Efficiency Evaluation of China's Large International Hub Airports Based on the DEA-Malmquist Model

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DOI: https://doi.org/10.30211/JIC.202503.001

Submitted: Feb. 02, 2025 Accepted: Mar. 25, 2025

ABSTRACT

China's civil aviation industry is in a rapid development phase. Concomitantly, civil airports are actively engaged in large - scale renovation and expansion projects. In this context, conducting targeted research and evaluation on airport operational efficiency, clarifying the key objects and projects for improvement, holds great practical significance. These can effectively promote the high - quality development of the civil aviation industry. Therefore, this paper conducts an in - depth evaluation and analysis of the operational efficiency of 18 large - scale international hub airports in China by employing the DEA - Malmquist model. Through the decomposition of the total factor productivity index (TFP), the operational efficiency of these airports and its dynamic changes are systematically evaluated from four dimensions: technical progress efficiency index (TC), comprehensive technical efficiency index (EFFC), pure technical efficiency index (PTEC), and scale efficiency index(SEC).The results indicate that the overall operational efficiency of large international hub airports in China is on the rise; however, the growth rate has decelerated. Technological progress emerges as the primary factor influencing the operational efficiency of large international hub airports in China, while the enhancement of comprehensive technical efficiency exerts a relatively minor impact on the overall efficiency. A substantial disparity exists in the operational efficiency among large international hub airports, and there is no direct correlation between the rate of improvement in airport operational efficiency and the size of the city where the airport is located.

Keywords: Large international hub airports in China, Operational efficiency, DEA-Malmquist index model, Total factor productivity

1. Introduction

Against the backdrop of globalization and economic integration, international aviation hubs, serving as crucial nodes connecting the global network, exert a profound influence on national economic development, the enhancement of international competitiveness and regional coordination.

The construction of international aviation hubs in China represents not merely a pivotal measure to boost economic growth, facilitate international trade, and attract foreign investment, but also serves as a significant pillar for optimizing the transportation network, promoting the development of the tourism industry and strengthening emergency response capabilities. Moreover, the development of international aviation hubs plays a vital role in driving scientific and technological innovation, facilitating cultural exchanges and elevating the country's international image. The ‘Guidance on Promoting the Construction of International Aviation Hubs’ sets forth the requirement to reinforce the construction of the functional system of international aviation hubs and to augment the all-round gateway complex function of international aviation hubs such as Beijing, Shanghai and Guangzhou. An international aviation hub constitutes the core node of the air - transport service system, with the airport acting as its operational carrier 錯誤! 找不到参照來源。. Driven by the rapid development of society and economy, China's air transport industry has been on a continuous and rapid development trajectory. Currently, the total turnover of civil aviation transportation, passenger turnover, and cargo and mail turnover in China rank second globally 錯誤! 找不到参照來源。. To satisfy the rapidly growing travel demands of the people, the number of new airport construction projects and airport expansion initiatives in China has been gradually increasing. During the 13th Five - Year Plan period, the number of runways in China increased by 41, and the number of civil transport airports grew from 207 in 2015 to 241 in 2020. As stipulated in the ‘14th Five-Year Plan’, by 2025, the number of civil transport airports in China is expected to reach 270, and the number of runways at transport airports will increase to 305. Moreover, the number of key construction projects at transport airports will reach 140 during the 14th Five-Year Plan period 錯誤! 找不到参照來源。.However, while mere expansion can temporarily alleviate resource constraints, large airports like those in Beijing, Shanghai, and Guangzhou still encounter time - related constraints and spillover effects. Airport operational efficiency is an all - encompassing and multi - level concept, which comprehensively reflects the overall capabilities of airport operations 錯誤! 找不到参照來源。錯誤! 找不到参照來源。.In the specific air transport market environment and under the established airport management model, airport operational efficiency is manifested in the following aspects. Firstly, compared with similar airports in other countries or regions, the airport can more effectively ensure the public safety of passengers and offer higher - quality services, demonstrating a more advanced level of overall operation. Secondly, it is reflected in a higher level of productivity and management compared to competitors or its own past performance, thereby generating more revenue. Therefore, apart from expansion, it is equally essential to conduct an analysis of airport operational efficiency, pinpoint the deficiencies that impede efficiency and implement a targeted optimization of resource allocation to avert resource wastage and effectively enhance the overall operational efficiency of airports. Furthermore, in the context of the increasingly intense competition in the global air transport sector, enhancing the operational efficiency of international aviation hubs has become of utmost importance. An efficient operation not only cuts down on operating costs but also bolsters the global competitiveness of the hub and propels the sustainable development of the regional economy. Therefore, it is imperative to establish a rational index system and evaluation model to conduct an in

