Journal of Air Transport Management 55 (2016) 67–75

Contents lists available at ScienceDirect

Journal of Air Transport Management

journal homepage: www.elsevier.com/locate/jairtraman

Performance evaluation of China's air routes based on network data envelopment analysis approach

Yanmin Shao [a, b, *], Changfu Sun [c]

[a] Academy of Mathematics and Systems Science, Chinese Academy of Sciences, China
[b] Center for Forecasting Science, Chinese Academy of Sciences, China
[c] School of Economics and Management, Beijing Jiao Tong University, China

ARTICLE INFO

Article history:
Received 1 November 2015
Received in revised form
22 December 2015
Accepted 30 January 2016

Keywords:
Network DEA
Air route
Efficiency
Passenger transport
Freight transport

ABSTRACT

Air routes are among the most important elements of civil aviation transport. Airlines' operations are mainly dependent on the structure and layout of air routes. This paper first divides the production process of air routes into two stages, allocation and transport, based on air route operational characteristics. Then, two network data envelopment analysis (DEA) models are proposed to analyze the efficiency of the system, allocation, passenger transport, and freight transport of 477 air routes. The research result demonstrates that the different constraints on intermediate measure in the network DEA models do affect the air routes' efficiency significantly; Most air routes have high allocation efficiency and passenger transport efficiency, while they have low freight transport efficiency. Furthermore, the efficiencies of 82 airports are also analyzed after aggregating the efficiencies of the air routes.

1. Introduction

With the development of society and economy, civil air transportation has become the most efficient and effective way to transport passengers and cargo. In recent years, China's civil aviation industry has developed rapidly. Its civil aviation transport turnover and passenger volume ranked the second in the world for several years, which follows the United States. In 2013, the total civil aviation passenger and freight volume reached 353.97 million persons and 5.61 million tons, increasing 103 and 63 times, respectively, compared to the data in 1980. In the same year, the domestic passenger turnover and cargo and mail turnover reached 451 billion person-kilometers and 6.11 billion ton-kilometers, increasing 143 and 121 times, respectively, compared to the data in 1980. Table 1 shows some detailed data on China's civil aviation transportation.

Since the beginning of China's economic reform in 1978, China's Civil Aviation Administration (CAAC) has taken several measures to change the way it regulates the civil aviation industry. For example, in 2005, the CAAC permitted private investors to invest in the civil aviation sector, and the number of private airlines has grown rapidly, with new airlines being established for the expanding local markets (Wang et al., 2016). To create a favorable business environment for airline companies, CAAC formulated and promulgated "The Approach on Further Reform of Domestic Air Routes' License for Flight Operation and Management" in 2010, which puts forward that the management of domestic flight routes should follow the principle of decentralization to improve the airline companies' operations. In line with the new approach, the license for operating flight on air routes in Beijing, Shanghai (Hongqiao and Pudong airports), and Guangzhou cities should adopt the approval/registration policy, while the license for operating flight on air routes in other airports should follow the registration management policy.[1] This means that the CAAC is only responsible for the approval of air routes' license for operating flight in the four airports, relaxing the access conditions of domestic air routes to give the airlines more autonomy, which is helpful to create a better competition environment for the operation of air routes. Air route is one of the most important elements of civil aviation transport. The operation of airlines is mainly dependent on the structure and layout of air routes. However, the existing studies mainly treated the airline

* Corresponding author. Institute of Systems Science, Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing, 100190, China.
E-mail address: yanminshao@amss.ac.cn (Y. Shao).

[1] http://www.gov.cn/gzdt/2010-02/04/content_1527959.htm.

http://dx.doi.org/10.1016/j.jairtraman.2016.01.006

Table 1
China's civil aviation transport data.

