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Research Article

Synergetic Development Measure of Airport Groups Composite System and Its Influencing Factors Analysis: Some Evidence from China

Peiwen Zhang,[1] **Rui Ding**,[2] **Yu Wang**,[1] **and Qiaoyan Zhang**[3]

[1]*School of Economics and Management, Civil Aviation Flight University of China, Guanghan 618307, China*
[2]*School of Airport, Civil Aviation Flight University of China, Guanghan 618307, China*
[3]*School of Air Service and Tourism Management, Guilin University of Aerospace Technology, Guilin 541004, China*

Correspondence should be addressed to Yu Wang; wangyu@cafuc.edu.cn

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Whether airport groups develop synergistically has become a concern for the aviation industry. Existing studies have neglected the dynamic comprehensive evaluation and analysis of influencing factors of synergy degree. Taking the synergistic development of airport groups as the research perspective, we integrate the dynamic comprehensive evaluation model into the traditional synergy model. From two dimensions of airport development and regional economy, we measured the static synergy degree of the Chengdu-Chongqing airport group and the dynamic synergetic development degree on the overall time series. Further, using a spatial econometric model, we construct a distance economy-nested spatial weight matrix so as to explore the influence of each indicator on the synergy degree of the composite system. The results show that the overall synergy of the Chengdu-Chongqing airport group is above 0.5 in terms of static synergy degree. The clustering spectrum shows that the Chengdu-Chongqing airport group can be divided into three categories and basically forms the characteristic of "two main and multiple auxiliary airports." In terms of dynamic synergetic development degree and comprehensive evaluation value, the change speed of synergy degree is relatively smooth in the early stage and fluctuates in the later stage, and the overall dynamic evaluation value of the Chongqing regional airports is high. The effects of the explanatory variables of the airport group composite system on the synergy degree show more direct effects than spillover effects, and the direct effects are all positive feedback effects, while the negative spillover effects of the explanatory variables cannot be ignored.

1. Introduction

The airport is a critical component of air transportation [1]. Since the Five-Year Plan was announced in 2016, the scale system and market structure of China's civil aviation have undergone significant changes. The National Civil Transport Airport Layout Plan promulgated in 2017 proposed "an airport system led by the construction of world airport groups," which immediately triggered a research boom. The current focus of global civil aviation development revolves around airport groups. The development model of airport groups is of great significance to the high-quality development of airport systems and even the high-quality development of civil aviation [2]. The outline for national comprehensive transport network promulgated in February 2021 highlighted the Chengdu-Chongqing economic circle, as the fourth pole after Beijing-Tianjin-Hebei, the Yangtze River Delta, and Guangdong-Hong Kong-Macao Greater Bay Area should build an integrated comprehensive transportation hub system and promote the construction of aviation hubs.

The airport group is an original concept advocated and proposed by Chinese research academia. Closer to this concept are the metropolitan airport system proposed in the 1960s–1970s [3] and the multiairport system proposed in the 1970s–1980s [4]. A multiairport system refers to a set composed of two or more large airports and other airports within a metropolitan area [3, 4]. The airport group refers to the spatial group formed by the ground transportation connection between airports and cities in the region based on aviation demand, with one or more large airports as the core within a certain region [5]. Multiairport systems focus on the landscape, relationships, and organization of primary and secondary hub airports within metropolitan areas [4], and airport groups focus on the overall development relationships of airport systems within city groups.

Many foreign airport groups have been developed and improved, such as the London Airport Group and the New York Airport Group [6, 7]. Domestic airport groups are also developing rapidly, but there is a lack of synergistic development compared to foreign airport groups [8]. With the rapid development of large aeronautic hubs, the situation of unbalanced development among airports has become increasingly prominent. Guo et al. pointed out that there is homogeneity among large airport groups in terms of route network, operational level, and airport capacity. It is important to assess the degree of homogeneity of airport groups [9]. In 2022, the Chengdu Shuangliu Airport and the Chongqing Jiangbei Airport account for more than 50% of the total passenger and cargo and mail throughput, greatly inhibiting the development of other airports in the same region. The serious homogenization of large hub airports [5, 10] and the large gap between the sizes of small- and medium-sized airports [11] seriously affect the development of airport groups. Thus, how to realize the synergistic development between large hub airports and small- and medium-sized airports within the airport groups is an urgent issue to be solved. Assessing the synergy degree of airport groups and analyzing its influencing factors are rich in theoretical and practical significance for improving the synergy degree of airport groups.

In terms of research methods, synergy theory has received a lot of attention in other fields and is one of the characteristic frontier topics in management science. The main studies have focused on the exploration of synergistic issues among economic [12, 13], ecological [14], and resource [15] systems. Guo et al. divided regional carbon emissions into different subsystems and used a traditional synergy model to assess the overall regional synergy degree [16]. Wang and Wang construct a synergistic evaluation framework and quantitative model of coal capacity removal policies in horizontal, vertical, and temporal dimensions. However, the traditional synergy model does not dynamically evaluate the change speed as well as the change trend of synergy degree on time series [17]. This problem also exists in the study by Zhou et al. [18]. However, there are relatively few studies on the synergistic development of airport groups, and most of them simply assess the static synergy of the composite systems. For example, Shen et al. [19] constructed a synergy model of the Beijing-Tianjin-Hebei air logistics industry to analyze the synergy of the regional air logistics industry. In comprehensive evaluation, the speed of synergy change is very important [13]. Combining the composite system synergy model with the dynamic comprehensive evaluation model can better carry out the comprehensive evaluation from both static and dynamic perspectives [20–22]. For example, Dongri et al. analyzed the factors affecting the efficiency of resource allocation for technological innovation in the aerospace industry. Then, a dynamic comprehensive evaluation model is used to evaluate the resource allocation based on speed characteristics' perspective [20].