- depth study on the construction of China's international aviation hubs and their operational efficiency. This research holds significant importance for achieving the construction of the ‘Four - Type Airports’, ensuring the sustained and healthy development of the civil aviation industry and enhancing the competitiveness of international aviation hubs.

2. Literature review

2.1 Selection of Indicators for Measuring Airport Operational Efficiency

In the current literature on airport operational efficiency, the output indicators are relatively consistent. Whether considering from a financial perspective or an infrastructure perspective, scholars both domestically and internationally take the three traditional civil aviation indicators, namely passenger throughput, cargo and mail throughput, the number of aircraft take - offs and landings as output indicators. As research theories and findings have become increasingly enriched, related studies have started to take non - expected outputs into account, such as carbon emissions, the annual number of passenger complaints, the percentage of flight delays, flight delay duration and average departure delay time 錯誤！找不到參照來源。錯誤！找不到參照來源。錯誤！找不到參照來源。.

Nevertheless, owing to the diverse research objectives of scholars, the input indicators exhibit greater diversification. Wang，Z.B. considered operating costs, the number of employees, the number of gates, the number of runways, etc.錯誤！找不到參照來源。. Chu, Y.C. considered the number of available seats, seat kilometers, etc. as input indicators 錯誤！找不到參照來源。. Wei, W. considered the area of airports, terminals, aprons, runways, etc. as input indicators and classified the output indicators into desired and non-desired outputs 錯誤！找不到參照來源。. Zhang, P.W. considered the labour force, fuel and the number of aircraft as input indicators 錯誤！找不到參照來源。. Hasan et al. carried out a systematic evaluation study on the operational effectiveness of major airports in Turkey, and established a system for evaluating airport operational effectiveness, which encompasses the length of the runway, the number of runways, passenger throughput, cargo and mail throughput, and the number of near - airplane slots 錯誤！找不到參照來源。.

Generally, based on the diverse research focuses of scholars, input indicators can be broadly classified into two categories. One category gives preference to financial and other software - related aspects as input indicators, while the other places emphasis on infrastructure construction as input indicators. In the realm of infrastructure, scholars commonly concur that the terminal area, apron area, number of aircraft slots, cargo terminal area, and the like are input indicators.

2.2 Airport Operational Efficiency Measurement Methodology

In the 1990s, numerous foreign scholars conducted research on airport operational efficiency. They assessed the operational status of airports by constructing diverse airport evaluation systems, aiming to assist airports in identifying the factors influencing their operational efficiency 錯誤！找不到參照來源。. Data Envelopment Analysis (DEA) is a non-parametric statistical method for evaluating the relative efficiency of multi-input and multi-output decision-making units, which avoids the influence of subjective factors on the evaluation results and has been widely used in academia. Gillen et al. pioneered the use of DEA methodology to scientifically evaluate the operational efficiency of airports 錯誤! 找不到參照來源。. In order to analyze the operational efficiency of Chinese airports, Wang, Z.B. used the DEA method to conduct an empirical study on the current efficiency status of 80 mainland Chinese airports from 2001 to 2005 錯誤! 找不到參照來源。. Nevertheless, the traditional Data Envelopment Analysis (DEA) model has certain limitations when evaluating airport efficiency. Firstly, it can merely identify whether an airport has achieved efficiency, but fails to compare the efficiency values among airports that have already reached the efficient state. Secondly, it can only conduct a static analysis of airports and is incapable of ascertaining the dynamic changes in airport efficiency.