Indicators	Unit	1980	1990	2000	2010	2012	2013
Passenger throughput	Million people	3.43	16.6	67.22	267.69	319.36	353.97
Passenger throughput of domestic routes	Million people	2.93	13.46	60.31	248.38	296	327.42
Passenger throughput of international routes	Million people	0.29	1.14	6.9	19.31	23.36	26.55
Passenger turnover	Billion person-kilometers	3.96	23.05	97.05	403.9	502.57	565.68
Passenger turnover of domestic routes	Billion person-kilometers	2.81	15.77	73.77	328.01	403.38	451.1
Passenger turnover of international routes	Billion person-kilometers	1.07	5.17	23.28	75.89	99.2	114.58
Cargo and mail throughput	Million tons	0.09	0.37	1.97	5.63	5.45	5.61
Cargo and mail throughput of domestic routes	Million tons	0.07	0.24	1.47	3.7	3.89	4.07
Cargo and mail throughput of international routes	Million tons	0.01	0.08	0.49	1.93	1.57	1.55
Cargo and mail freight turnover	Billion ton-kilometers	0.14	0.82	5.03	17.89	16.39	17.03
Cargo and mail freight turnover of domestic routes	Billion ton-kilometers	0.07	0.32	2.11	5.36	5.74	6.11
Cargo and mail freight turnover of international routes	Billion ton-kilometers	0.06	0.44	2.92	12.53	10.65	10.92
Total turnover	Billion ton-kilometers	0.43	2.5	12.25	53.84	61.03	67.17
Total turnover of domestic routes	Billion ton-kilometers	0.28	1.45	7.6	34.55	41.58	46.1
Total turnover of international routes	Billion ton-kilometers	0.14	0.83	4.65	19.3	19.45	21.07

companies or airports, rather than air routes, as decision-making units (DMUs). Since customers, competitors, and operating environments differ among air routes, managerial policies and operational analysis are best discussed from a route-based perspective by treating each route as a "strategic business unit" rather than merely employing a whole-company view (Chiou and Chen, 2006), which help gain insight into operational problems that arise along each route.

The objective of this research is to develop a comprehensive methodology to investigate the efficiency of air routes from a managerial perspective. Formulating multi-production processes is appropriate because the air routes use the operating expense and infrastructure to provide passenger transport service and freight shipment. Based on the functional analysis of the air routes, after establishing an index system in line with China's civil air operational status, two network DEA models are proposed to evaluate the performance of a group of air routes in China, where the constraints of the intermediate measure is distinguished, and the system efficiency obtained using the two network DEA models can be decomposed into a weighted average of the sub-functional efficiencies. The remainder of the paper is organized as follows. The second section briefly reviews the related literature. Section 3 proposes two network DEA models to study China's air route efficiency. Section 4 presents the data and results. Section 5 concludes.

2. Literature review

2.1. DEA model

The DEA based on nonparametric techniques (Farrell, 1957) is proposed by Charnes, Cooper, and Rhodes (Charnes et al., 1978). It is an effective methodology to evaluate the relative efficiencies of a set of comparable entities, which is referred to as decision-making units (DMUs). For each DMU, the input-oriented and constant returns to scale (CRS) DEA model can be expressed as follows:

$$\begin{aligned} &\max \frac{u' y_k}{v' x_k}, \\ &s.t. \frac{u' y_j}{v' x_j} \le 1, j = 1, 2, \ldots, n, \\ &u, v \ge 0. \end{aligned} \tag{1}$$

where x_k and y_k represent the input and output vectors of the evaluating k-th DMU; v and u are their weight vectors, respectively. To calculate the efficiency of the k-th DMU, it involves finding values for u and v, which maximize the efficiency of the k-th DMU. Meanwhile, they are subject to the constraint that all efficiency measures must be less than or equal to one. The equation can be transferred into a linear programming problem, and we can get the efficiency score for the k-th DMU under CRS assumption.

The DEA has been widely used in studies on civil air aviation's efficiency analysis. Specifically, some studies have evaluated the efficiency of China's airlines (see Cui and Li, 2015b; Cao et al., 2015) and airport (Fan et al., 2014; Fung et al., 2008; Cui and Li, 2015a).