Current studies on foreign airports in the United States, European countries, and Japan include the optimization of airspace operations in airport groups of aerodromes [23], comparisons of operations among large international airport groups [24], and competitive relationships among airports within multiairport systems [7]. For example, Cheung et al. found that the United States focused on developing its major airports into global hubs, while Western Europe, Southeast Asia, and the Middle East focused on developing their large airports into global hubs [25]. Studies on airport clusters in China include research and recommendations on the synergistic development of the Yangtze River Delta Airport Group [10, 26, 27], the synergistic layout and construction of the Beijing-Tianjin-Hebei Airport Group [19, 28], and the coordinated competition among airport groups in the Guangdong-Hong Kong-Macao-Great Bay region [11]. Research on the synergistic development of airport group composite systems has mainly focused on the evaluation of the level of synergistic development of airport groups. Through the qualitative analysis of many factors limiting the synergistic development of airport groups and the comparison of domestic and foreign airport groups [28], suggestions were made to promote the synergistic development of airport groups [26, 27, 29]. Most studies mainly construct composite system index systems by considering multiple factors and using traditional synergy models [19, 30] or coupled synergy models [31, 32] to calculate the composite system synergy. For example, Yangmin et al. established an aviation-industry-city (AIC) index system by selecting positive and negative internal and external indicators and using the synergy model to calculate the composite system synergy using Zhengzhou Aviation City as a case study [30]. These findings have some implications for the synergistic development of airport groups but are limited to a rough evaluation of the synergy of the system. It can be found as follows: (1) the existing studies have only evaluated the static synergy degree of the airport groups at a certain point in time but lack a comprehensive evaluation of the synergetic development degree in the overall time series and (2) the existing studies have only derived the synergy degree or coupled synergy degree of the composite system, without further analyzing the influence of each index on the synergy degree.

For this reason, this study took the Chengdu-Chongqing airport group as the research object and constructed the airport group synergy evaluation index system. First, we analyzed the static synergy degree of the airport group. Then, we added a dynamic comprehensive evaluation model with speed characteristics to evaluate the synergy of airport groups in terms of time series. Finally, an innovative spatial econometric model is added so as to explore the influence of the composite system index system as an explanatory variable on the synergy degree. This study is intended to provide a reference for promoting the high-quality development of airport groups and optimizing the synergy of airport groups.

This paper is structured as follows: Section 2 constructs the composite system synergy model, incorporates the dynamic integrated evaluation model, and finally constructs the spatial econometric model. Section 3 measures the synergy degree of the composite system of the airport group and the dynamic comprehensive evaluation value. Section 4 analyzes the degree of influence of each indicator on the synergy degree, including the direct and indirect effects. Section 5 provides conclusions and policy recommendations.

2. Methods and Construction of the Indicator System

Based on the synergy theory proposed by physicist Harken, first, the traditional synergy degree model was used to calculate the static synergy degree of the composite system of the airport group; then, the dynamic comprehensive evaluation model [33] was incorporated into the synergy model to measure the state and trend of the synergy change rate and the dynamic comprehensive evaluation value of the airport group on the overall time series. Figure 1 visualizes these different steps.

2.1. Composite System Synergy Model. The composite system of the Chengdu-Chongqing airport group ($S = \{S_1, S_2\}$) consists of the airport development subsystem and the twin-city economic subsystem. S_1 is the airport development subsystem, and S_2 is the twin-city economic subsystem. The order parameter of the subsystem is $h_{ij} = (h_{i1}, h_{i2}, \ldots, h_{in})$, where i denotes the subsystem ($i = 1.2$) and n is the number of indicators affecting the operation of the system ($n \geq 1$).

2.1.1. Order Degree Model for Indicators. According to the principle of ordinal parametrization and the principle of servitude of synergy theory [23, 34], the order degree is taken as the state function of the ordinal parametrization to reflect the order degree of the system, as shown in the following equation:

$$\zeta_j(h_{ij}) = \begin{cases} \dfrac{(h_{ij} - \alpha_{ij})}{(\beta_{ij} - \alpha_{ij})}, (\text{where } h_{ij} \text{ is a positive orde r parameter}), \\ \dfrac{(\beta_{ij} - h_{ij})}{(\beta_{ij} - \alpha_{ij})}, (\text{where } h_{ij} \text{ is a negative orde r parameter}), \end{cases} \quad (1)$$

where α and β are the upper and lower bounds of the critical point-order parameter of system stability ($\alpha_{ij} \leq h_{ij} \leq \beta_{ij}$). To eliminate the influence of zero numerators on the results, this paper sets the variable range of the upper limit and lower limit to 10% [19].

2.1.2. Degree of Order Model for Subsystems. The "total contribution" of the order parameter variable h_{ij} to the order degree of the system S_i can be achieved by the integration of $\zeta(h_{ij})$, which is usually used to determine the order degree of the subsystem by the geometric mean method

$$\zeta_j(h_j) = \sqrt[n]{\prod_{i=1}^{n} \zeta_j(h_{ij})}, \quad (2)$$

where $\zeta_j(h_j) \in [0, 1]$, the larger $\zeta_j(h_j)$ is, the greater the contribution of h_j to the order of the system, the higher the order degree of the system, and vice versa.

2.1.3. Composite System Degree of Synergy Model. To measure the degree of smoothness of the system, we add the time dimension to the measurement of the composite system synergy. Assuming that the initial time is t_0, the orderliness of each subsystem is $\zeta_j^0(h_j)$ and the degree of the subsystem is $\zeta_j^k(h_j)$ at the moment $t_k (k = 1, 2, 3, \ldots, m)$. Thus, the synergy degree of the composite system at the moment t_k can be calculated as follows:

$$\begin{cases} C_k = \tau_k \sqrt[n]{\left| \prod_{j=1}^{n} \left[\zeta_j^k(h_j) - \zeta_j^0(h_j) \right] \right|}, \\ \tau_k = \dfrac{\min\left[\zeta_j^k(h_j) - \zeta_j^0(h_j) \neq 0 \right]}{\left| \min\left[\zeta_j^k(h_j) - \zeta_i^0(h_j) \neq 0 \right] \right|}. \end{cases} \quad (3)$$

The higher the value of $C_k \in [-1, 1]$, the higher will be the synergy of the composite system. C_k reflects the static result of the synergy of the composite system of the airport groups. The coefficient τ_k indicates that the composite system is in a state of synergistic development when and only when $\zeta_j^k(h_j) - \zeta_j^0(h_j) > 0$; conversely, from time t_0 to t_k, at least one subsystem does not achieve orderly development.