The Malmquist index is an important tool for dynamic analysis in DEA (Data Envelopment Analysis). The DEA - Malmquist index model has the capacity to reveal the alterations in airport operational efficiency across different years. By decomposing the total factor productivity of each airport, it becomes possible to delve into the underlying causes of the changes in airport efficiency. It is able to conduct dynamic analysis on airport operational efficiency. Zhang, Y. et al. employed the Malmquist (productivity index analysis) model within the framework of Data Envelopment Analysis (DEA) to select nine large - scale airports over the period from 1995 to 2005. They then carried out an analysis and evaluation of the operational efficiency of these airports during that time span 錯誤! 找不到參照來源。. Wang, J.D. et al. used the BCC model in data envelopment analysis (DEA) and the Malmquist index to focus on the analysis of the operational efficiency of airports in China with a passenger throughput of 10 million passengers or more 錯誤! 找不到參照來源。. Chu, Y.C. et al. analyzed the operational efficiency of China's airport industry using the super-efficiency DEA-Malmquist index model 錯誤! 找不到參照來源。. Xu, A.Q. et al. conducted research on the operational efficiency of airports within the multi - airport system in Jiangsu Province. By leveraging the dynamic network Data Envelopment Analysis (DEA) model, they aimed to comprehensively analyze and understand the airport operational efficiency in this specific multi - airport system 錯誤! 找不到參照來源。. In addition, Hu, J. et al. developed an operational efficiency evaluation system grounded in the combined empowerment - TOPSIS model. This system was utilized to assess the operational efficiency of domestic airports from four distinct dimensions: slot operational efficiency, customer boarding efficiency, aircraft taxiing efficiency, and cooperative efficiency 錯誤! 找不到參照來源。.

A review of relevant domestic and international literature reveals that there is a scarcity of research on the evaluation of airport operational efficiency. Moreover, there is an almost absence of descriptions regarding the international hub characteristics of airports, such as taking into account international passenger traffic. As a result, it is difficult to reflect the current situation of the operational efficiency of China's international hub airports. In light of this, this paper employs the DEA - Malmquist index model to measure and evaluate the operational efficiency of 18 large - scale international hub airports in China. The findings are intended to offer a theoretical foundation and decision - making reference for the construction of large - scale international hub airports in China.

3. China's Large International Hub Airport Operation Efficiency Evaluation Index System and Model Construction

3.1 Construction of the Indicator System

Taking into account the data availability and the fact that this paper primarily focuses on the operational efficiency of large - scale international aviation hub airports, the terminal area, the number of parking spaces, the total length of the runway, and the area of the cargo terminal are selected as the four input indicators. The annual passenger throughput, the cargo and mail throughput, the number of aircraft landings and takeoffs, and the international passenger throughput are chosen as the output indicators, as presented in Table. 1.

Table 1. Evaluation Indicator System for Large International Hub Airports

Category	Name of indicator	Explanation of indicator
Input indicators	Terminal area	The total area of the terminals in use at this airport
	Number of parking spot	Includes near and far sparking spot
	Total runway length	Total length of all runways in use at the airport
	Freight station area	Total freight station area of the terminal
Output indicators	passenger throughput	Total number of passengers transported annually at the airport
	cargo and mail throughput	Total annual cargo and mail traffic at the airport
	Number of aircraft movements	Total annual aircraft movements at the airport
	International passenger throughput	The airport carries a total of international passengers per year

3.2 DEA-Malmquist Index Model

The Data Envelopment Analysis (DEA) method contains two basic models: the Constant Return to Scale (CCR) model and the Variable Return to Scale (BCC) model. As the CCR model presumes a constant return to scale, which is overly idealistic. In practice, it is frequently challenging for actual decision - making units to perpetually remain in the optimal scale stage. So the DEA - BCC model is closer to the real situation. The traditional Data Envelopment Analysis (DEA) model is only capable of evaluating the efficiency level of decision - making units within a specific time cross - section. It fails to mirror the dynamic change characteristics of efficiency over time. In contrast, the Malmquist index is applied for dynamic efficiency analysis, which can capture these temporal changes in efficiency. Therefore, in this paper, the DEA-Malmquist model is chosen to study the changes in the operational efficiency of China's large international aviation hubs. Färe et al. combined the Malmquist index proposed by the Swedish economist Malmquist with the DEA theory to form the DEA-Malmquist model 錯誤！找不到參照來源。. This model is developed on the basis of the fundamental CCR model proposed by A. Charnes, W.W. Cooper and E. Rhodes in 1978. It addresses the limitations of the traditional model, which was only capable of conducting analyses for a specific year. In contrast, DEA-Malmquist model can examine the changes in operational efficiency over a continuous period of time.

