.746	0.000	0.166	0.086	0.077	0.155
HDG	0.705	0.669	0.642	0.528	0.166	0.000	0.141	0.018	0.176
ZQZ	0.560	0.617	0.581	0.616	0.086	0.141	0.000	0.158	0.094
TVS	0.613	0.597	0.493	0.612	0.077	0.018	0.158	0.000	0.273
CDE	0.745	0.770	0.701	0.911	0.155	0.176	0.094	0.273	0.000

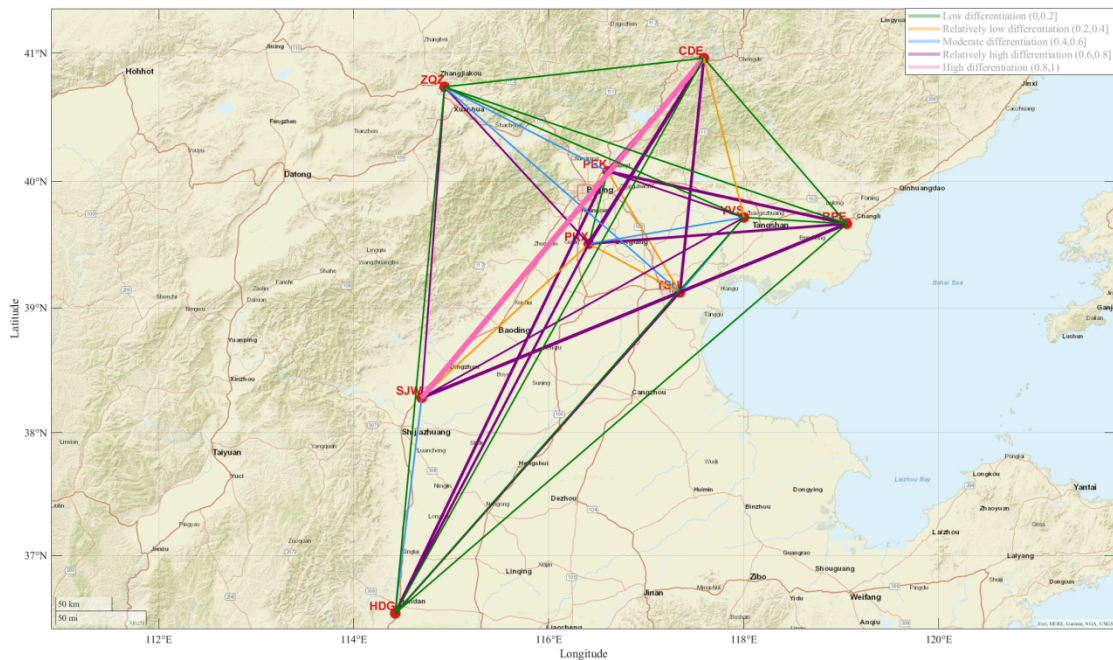


Figure 5. Route network

Source: Figure was generated using MATLAB version.

**Comprehensive differentiated development level of the Beijing–Tianjin–Hebei MAS**

This study operates under the assumption that the airport attribute and the route network are of equal importance. The combined weights are presented in Table 22

Table 22. Weights of guideline layers

Guideline layer	Subjective weight	Objective weights	Combined weight
airport attribute	1/2	0.44	0.47
route network	1/2	0.56	0.53

By integrating the levels of guideline layers with their corresponding weights, the comprehensive differentiated development level is obtained, as shown in Table 23 and Figure 6. The results indicate that the level of differentiation among hub airports is generally low. For instance, the score between PEK and PKX is only 0.079, and that between TSN and SJW is 0.111, suggesting that a clear division of functions among hub airports has not yet been established. Issues related to functional homogeneity and convergence in development trajectories remain evident. Similarly, the level of differentiation among feeder airports is also limited. For example, the score between HDG and TVS is as low as 0.044, and that between BPE and ZQZ is only 0.101, indicating that effective functional division and complementarity among these airports have yet to be achieved. In contrast, the differentiation between hub airports and regional airports is relatively pronounced, suggesting that the MAS has formed a certain degree of hierarchical structure. Overall, however, the Beijing–Tianjin–Hebei MAS has not yet established a coordinated development pattern with clear functional specialization. Although a hierarchical structure between hub and regional airports exists, the differentiation within each tier remains insufficient. Therefore, it is imperative to strengthen functional positioning and optimize route planning to promote differentiated development among airports, thereby fostering a coordinated, complementary, and orderly MAS.