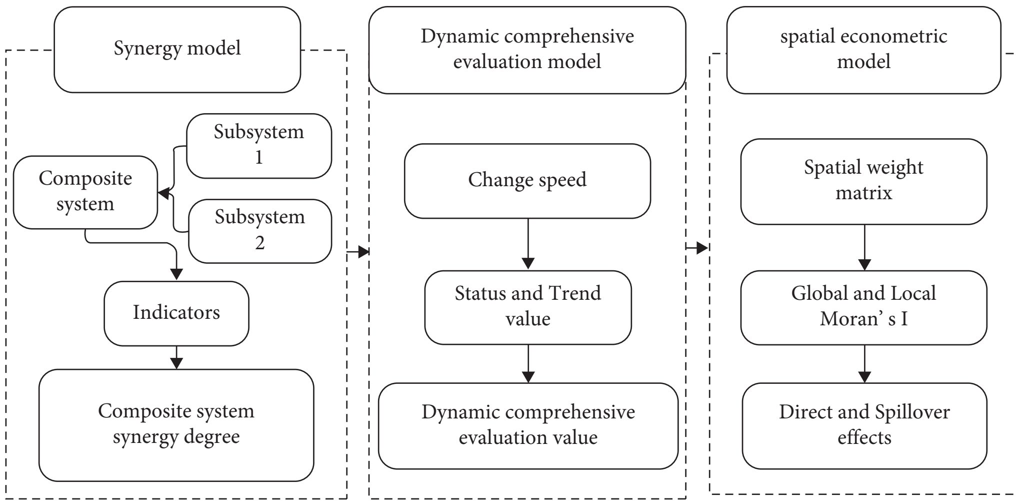

Figure 1: Flowchart of research methodology.

2.2. Dynamic Comprehensive Evaluation Model of Synergy

2.2.1. Timing Sequence Matrix of the Change Speed in Synergy Degree. Assuming that the change speed in synergy degree C_k in the time interval $[t_k, t_{k+1}]$ is V_{ik} $(i = 1, 2, \ldots, m; k = 1, 2, \ldots, h)$, then the temporal information matrix of the V_{ik} is as follows:

$$V = [V_{ik}]_{m\times l} = \begin{bmatrix} v_{11}-v_{12}-\cdots & v_{1l} \\ v_{21}-v_{22}-\cdots & v_{2l} \\ \vdots - \vdots - \ddots & \vdots \\ v_{m1}-v_{m2}-\cdots & v_{ml} \end{bmatrix}, \tag{4}$$

where $V_{ik} = (C_{i,k+1} - C_{ik})/(t_{k+1} - t_k)$. When the composite system synergy of the airport group is in a growing trend, the V_{ik} is positive. Conversely, the V_{ik} is negative if the composite system synergy remains unchanged, and the V_{ik} is 0.

2.2.2. The Dynamic Change Speed State Value. Assuming that the change speed of the composite system is uniformly variable, a multiperiod information agglomeration model of the status value of change speed will be formed according to the information agglomeration theory as follows:

$$\mu_i^v(t_k, t_{k+1}) = \int_{t_k}^{t_{k+1}} \left[v_{ik} + (t - t_k) \times \frac{v_{i,k+1} - v_{ik}}{t_{k+1} - t_k} \right] dt. \tag{5}$$

2.2.3. The Dynamic Change Speed Trend Value. Assume that a_{ik} is the linear growth rate of the change in speed in the interval $[t_k, t_{k+1}]$, i.e., the slope, the calculations are as follows:

$$a_{ik} = \begin{cases} 0, & t_{k+1} = 1, \\ \dfrac{v_{i,k+1} - v_{ik}}{t_{k+1} - t_k}, & t_{k+1} > 1, \end{cases} \tag{6}$$

where $(i = 1, 2, \ldots, m; k = 1, 2, \ldots, h - 1)$. Assuming that χ is a function of a_{ik}, the specific formula for the change speed trend value of the composite system is given as follows:

$$\chi(a_{ik}) = \frac{\omega}{1 + e^{-a_{ik}}}. \tag{7}$$

$\chi(a_{ik})$ is a monotonically increasing function. Let $\chi(a_{ik}) = 1$ when $a_{ik} = 0$ to find the constant $\omega = 2$. This function reflects the motivating effect of the change speed state value on the change speed trend value. When $a_{ik} > 0$, the number greater than 1 is multiplied by the change speed state value being evaluated, indicating that change speed with an upward trend is given incentives, while change speed with a downward trend is given penalties; when $a_{ik} = 0$, change speed value with a smooth trend is not treated.

2.2.4. Dynamic Comprehensive Evaluation Value of Synergy. Applying Newton's second law to the dynamic integrated evaluation, the dynamic comprehensive evaluation value combining the change speed state value and the change speed trend value can be obtained, which is expressed by equation (9):

$$\eta_i^* = \sum_{k}^{h-1} \mu_i^v(t_k, t_{k+1}) \times \chi(a_{ik}), \tag{8}$$

when $\eta_i^* > 0$, it means that the change speed of the composite system synergy in the period of $[t_1, t_l]$ shows a good increasing trend; when $\eta_i^* < 0$, it means that the change speed of the composite system synergy in the period of $[t_1, t_l]$ shows a decreasing trend; when $\eta_i^* = 0$, it means that the change speed of the composite system synergy in the period of $[t_1, t_l]$ shows a smooth trend.

2.3. Influencing Factor Analysis Method. The synergistic development of airport groups requires consideration of spatial factors. Airports within airport groups are susceptible to spatial direct and spillover effects from neighboring airports and the regions where the airports are located [35].