The Malmquist Index is equivalent to Total Factor Productivity (TFP). The value of the Malmquist productivity change is the value of the total factor productivity (TFP) change, and the Malmquist index $M(t+1)$ of the change in productivity of the ith DMU from period t to period t+1 can be expressed as

$$M(t+1)=\sqrt{\frac{D_i(x_{i+1}, y_{i+1})}{D_i(x_i, y_i)} \bullet \frac{D_{i+1}(x_{i+1}, y_{i+1})}{D_{i+1}(x_i, y_i)}}$$ [Formular 1]

Where (x_i, y_i) and (x_{i+1}, y_{i+1}) respectively denote the input-output vectors of the production system in periods t and t+1. $D_i = (x_i, y_i)$ and $D_{i+1} = (x_{i+1}, y_{i+1})$ respectively denote the distance functions in periods t and t+1. The Malmquist index can be decomposed to form the pure technical efficiency change index (PTEC), the scale efficiency change index (SEC), and the technological progress index (TC), and then the M index can be expressed as

$$M(t+1) = PTEC \cdot SEC \cdot TC$$ [Formular 2]

If the Malmquist Index is greater than 1, the operational efficiency of the airport has improved; if the Malmquist Index is less than 1, the operational efficiency of the airport has decreased. The Composite Technical Efficiency Index (EFFC) is the product of the Pure Technical Efficiency Index (PTEC) and the Scale Efficiency Index (SEC). The Comprehensive Technical Efficiency Index reflects the efficiency of the airport's overall resource utilisation. The Pure Technical Efficiency Index reflects the actual efficiency of the airport's management aspects and technological application. And the Scale Efficiency Index reflects whether the airport's scale is reasonable or not. The Technical Progress Index reflects the progress made by the airport in technological innovation and application, such as intelligent equipment, automated processes, etc.

3.3 Source of Data

In this paper, following the principles of relevance, comprehensiveness and data availability, 18 large - scale international hub airports in China were chosen as the research subjects. The relevant data were sourced from the Statistical Bulletin on the Development of the Civil Aviation Industry (2017 - 2019) and the official website introductions of each large - scale international hub airport. This study focuses on the patterns of efficiency in China's large international hub airports under normal economic and social conditions, selecting panel data from 2017 to 2019, aiming to exclude abnormal interference from major public health emergencies on core variables.

4. Empirical Analysis

Based on the input - output orientation, the DEA - Malmquist index method is employed to calculate and analyze the inputs and outputs of 18 large - scale international hub airports in China. Using the software DEAP2.1, the Malmquist index on the panel data of these 18 large - scale international hub airports in China from 2017 to 2019 is measured and decomposed, and the corresponding results are obtained.

4.1 Overall Analysis of the Operational Efficiency of China's Large International Hub Airports

This paper conducts a comprehensive analysis of operational efficiency in China's major international hub airports, focusing on development trends unaffected by pandemic impacts to better understand their historical patterns in the recent period. This article calculates and decomposes the Malmquist index using panel data from China's large international hub airports from 2017 to 2019, with the efficiency indicators organized as shown in Table 2.

Table 2. 2017-2019 Malmquist Index and Its Decomposition of Operational Efficiency for China's Large International Hub Airports

year	EFFC	TC	PTEC	SEC	TFP
2017-2018	1.007	1.047	1.005	1.002	1.055
2018-2019	1.002	1.033	1.001	1.000	1.034
average value	1.004	1.040	1.003	1.001	1.044

Source: By authors.

（1）Analyzed in terms of total factor productivity (M-index)

In Table 2, the average value of the Malmquist index of the operational efficiency of China's 18 large international hub airports in 2017-2019 is 1.044. Therefore, in terms of the overall operation of airports, the operational efficiency of China's 18 large international hub airports has continued to improve, with an average annual growth rate of 4.4%. Among them, the average value of the Malmquist index of the operational efficiency of the 18 large international hub airports in 2017-2018 was 1.055, which is significantly higher than that of 1.034 in 2018-2019. And it can be seen that the growth rate of 3.4 percent in 2019 is significantly lower than the growth rate of 5.5 per cent in 2018.