2.2. Network DEA models in air aviation transport performance evaluation

The DEA method has been widely employed in studies on civil air aviation, and provides meaningful insights. Nowadays, after accounting for the intermediate sub-production process, some literatures have paid attention to the efficiency of the sub-function of the civil air aviation. Yu (2010) first proposed a slacks-based measure network data envelopment analysis (SBM-NDEA) model to evaluate the efficiency of the production process, airside service process, and landside service process of airports in Taiwan in 2006. Wanke (2013) used a two-stage approach to calculate the airport's operation efficiency, which focused on the efficiency of physical infrastructure and flight consolidation. Adler et al. (2013) provided a network DEA model after considering airport's production process from a managerial perspective. Mallikarjun (2015) and Li et al. (2015) proposed a three-stage un-oriented network DEA to measure the airport's efficiency of operation, service, and sales. The efficiencies of airlines were also carried out using network DEA models. Merkert and Hensher (2011) examined the impact of strategic management and fleet panning on technical, allocative, and cost efficiency of the airline. Lu et al. (2012) applied a two-stage DEA model to evaluate the production and marketing efficiencies of airlines. Tavassoli et al. (2014) estimated the technical and service efficiencies of airlines using a SBM-NDEA model in the presence of shared input.The explosive air transportation of China has raised the concern on its air transport efficiency. Zhang et al. (2012) and Chang et al. (2013) applied the DEA framework to the efficiency evaluation of the China's airport. Fan et al. (2014) evaluated the airport's efficiency after considering flight delays using directional distance function. Chi-Lok and Zhang (2009) investigated the influence of competition and aviation policy reform on the efficiency of Chinese airports. Some studies also focused on the efficiency and the determinants of Chinese airlines (Cao et al., 2015; Chow, 2010;

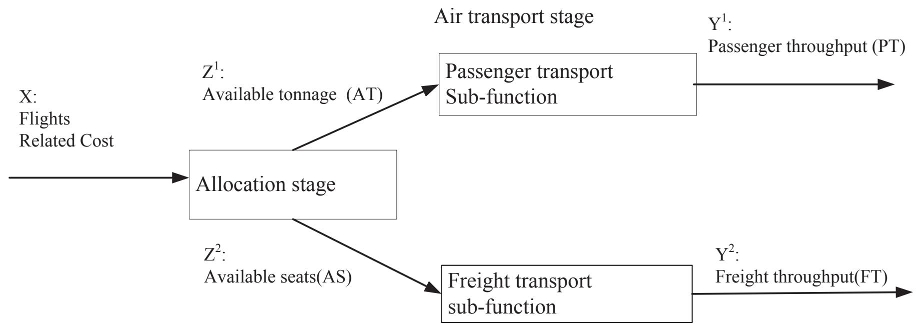

Fig. 1. Production process of air route.

Cui & Li, 2015). Owing to the lack of detailed information on air routes of China, previous studies mainly evaluated the efficiency of the airport and airline companies. To date, only Chiou and Chen (2006) gave insight into operational problems that arose along each air route, but they did not take account of the internal structure of the air route, and they did not calculate the efficiency of sub-production process, which might be more informative for the relevant airline companies and airports.

3. Network DEA model for performance evaluation of air route

Since air routes can facilitate transport of both passengers and freight, formulating multi-production processes is appropriate because air routes can provide airside and landside transport services, including aircraft takeoff and landing, passenger services, cargo shipment, etc. Mallikarjun (2015) established that in the first stage or operations stage, the airline uses operating expenses to produce available seat miles (ASM), and in the second stage, it consumes ASM and produces revenue passenger miles (RPM). ASM and RPM are the two vital indicators that measure the relevant operational performance of the airline (Cento, 2008). Similarly, as the airline's important elements, it is necessary to analyze the air route's operational performance characteristics and find the weakness in the air route system.

The air route service can also be classified into two stages: allocation stage and transport stage. For the air route, the first stage of resource allocation uses the operating cost and airplane to determine the available seats (AS) and available tonnage (AT), which represent the supply capacity of the air route. AS and AT are the intermediate products in the model that connect the first and second stages. In the second transport stage, the air route provides civil air transport service for passengers and freights. Accordingly, the air route's transport function can be divided into two paralleled sub-functions–passenger transport sub-function and freight transport sub-function, which determine the corresponding passenger throughput (PT) and freight throughput (FT), respectively. Fig. 1 shows the sub-functions of the air route. Besides the air routes' system efficiency (ES), its allocation service efficiency (EA), passenger transport efficiency (EP), and freight transport efficiency (EF) can be distinguished after considering the different functions of the air route.