However, spatial econometric models can address spatial dependence effects, interaction effects, and network effects between neighboring geographic units. Therefore, this study used a spatial econometric model to analyze the influence of synergy degree. This accurately revealed the impact of each factor on the degree of synergy.

This study used a spatial panel data model. The general nested space model is given as follows:

$$\begin{cases} Y = \rho WY + X\beta + WX\theta + \mu, \\ \mu = \lambda W\mu + \varepsilon, \end{cases} \tag{9}$$

where Y is the explained variable, WY is the endogenous interaction effect existing between the explained variables, X is the explanatory variable, WX is the exogenous interaction effect existing between the explanatory variables, $W\mu$ is the interaction effect existing between different disturbance terms, ρ and λ represent the spatial autoregressive coefficients and spatial autocorrelation coefficients, which are parameters to be estimated, W represents the spatial weight matrix, and ε is the error term.

The following three models are used in this study, and the model degeneracy form is shown in Figure 2. The spatial autoregressive model (SAR) when $\theta = \lambda = 0$; the spatial Durbin model (SDM) when $\lambda = 0$; when $\rho = \theta = 0$ is the spatial error model (SEM), the optimal model is finally selected based on the relevant hypothesis tests.

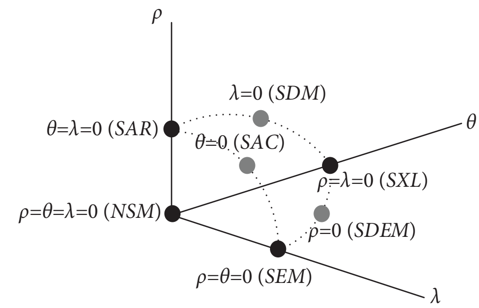

Figure 2: Degenerate forms of spatial econometric models.

2.4. Construction of the Indicator System and Data Sources. The development model of airport groups is a regional development model with strong vitality. Its goal is to sufficiently integrate the elements and resources of airport groups, coordinate the interests among airports, provide a harmonious industrial development space, and achieve leapfrog development and rapid rise. In addition, the composite system emphasizes synergistic development and integrates factors such as airports, airlines, and population as well as the economy to achieve common, synergistic, equitable, and efficient development of airport groups [30, 35].

The construction of an indicator system is a prerequisite for the quantitative evaluation of the system's state [36]. At present, many scholars have established synergy measurement models and conducted empirical studies, which provide some reference for the selection of order parameters in the indicator system [14, 19, 30]. In this paper, based on the existing synergy evaluation indicator system, key indicators that have an impact on the synergy degree are selected from the perspectives of airport development, airline operation, and economic development.

The airport development subsystem and the twin-city economic subsystem interact to form a composite system for the synergetic development of airport groups. Considering the complexity of airport synergetic development, indicators are selected from the perspectives of scientificity, comprehensiveness, and operability. The indicators of the airport development subsystem are selected from two perspectives: airport transportation scale and airport operation capacity. The airport transportation scale includes passenger throughput, cargo throughput, and aircraft take-off and landing sorties. The operational capacity of the airport includes the number of air routes and airlines. The development of the economy and civil aviation are complementary to each other. Economic status includes urban GDP and tertiary industry share. The consumption level includes per capita disposable income and resident population. The specific indicators are shown in Table 1.

Airport development subsystem data are obtained from the Civil Aviation Administration of China's Annual Airport Production Bulletin (2012–2022), the national airline launch flight schedule (2012–2022), and the official websites of airports. The data for the Twin Cities Economic Subsystem are obtained from the Chongqing Statistical Yearbook (2012–2022), the Sichuan Statistical Yearbook (2012–2022), and the China Statistical Yearbook (2012–2022). The short opening times of Chengdu Tianfu Airport and Chongqing Wushan Airport resulted in some missing data. Therefore, these airports are not considered in this study. There are statistical methods to compensate for a small number of missing data cases. To eliminate the influence of the magnitude factor, the Z-score is used to normalize the data.

3. Measurement of the Synergy of Composite Systems

3.1. Static Synergy Evaluation Analysis. The airport group composite system is influenced by many factors. Using the traditional synergy model, we can objectively measure the static synergy of airport groups. The Z-score function is used to standardize the index data, and the synergy of airports from 2012 to 2022 can be calculated in Table 2.

As shown in Table 2, the synergy degree of airports rises year by year. However, the synergy degree of most airports shows a different decline in 2019-2020, influenced by COVID-19, and it fluctuates between 2020 and 2022. The development of airports drives the economic development of the Chengdu-Chongqing region, while the economic development has a feedback adjustment effect on the development of airports. It is worth noting that the name of each airport is represented by the corresponding ICAO code, as shown in Table 3. Specifically, ZUUU and ZUCK, as international air hub airports, have been leading the synergy level over the years and have been on an upward trend. Their synergy degrees reached 0.7684 and 0.7666, respectively, in 2019.

Table 1: Index of the Chengdu-Chongqing airport group composite system order parameter.

Composite system	Subsystem	Characteristics	Order parameters	Unit
Airport group composite system (S)	Airport development subsystem (S_1)	Air transportation scale	Air passenger throughput (h_{11})	Person
			Air cargo throughput (h_{12})	ton
			Aircraft take-off and landing sorties (h_{13})	Sortie
		Operational capacity of the airport	The number of air routes (h_{14})	Strips
			The number of airlines (h_{15})	—
	Twin-city economic subsystem (S_2)	Economic status	Urban GDP (h_{21})	Yuan
			Tertiary industry share (h_{22})	%
		Consumption level	Per capita disposable income (h_{23})	Yuan
			Resident population (h_{24})	Person

Table 2: Synergy degree of the composite system of each airport in the Chengdu-Chongqing airport group.