In terms of the decomposition of total factor productivity, the Malmquist index (TFP) can be decomposed into the product of the composite comprehensive technical efficiency index (EFFC) and the technical progress index (TC), i.e., TFP = EFFC * TC. Therefore, we can analyze the reasons for the changes in Total Factor Productivity (TFP) by examining the specific changes in each decomposition item in Table 2. The comprehensive technical efficiency index exhibited an annual increase of 0.4%. Meanwhile, the technical progress index registered an annual growth of 4%, which was tenfold the value of the average annual change in comprehensive technical efficiency change index. In terms of phasing, the technical progress index in 2017-2018 increased by 4.7%, which is much higher than the comprehensive technical efficiency index; in 2018-2019, the growth of the technical progress index declined somewhat, but the technical progress index of 1.033 in that year is still higher than the comprehensive technical efficiency index of 1.002. Therefore, it can be stated that the technical progress index plays a significant role in promoting the improvement of total factor productivity.

（2）Analyzed from the perspective of the comprehensive technical efficiency change index (EFFC)

The comprehensive technical efficiency change index can be further decomposed into the product of the pure technical efficiency change index (PTEC) and the scale efficiency change index (SEC), i.e., EFFC=PTEC*SEC. From the decomposition terms in Table 2, it can be seen that the changes in the pure technical efficiency change index and the scale efficiency change index in the

2017-2019 period are basically in line with the changes in the comprehensive technical efficiency: the change in pure technical efficiency was more significant, indicating that to some extent, pure technical efficiency restricted the progress of comprehensive technical efficiency. Meanwhile, the scale efficiency change index showed a slight decline, dropping from a growth rate of 0.2% from 2017 to 2018 to a zero - growth rate from 2018 to 2019. Therefore, it can be concluded that the decline of the comprehensive technical efficiency change index from 2017 to 2019 was mainly influenced by pure technical efficiency index.

4.2 Comparative Analysis of Operational Efficiency of Large International Hub Airports in China

After conducting an overall analysis of airport operational efficiency, this paper further conducts a comparative analysis of the operational efficiency change results from the perspective of each airport. The summarized results are presented in

Table 3.

Table 3 The Malmquist Index and its Decomposition of Operational Efficiency for China's 18 Large International Hub Airports

year	EFFC	TC	PTEC	SEC	TFP
Guangzhou Baiyun International Airportt	1.029	1.009	1.021	1.008	1.038
Chengdu Shuangliu International Airport	1.000	1.057	1.000	1.000	1.057
Shenzhen Bao'an International Airport	1.000	1.079	1.000	1.000	1.079
Chongqing Jiangbei International Airport	1.014	1.047	1.029	0.985	1.061
Beijing Capital International Airport	1.000	0.998	1.000	1.000	0.998
Kunming Changshui International Airport	1.000	1.030	1.000	1.000	1.030
Shanghai Hongqiao International Airport	1.000	1.029	1.000	1.000	1.029
Xi'an Xianyang International Airport	1.000	1.070	1.000	1.000	1.070
Shanghai Pudong International Airport	1.000	1.016	1.000	1.000	1.016
Ürümqi Diwopu International Airport	1.000	1.031	1.000	1.000	1.031
Harbin Taiping International Airport	1.010	1.029	1.000	1.010	1.040
Hangzhou Xiaoshan International Airport	1.000	1.058	1.000	1.000	1.058
Nanjing Lukou International Airport	1.006	1.057	1.005	1.001	1.064
Changsha Huanghua International Airport	1.026	1.049	1.018	1.008	1.076
Xiamen Gaoqi International Airport	0.993	1.021	0.988	1.005	1.014
Guiyang Longdongbao International Airport	1.000	1.065	1.000	1.000	1.065
Haikou Meilan International Airport	1.000	1.041	1.000	1.000	1.041
Sanya Phoenix International Airport	1.000	1.038	1.000	1.000	1.038
Average	1.004	1.040	1.003	1.001	1.044

Source: By authors.