We can obtain the input variables X_{ij}(i = 1, …,m, j = 1, …,n), intermediate measures $Z^1_{p^1j}(p^1 = 1,\ldots,q^1, j = 1,\ldots,n)$, and $Z^2_{p^2j}(p^2 = 1,\ldots,q^2, j = 1,\ldots,n)$, and output variables $Y^1_{s^1j}(s^1 = 1,\ldots,t^1, j = 1,\ldots,n)$ and $Y^2_{s^2j}(s^2 = 1,\ldots,t^2, j = 1,\ldots,n)$ for the j-th air route. In this section, we propose two network DEA models for measuring the air route performance. The main objective of the models is to maximize the overall efficiency of the production system. In the network structured DEA models, there are several ways of modeling the intermediate measures; for example, some researchers assign the same weight for the intermediate variable over different stages (Kao and Hwang, 2008; Liang et al., 2008; Chen et al., 2010), and some researchers assume that the output of the component should not be larger than the input of the component (Tavassoli et al., 2014b; Akther et al., 2013). In our paper, we propose two network DEA models after considering the two ways of disposing the intermediate measures.

Case (I): Intermediate measure with same weights

Generally, the following network DEA model can be used to calculate the air route's system efficiency:

$$
\begin{aligned}
&E_k^{S1} = \max \frac{\sum_{p^1=1}^{q^1} w^1_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} w^2_{p^2} Z^2_{p^2k} + \sum_{s^1=1}^{t^1} u^1_{s^1} Y^1_{s^1k} + \sum_{s^2=1}^{t^2} u^2_{s^2} Y^2_{s^2k}}{\sum_{i=1}^{m} v_i X_{ik} + \sum_{p^1=1}^{q^1} v^1_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} v^2_{p^2} Z^2_{p^2k}} \\
&s.t. \frac{\sum_{p^1=1}^{q^1} w^1_{p^1} Z^1_{p^1j} + \sum_{p^2=1}^{q^2} w^2_{p^2} Z^2_{p^2j} + \sum_{s^1=1}^{t^1} u^1_{s^1} Y^1_{s^1j} + \sum_{s^2=1}^{t^2} u^2_{s^2} Y^2_{s^2j}}{\sum_{i=1}^{m} v_i X_{ij} + \sum_{p^1=1}^{q^1} v^1_{p^1} Z^1_{p^1j} + \sum_{p^2=1}^{q^2} v^2_{p^2} Z^2_{p^2j}} \\
&\quad \le 1, j = 1,\ldots,n, \\
&\frac{\sum_{p^1=1}^{q^1} w^1_{p^1} Z^1_{p^1j} + \sum_{p^2=1}^{q^2} w^2_{p^2} Z^2_{p^2j}}{\sum_{i=1}^{m} v_i X_{ij}} \le 1, j = 1,\ldots,n, \\
&\frac{\sum_{s^1=1}^{t^1} u^1_{s^1} Y^1_{s^1j}}{\sum_{p^1=1}^{q^1} v^1_{p^1} Z^1_{p^1j}} \le 1, j = 1,\ldots,n, \\
&\frac{\sum_{s^2=1}^{t^2} u^2_{s^2} Y^2_{s^2j}}{\sum_{p^2=1}^{q^2} v^2_{p^2} Z^2_{p^2j}} \le 1, j = 1,\ldots,n, \\
&v_i, v^1_{p^1}, v^2_{p^2}, w^1_{p^1}, w^2_{p^2}, u^1_{s^1}, u^2_{s^2} \ge \varepsilon.
\end{aligned} \tag{2}
$$

where $v_i, v^1_{p^1}, v^2_{p^2}, w^1_{p^1}, w^2_{p^2}, u^1_{s^1}, u^2_{s^2}$ define the efficiency of the k-th airport. The first, second, third, and fourth constraints of Model (2) minimize the input at a given level of output for the system's production and three sub-functions' production. Following Kao and Hwang (2008), Liang et al. (2008), and Chen et al. (2010), we assume that $v^1_{p^1} = w^1_{p^1}(p^1 = 1, \ldots, q^1)$ and $v^2_{p^2} = w^2_{p^2}(p^2 = 1, \ldots, q^2)$ because these are similar variables. To solve the efficiency, we define $\frac{1}{\sum_{i=1}^m v_i X_{ik} + \sum_{p^1=1}^{q^1} v^1_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} v^2_{p^2} Z^2_{p^2k}} = \varphi$, $V_i = \varphi v_i (i=1,\ldots,m)$, and $W_{p^\alpha} = \varphi w^\alpha_{p^\alpha}(\alpha = 1,2, p^\alpha = 1, \ldots, q^\alpha)$, $U^\beta_{p^\beta} = \varphi u^\beta_{p^\beta}(\beta = 1,2, p^\beta = 1, \ldots, q^\beta)$. The fractional program is transformed into the following linear model:

$$
\begin{aligned}
E^{S1}_k = \max & \sum_{p^1=1}^{q^1} W^1_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} W^2_{p^2} Z^2_{p^2k} + \sum_{s^1=1}^{t^1} U^1_{s^1} Y^1_{s^1k} + \sum_{s^2=1}^{t^2} U^2_{s^2} Y^2_{s^2k} \\
s.t. & \sum_{s^1=1}^{t^1} U^1_{s^1} Y^1_{s^1j} + \sum_{s^2=1}^{t^2} U^2_{s^2} Y^2_{s^2j} - \sum_{i=1}^{m} V_i X_{ij} \le 0, j = 1, \ldots, n, \\
& \sum_{p^1=1}^{q^1} W^1_{p^1} Z^1_{p^1j} + \sum_{p^2=1}^{q^2} W^2_{p^2} Z^2_{p^2j} - \sum_{i=1}^{m} V_i X_{ij}, \le 0, j = 1, \ldots, n, \\
& \sum_{s^1=1}^{t^1} U^1_{s^1} Y^1_{s^1j} - \sum_{p^1=1}^{q^1} W^1_{p^1} Z^1_{p^1j} \le 0, j = 1, \ldots, n, \\
& \sum_{s^2=1}^{t^2} U^2_{s^2} Y^2_{s^2j} - \sum_{p^2=1}^{q^2} W^2_{p^2} Z^2_{p^2j} \le 0, j = 1, \ldots, n, \\
& V_i, W^1_{p^1}, W^2_{p^2}, U^1_{s^1}, U^2_{s^2} \ge \varepsilon.
\end{aligned} \tag{3}
$$

The air route's system efficiency and three sub-functional efficiencies can be calculated using the following four equations:

$$
\begin{aligned}
E^{S1}_k &= \frac{\sum_{p^1=1}^{q^1} W^{1*}_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} W^{2*}_{p^2} Z^2_{p^2k} + \sum_{s^1=1}^{t^1} U^{1*}_{s^1} Y^1_{s^1k} + \sum_{s^2=1}^{t^2} U^{2*}_{s^2} Y^2_{s^2k}}{\sum_{i=1}^m V^*_i X_{ik} + \sum_{p^1=1}^{q^1} W^{1*}_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} W^{2*}_{p^2} Z^2_{p^2k}} \\
E^{A1}_k &= \frac{\sum_{p^1=1}^{q^1} W^{1*}_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} W^{2*}_{p^2} Z^2_{p^2k}}{\sum_{i=1}^m V^*_i X_{ik}} \\
E^{P1}_k &= \frac{\sum_{s^1=1}^{t^1} U^{1*}_{s^1} Y^1_{s^1k}}{\sum_{p^1=1}^{q^1} W^{1*}_{p^1} Z^1_{p^1k}} \\
E^{F1}_k &= \frac{\sum_{s^2=1}^{t^2} U^{2*}_{s^2} Y^2_{s^2k}}{\sum_{p^2=1}^{q^2} W^{2*}_{p^2} Z^2_{p^2k}}
\end{aligned} \tag{4}
$$

where $V^*_i, W^{1*}_{p^1}, W^{2*}_{p^2}, U^{1*}_{s^1}, U^{2*}_{s^2}$ represent the optimal multipliers of the mathematical model (3), and E^{S1}, E^{A1}, E^{P1} ,and E^{F1} are air routes' ES, EA, EP, and EF scores, respectively.

Moreover, the system efficiency can be decomposed into a weighted average of the process efficiencies (Kao and Hwang, 2008),

$$E^{S1} = \omega^1_1 E^{A1} + \omega^1_2 E^{P1} + \omega^1_3 E^{F1} \tag{5}$$

where $\omega^1_1 = \frac{\sum_{i=1}^m V^*_i X_{ik}}{\sum_{i=1}^m V^*_i X_{ik} + \sum_{p^1=1}^{q^1} W^{1*}_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} W^{2*}_{p^2} Z^2_{p^2k}}$,