Airport	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean value
ZUCK	0.1047	0.2486	0.3476	0.4527	0.4750	0.6475	0.7684	0.6541	0.7516	0.7432	0.5193
ZUUU	0.0303	0.1683	0.2660	0.3843	0.4806	0.5835	0.7666	0.6721	0.7366	0.6086	0.4697
ZUMY	0.0491	0.1671	0.1684	0.3409	0.3967	0.5589	0.6892	0.6167	0.6391	0.5596	0.4186
ZULZ	0.0777	0.1118	0.1354	0.2803	0.1621	−0.0927	0.6690	0.6710	0.6107	0.4190	0.3044
ZUYB	0.1175	0.1098	0.1915	0.1927	0.2653	0.4276	0.4218	0.5190	0.6297	0.5526	0.3427
ZUNC	−0.0373	0.1422	0.1316	0.2391	0.3127	0.4766	0.3863	0.2974	0.3083	0.3147	0.2572
ZUDX	0.1059	0.0755	0.2588	0.3540	0.2682	0.5493	0.5349	0.4036	0.4122	0.3657	0.3328
ZUWX	−0.0043	−0.0143	0.1157	0.1761	0.2909	0.4682	0.5324	0.5341	0.5501	0.4050	0.3054
ZUQJ	0.0953	0.1344	0.1869	0.1880	0.2712	0.4057	0.4158	0.7343	0.6528	0.4072	0.3492

Note. The name of each airport is replaced by the ICAO code (the name of the airport is replaced by the ICAO code in the latter part of the paper (see Table 3)).

ZULZ, ZUNC, ZUDX, ZUWX, and ZUQJ have a low average synergy degree. The synergy degree of ZULZ was at a low level in the early years, even negative in 2018, but close to ZUCK and ZUUU in 2019. This reason is due to the fact that ZULZ started its operations in September 2018. Compared to the Luzhou Lantian Airport (former ZULZ) before the relocation, ZULZ is larger and the safety issues due to airspace restrictions are resolved. Therefore, the synergy degree of ZULZ has increased dramatically. ZUQJ is not as large as ZUWX in size of the airport and throughput, but it has a higher average synergy than ZUWX. The reason is that since 2011, when Qianjiang Zhoubai Airport (the former ZUQJ) was renamed ZUQJ, the expansion of the airport and the addition of new routes have led to an increase in the overall business volume of the airport. The synergy degree of airports is closely related to the level of regional economic development.

The Chengdu-Chongqing airport group has formed the characteristic of "two main and many auxiliary airports." In order to better analyze the evaluation results, the recent synergetic development level of the Chengdu-Chongqing airport group in 2022 is selected for horizontal static analysis and the order degree of each airport in 2022 is analyzed by system clustering analysis. The results are shown in Figure 3.

As shown in Figure 3, the relationship of the Chengdu-Chongqing airport group can be divided into the following 3 categories: the first category is the highest synergy international hub airports, including ZUUU and ZUCK, which are large international hubs within the airport group and even nationwide. The second category is medium-sized airports with a high synergy degree, including ZUWX and ZUMY. The third category is small airports with low overall synergy, including ZUQJ, ZUDX, ZUNC, ZUYB, and ZULZ. Specifically, airports in Chongqing and Chengdu are distributed in all three categories, indicating that the distribution of airport types in Chongqing and Chengdu is relatively even. It shows the situation that large airports drive the development of small airports and coordinate the development of regional airports to form a positive interaction to promote the enhancement of synergy. More than half of the airports with low airport development subsystem indicators and economic indicators have a low degree of synergy. Generally speaking, airports with higher levels of scale and economic development have a higher degree of synergy.

Table 3: The full names of airports corresponding to the International Civil Aviation Organization airport (ICAO) code.

ICAO code	Airport
ZUCK	Chongqing Jiangbei International Airport
ZUUU	Chengdu Shuangliu International Airport
ZUMY	Mianyang Nanjiao Airport
ZULZ	Luzhou Yunlong Airport
ZUYB	Yibin Wuliangye Airport
ZUNC	Nanchong Gaoping Airport
ZUDX	Dazhou Heshi Airport
ZUWX	Wanzhou Wuqiao Airport
ZUQJ	Qianjiang Wulingshan Airport

3.2. Dynamic Synergy Evaluation Analysis. The static evaluation only reflects the synergistic development of the airport group in the time section; based on the static evaluation, dynamic comprehensive evaluation can further reveal the synergistic development and changes of the Chengdu-Chongqing airport composite system.

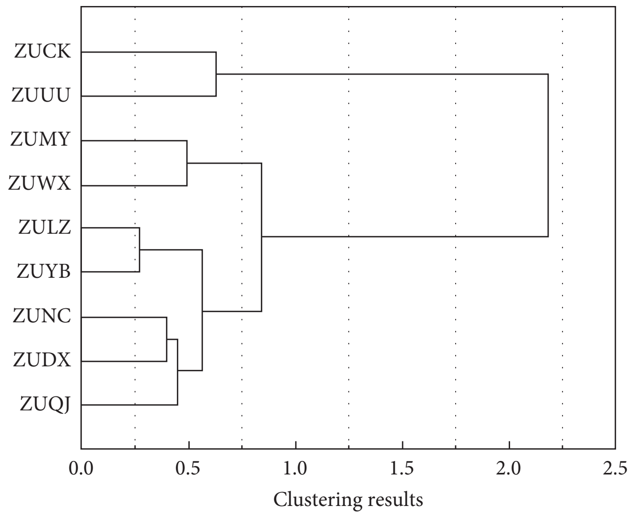

FIGURE 3: 2022 synergy clustering analysis results by airport.

As shown in Figure 4(a), the change speed of the synergy degree is basically in a stable stage in the early stage and there is no negative value, indicating that the synergy degree of each airport increases steadily, while the change speed fluctuates in the middle and late stages. The main reasons include the frequent heavy precipitation at ZUDX that affects the normal take-off and landing of aircraft, the relocation of ZUYB and ZULZ, and the extension of ZUNC. Impacted by COVID-19, the change speed decreases precipitously and reduces to negative values for almost all airports. The change speed shows varying degrees of fluctuation in 2020–2022. The larger the size and business volume of the airport are, the smoother the change speed curve and change speed state values in the time series would be. For example, the curves for ZUCK, ZUUU, and ZUMY are relatively smooth, while the other airports are more volatile. The change in speed state values implies acceleration in the level of synergistic development. In Figure 4(b), except for ZULZ, the change speed state values are basically stable throughout the time series and show a downward trend, decreasing to negative values in 2022. This indicates that the change speed of synergy degree has an upward trend throughout the time series and shows a downward trend at a later stage.