Malmquist index greater than 1 indicates an increase in efficiency, while less than 1 indicates a decrease in efficiency. Moreover, the average Malmquist index for the operational efficiency of 18 large international hub airports from 2017 to 2019 is 1.044. Using a Malmquist index of 1 and a Malmquist index of 1.044 as dividing lines, China's 18 large international hub airports can be categorized into the following three parts.

(1) Part I: Malmquist index ∈ [1.044, +∞)

As shown in

Table 3, there are eight airports with Malmquist indexes in this range, namely Chengdu Shuangliu International Airport, Shenzhen Bao'an International Airport, Chongqing Jiangbei International Airport, Xi'an Xianyang International Airport, Hangzhou Xiaoshan International Airport, Nanjing Lukou International Airport, Changsha Huanghua International Airport and Guiyang Longdongbao International Airport. Among these airports, Shenzhen Bao'an International Airport boasted the highest average operational efficiency between 2017 and 2019, with an Malmquist index of 1.079. This indicates that the operational efficiency of Shenzhen Bao'an International Airport maintained an annual growth rate of 7.9% over these three years. By analyzing the decomposition components of its Malmquist index, it is evident that its technological progress index was relatively high, reaching 1.079, whereas the comprehensive technological efficiency index was below 1. Therefore, it can be concluded that the efficiency growth of Shenzhen Bao'an International Airport primarily stems from the contribution of technological progress. Therefore, Shenzhen Bao'an International Airport should focus on improving its comprehensive technical efficiency to match the technical progress. Xi'an Xianyang International Airport, Guiyang Longdongbao International Airport, Hangzhou Xiaoshan International Airport and Chengdu Shuangliu International Airport are also in a similar situation as Shenzhen Bao'an International Airport . The improvement in total factor productivity of the above airports comes from technological progress. Therefore, in future development, efforts should be intensified on the progress of comprehensive technological efficiency to promote further improvement in total factor productivity.In addition to the relatively high technological progress indices of Changsha Huanghua International Airport, Nanjing Lukou International Airport and Chongqing Jiangbei International Airport, which reached 1.049, 1.057, and 1.047 respectively. The comprehensive technological efficiency indices of these three airports also increased to varying degrees. However, there is still a significant gap when compared with the technology progress indices. For Chongqing Jiangbei Airport, the scale efficiency index is less than 1, only 0.985, indicating that there is still room for improvement in terms of scale efficiency.

（2）Part II: M ∈ [1, 1.044)

There are nine airports with Malmquist indexes in this range, Guangzhou Baiyun International Airport, Kunming Changshui International Airport,Shanghai Hongqiao International Airport, Shanghai Pudong International Airport, Ürümqi Diwopu International Airport, Harbin Taiping International Airport, Xiamen Gaoqi International Airport, Haikou Meilan International Airport and Sanya Phoenix International Airport are nine airports. Among these airports, total factor productivity indexes are all greater than 1, but still smaller than the average. It can be concluded that their operational efficiency growth was not significant enough during 2017-2019. Among these airports, with the exception of Guangzhou Baiyun International Airport, the enhancement of operational efficiency at the other eight airports primarily stems from technological progress. However, the improvement in comprehensive technical efficiency change index is generally not prominent. Even there is even a slight decline in the comprehensive technical efficiency change index of Xiamen Gaoqi International Airport. This implies that in the future, these eight airports should also prioritize the enhancement and advancement of comprehensive technical efficiency change index. For Guangzhou Baiyun International Airport, its Malmquist index stands at 1.038. Through the decomposition of the index, it is found that the improvement of total factor productivity is primarily attributed to the improvement in comprehensive technical efficiency index (1.029), while the improvement in technological progress index(1.009) is relatively negligible. Further decomposition reveals that the comprehensive technical efficiency is mainly propelled by the advancement of pure technical efficiency change index, with the change in scale efficiency index being inconspicuous. This implies that Guangzhou Baiyun International Airport should place greater emphasis on technological progress and the enhancement of scale efficiency.