Table 23. Comprehensive differentiated development

Airport	PEK	PKX	TSN	SJW	BPE	HDG	ZQZ	TVS	CDE
PEK	0.000	0.079	0.299	0.420	0.748	0.666	0.669	0.591	0.800
PKX	0.079	0.000	0.248	0.361	0.738	0.651	0.705	0.586	0.819
TSN	0.299	0.248	0.000	0.111	0.624	0.492	0.616	0.385	0.741
SJW	0.420	0.361	0.111	0.000	0.636	0.341	0.573	0.382	0.802
BPE	0.748	0.738	0.624	0.636	0.000	0.224	0.101	0.140	0.245
HDG	0.666	0.651	0.492	0.341	0.224	0.000	0.196	0.044	0.338
ZQZ	0.669	0.705	0.616	0.573	0.101	0.196	0.000	0.219	0.153
TVS	0.591	0.586	0.385	0.382	0.140	0.044	0.219	0.000	0.323
CDE	0.800	0.819	0.741	0.802	0.245	0.338	0.153	0.323	0.000



passengers. Meanwhile, airports can implement differentiated landing fees and service charges. Hub airports may maintain standard rates but focus on improving service quality, whereas non-hub airports could adopt flexible pricing or off-peak discount schemes. For instance, TSN and SJW could introduce off-peak discounts to encourage staggered flight scheduling and enhance resource utilization.

### (3) Developing Aviation-Related Industries

The aviation industry also includes sectors such as aircraft manufacturing and aviation logistics. Developing aviation-related industries can diversify development pathways and strengthen the overall competitiveness of MAS. For instance, the potential exists for BPE to expand into aviation leisure services, thereby enriching its tourism offerings. Similarly, TSN, with its robust maintenance base, could develop a comprehensive repair and supply chain. Moreover, the region as a whole could leverage seaport–rail–air integration to strengthen aviation logistics and dual-hub functions.

## CONCLUSION

This study evaluates the degree of differentiation within the MAS. By examining airport attribute and route network, a three-tier evaluation system is established. A combined objective–subjective weighting approach is used for systematic quantitative assessment. The Beijing–Tianjin–Hebei MAS was selected as a case study, and corresponding strategies and recommendations for differentiated development were proposed. The main findings are as follows: (1) At the airport attribute, a hierarchical division between hub airports and feeder airports has been established; however, differentiation among airports within the same layer remains insufficient, with only a preliminary form of functional division beginning to emerge. (2) At the route network, the intra-layer differentiation among both hub and feeder airports is generally low, indicating that functional complementarity within each layer needs to be further strengthened. Meanwhile, feeder airports overall lag behind hub airports in terms of development. Although the inter-layer differentiation is relatively well established, excessively high differentiation between certain airport pairs suggests the presence of potential operational risks. (3) At the comprehensive differentiation, although the MAS exhibits a clear hierarchical structure between hub and feeder airports, intra-layer development remains highly redundant. A well-defined pattern of functional differentiation has yet to be formed, indicating substantial room for improvement.

In summary, the proposed evaluation system effectively reveals the distinctive characteristics of airports within the MAS in terms of scale, function, and other dimensions. This system demonstrates strong validity

and adaptability. It also provides a theoretical basis for strategies on differentiated development and resource optimization, promoting coordination and complementarity within the MAS.

#### *Author Contributions*

Conceptualization – Zhijian Ye; methodology – Zhijian Ye; formal analysis – Ziyou Zhou; investigation – Zhijian Ye; resources – Ziyou Zhou; writing-original draft preparation – Zhijian Ye; writing-review and editing – Ziyou Zhou; visualization – Zhijian Ye; supervision – Zhijian Ye. All authors have read and agreed to the published version of the manuscript.

#### *Conflicts of Interest*

The authors declare no conflict of interest.

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