According to (6) and (7), the dynamic integrated evaluation value of the airport group on the time series is calculated and the final results are shown in Figure 5.

In Figure 5, the dynamic composite evaluation value of airport group synergy is positive in the time series, indicating that the synergy change of the Chengdu-Chongqing airport group shows an upward development.

Specifically, the dynamic comprehensive evaluation value varies somewhat from airport to airport. ZUCK and ZUUU have the highest dynamic comprehensive evaluation value, which is consistent with the static synergy analysis results for 2022. These two airports play a key role in promoting the in-depth synergy of the Chengdu-Chongqing airport group. In comparison, the dynamic evaluation results of airports in the Chengdu region vary widely. ZUMY and ZUYB show strong growth momentum, while ZULZ, ZUNC, and ZUDX have lower growth rates. ZUCK, ZUWX, and ZUQJ in the Chongqing region have higher dynamic comprehensive evaluation values. This is because Chongqing is the center of economy, finance, science and innovation, shipping and trade, and logistics in the upper reaches of the Yangtze River. It is also the largest industrial and commercial city in the southwest. It has developed the civil transportation industry to a high level with its resources and advantages. Therefore, the overall dynamic and comprehensive evaluation values show a higher development momentum.

4. Analysis of Factors Influencing the Degree of Synergy

4.1. Spatial Weight Matrix Construction. For the selection of relevant variables in the composite system of the Chengdu-Chongqing Airport Group from 2013 to 2022, the composite system index system has a total of 9 variables. Since the spatial weight matrix is a distance economy (GDP) nested, GDP (h_{21}) and disposable income per capita (h_{23}) have severe multicollinearity by VIF hypothesis testing. The explanatory variables (h_{21}) and (h_{23}) have VIF values of 62.51 and 51.29, respectively, which are much greater than 10 [37]. This seriously affects the reliability of the results. Therefore, the explanatory variables GDP (h_{21}) and disposable income per capita (h_{23}) were excluded before the spatial econometric regression [38]. The maximum value of VIF for the remaining 7 explanatory variables does not exceed 2.93.

The premise of spatial econometric analysis is to construct a weight matrix for the composite system. The current forms of spatial weight matrix mainly include neighboring weight matrix, geographic distance weight matrix, and economic distance weight matrix [28, 39]. While constructing the spatial weight matrix of the composite system of airport groups, it is necessary to consider the spatial connection between the airport and the city where the airport is located. After comparing multiple spatial weight matrices through experiments, we finally chose the nested weight matrix combining distance and economy. The nested matrix form is as follows:

$$\begin{cases} W = W_d \cdot \operatorname{diag}\left(\dfrac{\overline{X}_1}{\overline{X}}, \dfrac{\overline{X}_2}{\overline{X}}, \cdots, \dfrac{\overline{X}_n}{\overline{X}}\right), \\ \overline{X} = \dfrac{\sum_{i=1}^{n}\sum_{t_0}^{t_2} X_{it}}{n\left(t_1 - t_0 + 1\right)}, \\ \overline{X}_i = \dfrac{\sum_{t_0}^{t_1} X_{it}}{\left(t_1 - t_0 + 1\right)}, \end{cases} \tag{10}$$

where diag is the diagonal element matrix; $\overline{X}_i$ is the mean value of GDP for spatial cross-section i during the period t_0 to t_1; X is the mean value of spatial panel data GDP; W_d is the distance weight matrix, and the matrix elements take the values $W_{ij} = d_{ij}$; and d_{ij} is the great circle distance between two airports. The latitudes of airport i and airport j are φ_1

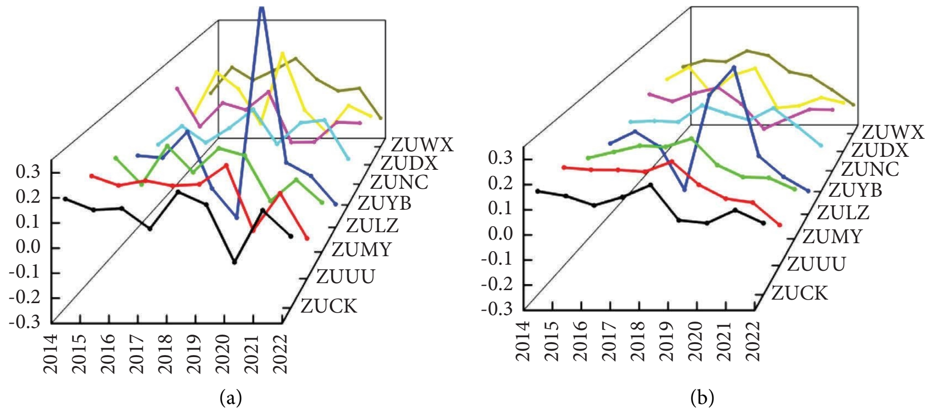

Figure 4: Composite system change speed value and the change speed state value. (a) The change speed value. (b) The change speed state value. (The years of the vertical coordinates of (a) and (b) in Figure 4, 2014 indicates 2013-2014, 2015 indicates 2014-2015, and so on).