（3）Part III: M ∈ [0, 1)

Beijing Capital International Airport is the sole airport with an operational efficiency below 1, boasting an Malmquist index of merely 0.998. This indicates that the airport failed to enhance its operational efficiency during the study period. Analysis of the Malmquist index decomposition reveals that both the technological progress index of Beijing Capital International Airport is less than 1 and its comprehensive technical efficiency index has remained stagnant, jointly contributing to the low level of its total factor productivity. Consequently, to boost its operational efficiency, the airport should intensify efforts in improving both comprehensive technical efficiency and technological progress.

5. Conclusions and Recommendations

Based on the data from 18 large international hub airports in China from 2017 to 2019, this paper evaluates the operational efficiency of China's large international hubs using the DEA-Malmquist model and draws the following conclusions:

(1)From 2017 to 2019, the operational efficiency of China's large - scale international hub airports maintained an overall average annual growth rate of 0.44%. Nevertheless, within this period, the pace of improvement in operational efficiency slowed down. Technological advancements index notably enhanced the operational efficiency of these airports, whereas the improvement in comprehensive technical efficiency index was negligible. This suggests that comprehensive technical efficiency index is constraining the further enhancement of the operational efficiency of China's large - scale international hub airports.

(2)An assessment of the operational efficiency of each of the 18 large - scale international hub airports show that, despite the average Malmquist index reaching 1.044 and presenting an upward trend, there are significant disparities among the airports. Shenzhen Bao'an International Airport, Xi'an Xianyang International Airport and Changsha Huanghua International Airport have seen a faster growth in efficiency, with an average annual increase of more than 7% already. In contrast, Beijing Capital International Airport, Xiamen Gaoqi International Airport, and Shanghai Pudong International Airport have not experienced significant efficiency growth. Notably, the operational efficiency of Beijing Capital International Airport has even declined. A decomposition of the Malmquist index indicates that these airports have relatively low comprehensive technological progress index and technical efficiency index, suggesting considerable room for improvement in both aspects.

(3) In terms of airport scale and the cities they are situated in, generally, most of these airports with the highest operational efficiency are located in the hubs of large and medium cities , such as Chongqing, Changsha, Nanjing, and others. In contrast, the operational efficiency of international hub airports in large cities like Beijing, Shanghai, and Guangzhou has generally not improved significantly. This indicates that there is no obvious positive correlation between the enhancement of airport operational efficiency and the size of the city. It also suggests that a larger city does not

necessarily lead to a higher rate of improvement in airport operational efficiency. This phenomenon might be attributed to the excessively high concentration of flights at the hub airports in these megacities. As a result, these airports become overly congested, leading to inefficiencies such as flight delays, which in turn have a negative impact on their operational efficiency.

In response to the results of the analyses, this study proposes the following policy implications: Based on the above analyses, the total factor productivity of China's international hub airports has increased due to the improvement of the technical progress index. The technical efficiency index has increased slowly, and some airports have the problems of decreasing scale efficiency and decreasing pure technical efficiency. To enhance the total factor productivity of China's international hub airports, the following suggestions are proposed. Firstly, it is recommended to continuously increase investment in technological innovation, promote the application of intelligent equipment and advanced management techniques. Meanwhile, optimize resource allocation and process management to improve technical efficiency. Secondly, in response to the decline in scale efficiency observed at some airports, it is essential to rationally plan the scale of these airports. Strengthen multimodal transportation and collaborative management, and scientifically allocate airport resources. Finally, regarding the decline in pure technical efficiency at certain airports, it is necessary to improve the technical management system and increase investment in scientific and technological research and development. By optimizing airport layout, rationally planning the construction and renovation of facilities such as terminals and runways, improving the baggage handling system, security equipment, and other ancillary facilities, and introducing intelligent facilities to enhance operational automation and information levels, the efficiency of airport infrastructure use and service capabilities can be improved. Moreover, efforts should be made to promote the application of emerging information technologies in airport services and operations.

Acknowledgements

We are grateful for the financial support from the National Natural Science Foundation of China (U2333206); the Major Project of Key Research Base of Humanities and Social Sciences of the Ministry of Education of China (22JJD630006); the Civil Aviation Safety Capacity Building Project of 2024 "Domestic Air Shuttle Safety Supervision"; and the Major Project of Social Sciences of Tianjin Municipal Commission of Education (2018JWZD52); Civil Aviation University of China Graduate Student Research Innovation Program (No. [2023YJSKC07006]).

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