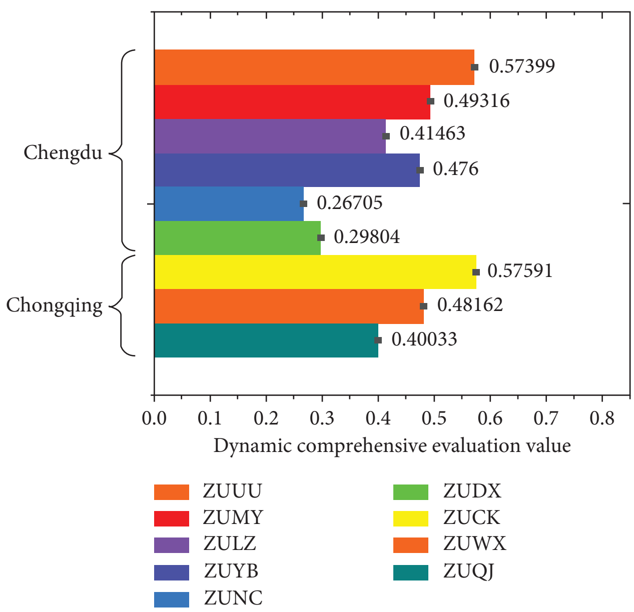

Figure 5: Airport group composite system dynamic comprehensive evaluation value.

and φ_2, the difference in longitude is ϖ, and the radius of the earth R is 6,371 km. The calculations are as follows:

$$d_{ij} = \begin{cases} R \times \arccos(\vartheta), \\ \vartheta = \cos\varphi_1 \cos\varphi_2 \cos\varpi + \sin\varphi_1 \sin\varphi_2. \end{cases} \quad (11)$$

4.2. Model Estimation and Testing. To analyze the spatial dependence of airport units, the global Moran's I index (Table 4) and local Moran's I index (Figure 6) of the synergy of 9 airports in the Chengdu-Chongqing airport group from 2013 to 2022 were calculated and the significance levels of the calculated results were tested (Table 4). The original hypothesis of no spatial autocorrelation is rejected at the significant level of 0.1 in most years, indicating that the Chengdu-Chongqing airport group shows a significant negative correlation or spatial dependence in economic space and geographical space.

Table 4: Global Moran's I index value of synergy.

Year	Moran's I	p value*
2013	−0.105	0.045*
2014	−0.215	0.029*
2015	−0.285	0.233
2016	−0.224	0.058*
2017	−0.039	0.049**
2018	−0.181	0.044*
2019	−0.150	0.001***
2020	−0.227	0.198
2021	−0.240	0.022**
2022	−0.299	0.030**

Note. *10% significance, **5% significance, and ***1% significance.

As shown in Figure 6, the synergy degree shows a negative spatial correlation. Therefore, the airports within the Chengdu-Chongqing airport group show spatial autocorrelation, and a spatial panel model needs to be constructed for analysis.

In Table 5, the LM test results under the nested matrix of distance and economy show that LM-Lag, LM-Error, Robust LM-Lag, and Robust LM-Error all pass the 10% significance test. It shows that the spatial Durbin model (SDM), the spatial autoregressive model (SAR), and the spatial error model (SEM) are applicable under the nested matrix; the Hausman test rejects the original hypothesis of using a random-effects model at the 1% significance level, so a fixed-effects model is used; meanwhile, the SAR and SEM models were tested by LR and Wald, and their statistical values all rejected the original hypothesis that the SDM model could be transformed into SAR and SEM models at 1%, 5%, and 10% significance levels, so the SDM under fixed effects, which is more suitable for the analysis of the impact factors of the Chengdu-Chongqing airport, was finally selected. Finally, the regression results of the SDM model for time fixed effects, spatial fixed effects, and spatial and time fixed effects show that the best for within is individual fixed ($R^2 = 0.9569$). Therefore, we finally chose the spatial Durbin model with individual fixed effects.

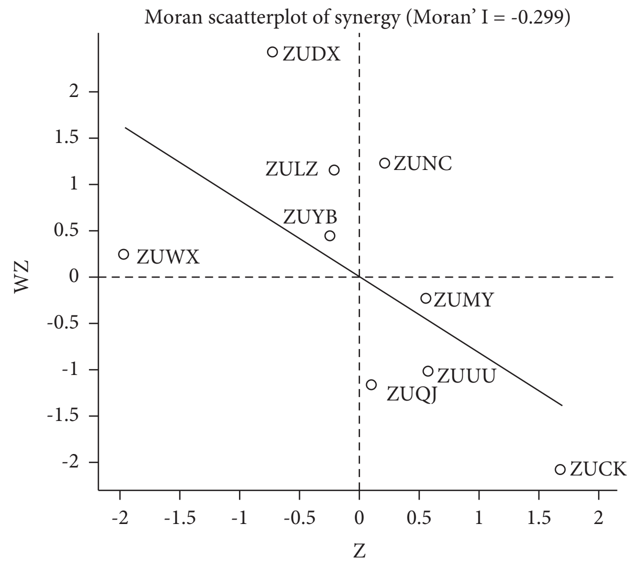

Figure 6: Moran's I scatterplot in 2019.

Table 5: Spatial econometric model test results.

Test	Nested weight matrix		
	Statistical values		p value
		LM test Spatial error (SEM)	
Lagrange multiplier	4.959		0.026*
Robust Lagrange multiplier	1.772		0.018*
		Spatial lag (SLM) or (SAR)	
Lagrange multiplier	5.691		0.017*
Robust Lagrange multiplier	2.505		0.011*
		Hausman test	
Ho: Difference in coefficients not systematic	16.92		0.018*
		LR test	
LR test (H0: SAR nested in SDM)	26.96		0.003**
LR test (H0: SEM nested in SDM)	59.67		≤0.001***
		Wald test	
Wald test for SAR	23.58		≤0.001***
Wald test for SEM	34.27		≤0.001**
		SDM regression	
	Within	Between	Overall
SDM with time fixed-effects	0.9176	0.9031	0.8987
SDM with spatial fixed-effects	0.9569	0.7017	0.9204
SDM with spatial and time fixed-effects	0.9481	0.7535	0.9122

Note. *10% significance; **5% significance; ***1% significance.

4.3. Decomposition of Spatial Measurement Effects. To further reveal the spatial influence of the explanatory variables on the synergy of the composite system, the spatial effect is decomposed through partial differential equations. The results are shown in Table 6.

The regression results of the direct effects and spillover effects under the distance economy nested weight matrix indicate the following:

(1) The influence of the direct effect is greater than that of the spillover effect. The explanatory variables all pass the significance test under direct effects, and only a small number of explanatory variables show significance in spillover effects. Taking h_{14} as an example, its direct effect on the synergy of one airport is very significant, while the spillover effect on neighboring airports is not significant. Specifically, for every 1% increase in the number of airport routes, the synergy of the airport will increase by 0.0416%; this is directly related to the connection characteristics of air routes. When an airport increases routes, the vast majority of airports are connected to airports outside the composite system, with a little spillover effect on neighboring airports.

Table 6: SDM model effect analysis of the factors influencing synergy.

Variables	Direct effects	Spillover effects
Air passenger throughput (h_{11})	0.2853*** (0.0345)	−0.1941*** (0.0600)
Air cargo throughput (h_{12})	0.2003*** (0.0218)	0.1803** (0.0598)
Aircraft movements (h_{13})	0.1294*** (0.0200)	0.0517* (0.0421)
The number of air routes (h_{14})	0.0416*** (0.0346)	0.0147 (0.0518)
The number of airlines (h_{15})	0.1866*** (0.0250)	0.0193 (0.0425)
Urban GDP (h_{21})	—	—
Tertiary industry share (h_{22})	0.1554*** (0.0413)	0.1151 (0.0554)
Per capita disposable income (h_{23})	—	—
Resident population (h_{24})	0.1659*** (0.0216)	−0.0238 (0.0537)

Note. Values in parentheses are standard deviations; *10% significance; **5% significance; ***1% significance.

(2) The direct effects of the explanatory variables on airport synergy are all positive feedback effects. In comparison, h_{11} has the greatest effect on synergy degree. For each 1% increase in passenger throughput, the synergy of the airport will increase by 0.2853%, indicating that h_{11} has an extremely strong positive feedback effect. h_{12}, h_{13}, h_{14}, h_{15}, and h_{22} have positive feedback effects on synergy at varying levels, h_{14} has the least effect on the synergy, and for every 1% increase in the constant population, the airport synergy will increase by 0.0416%.

(3) The negative spillover effects of the explanatory variables cannot be ignored. Taking h_{11} as an example, its spillover effect has a negative effect, for every 1% increase in h_{11}, the synergy of the airport will increase by 0.1853%, and the synergy degree of neighboring airports will decrease by 0.1941%. When passenger throughput increases at one airport, the airport has no or few connecting air routes to neighboring airports, and then the neighboring airports lose that portion of the passenger market. The negative spillover effect of passenger throughput is most directly manifested in the competition between airports within the airport group.

5. Conclusion and Implications

5.1. Conclusion. This paper combines the synergy model with the dynamic comprehensive evaluation model to analyze the synergistic development status of the Chengdu-Chongqing airport group from two perspectives: static and dynamic. Further, the economic distance weight matrix is constructed, and the spatial econometric model is used to decompose the effects of the explanatory variables in the index system. The findings are as follows:

(1) From the static evaluation results, the average synergy of airports is low due to COVID-19, but ZUCK and ZUUU are in the top two. The clustering results of the airport group in 2022 show that the airports in the Chengdu-Chongqing airport group can be divided into three categories, basically forming the feature of “two main and many auxiliary airports.”

(2) The dynamic comprehensive evaluation results show that change speed of synergy is relatively stable in the first period and fluctuates in the later period. ZUCK and ZUUU have the highest dynamic comprehensive evaluation values. There are large differences in the values of airports in the Chengdu region, and the values in the Chongqing region are higher. The rate of increase in the synergy of the Chengdu-Chongqing airport group is not stable in the time series, and the dynamic comprehensive evaluation value varies widely.

(3) The explanatory variables of the airport group have a greater direct effect than the spillover effect on synergy. Most of the explanatory variables for an airport directly affect the airport where it is located and less frequently affect other airports. Air passenger throughput has a very high positive feedback effect, while the number of airlines has the lowest positive feedback effect. The negative spillover effect of the explanatory variables cannot be ignored, and the negative spillover effect is most directly manifested in the competition among airports.

5.2. Policy Implications. Based on the abovementioned findings, this paper argues that to comprehensively improve the level of synergy development of the Chengdu-Chongqing airport group, the characteristics of the static and dynamic evaluation results of different airports need to be considered. The direct and spillover effects of each index on the degree of synergy are equally important. Therefore, the differentiated development strategies are targeted from the abovementioned perspectives.

(1) Airports with high static and dynamic evaluation results (e.g., ZUCK and ZUUU) should continue to take advantage of the airport's conditions and the resources of the region. At the same time, the hub distribution function should be enhanced to further improve the synergy of the airport group, while avoiding vicious competition in terms of market resources. This will lead to a good situation of "clear division of labor and moderate competition."

(2) For airports with a high static evaluation value but a low dynamic evaluation value (e.g., ZULZ and ZUYB, located in southern Sichuan), they should continue to radiate to southern Sichuan and northern Guizhou, western Chongqing, and eastern Yunnan. At the same time, the synergistic operation among airports should be strengthened to accelerate the development of the airport into an important aviation hub in the combined areas of Sichuan, Yunnan, Guizhou, and Chongqing.

(3) For airports with medium static and dynamic comprehensive evaluation values, they should continue to improve their airport synergy degree in many ways. The airport maintains a coordinated linkage and continues healthy development. Under the conditions that the existing airlines support, the potential of the market should be fully explored and the capacity and efficiency should be continuously expanded.

In this study, the synergy degree of airport groups is first analyzed statically and then evaluated on an overall time series. Second, a comprehensive dynamic evaluation model with speed characteristics is incorporated. Finally, a spatial econometric model is incorporated to explore the influence of explanatory variables on the degree of synergy. It has important theoretical significance for the innovation of research methods. It is of great practical significance in promoting the high-quality development of airport clusters and providing references for optimizing the synergistic development of airport groups.

Our study has some limitations that can be addressed in future studies. Our index system is divided into two parts, and the synergy of airport groups can be evaluated from more perspectives in the future. In addition, studying the synergy of airport groups from the perspective of passengers' travel choices is also an important direction.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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