$\omega^1_2 = \frac{\sum_{i=1}^m W^{1*}_{p^1} Z^1_{p^1k}}{\sum_{i=1}^m V^*_i X_{ik} + \sum_{p^1=1}^{q^1} W^{1*}_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} W^{2*}_{p^2} Z^2_{p^2k}}$,

$\omega^1_3 = \frac{\sum_{p^2=1}^{q^2} W^{2*}_{p^2} Z^2_{p^2k}}{\sum_{i=1}^m V^*_i X_{ik} + \sum_{p^1=1}^{q^1} W^{1*}_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} W^{2*}_{p^2} Z^2_{p^2k}}$, and $\omega^1_1 + \omega^1_2 + \omega^1_3 = 1.\omega^1_h$, $h = 1,2,3$ is the relative weight of the h-th sub-function, which is determined corresponding to its resource consumption.

Case (II) Intermediate measure with different weights

Assume that the output of the component is smaller than the input of the component, the following network DEA model can be used to calculate the airport's system efficiency:

$$
\begin{aligned}
E^{S2}_k = \max & \frac{\sum_{p^1=1}^{q^1} w^1_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} w^2_{p^2} Z^2_{p^2k} + \sum_{s^1=1}^{t^1} u^1_{s^1} Y^1_{s^1k} + \sum_{s^2=1}^{t^2} u^2_{s^2} Y^2_{s^2k}}{\sum_{i=1}^m v_i X_{ik} + \sum_{p^1=1}^{q^1} v^1_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} v^2_{p^2} Z^2_{p^2k}} \\
s.t. & \frac{\sum_{p^1=1}^{q^1} w^1_{p^1} Z^1_{p^1j} + \sum_{p^2=1}^{q^2} w^2_{p^2} Z^2_{p^2j} + \sum_{s^1=1}^{t^1} u^1_{s^1} Y^1_{s^1j} + \sum_{s^2=1}^{t^2} u^2_{s^2} Y^2_{s^2j}}{\sum_{i=1}^m v_i X_{ij} + \sum_{p^1=1}^{q^1} v^1_{p^1} Z^1_{p^1j} + \sum_{p^2=1}^{q^2} v^2_{p^2} Z^2_{p^2j}} \\
& \le 1, j = 1, \ldots, n, \\
& \frac{\sum_{p^1=1}^{q^1} w^1_{p^1} Z^1_{p^1j} + \sum_{p^2=1}^{q^2} w^2_{p^2} Z^2_{p^2j}}{\sum_{i=1}^m v_i X_{ij}} \le 1, j = 1, \ldots, n, \\
& \frac{\sum_{s^1=1}^{t^1} u^1_{s^1} Y^1_{s^1j}}{\sum_{p^1=1}^{q^1} v^1_{p^1} Z^1_{p^1j}} \le 1, j = 1, \ldots, n, \\
& \frac{\sum_{s^2=1}^{t^2} u^2_{s^2} Y^2_{s^2j}}{\sum_{p^2=1}^{q^2} v^2_{p^2} Z^2_{p^2j}} \le 1, j = 1, \ldots, n, \\
& \sum_{p^1=1}^{q^1} w^1_{p^1} Z^1_{p^1j} \le \sum_{p^1=1}^{q^1} v^1_{p^1} Z^1_{p^1j}, j = 1, \ldots, n, \\
& \sum_{p^2=1}^{q^2} w^2_{p^2} Z^2_{p^2j} \le \sum_{p^2=1}^{q^2} v^2_{p^2} Z^2_{p^2j}, j = 1, \ldots, n, \\
& v_i, v^1_{p^1}, v^2_{p^2}, w^1_{p^1}, w^2_{p^2}, u^1_{s^1}, u^2_{s^2} \ge \varepsilon.
\end{aligned} \tag{6}
$$

where $v_i, v^1_{p^1}, v^2_{p^2}, w^1_{p^1}, w^2_{p^2}, u^1_{s^1}, u^2_{s^2}$ define the efficiency of the k-th air route. The first, second, third, and fourth constraints of Model (6) minimize the input at a given level of the final output. The fifth and sixth constraints correspond to the intermediate measures, which ensure that the output of each component is not larger than its input.

To solve the efficiency, we define $\frac{1}{\sum_{i=1}^m v_i X_{ik} + \sum_{p^1=1}^{q^1} v^1_{p^1} Z^1_{p^1k} + \sum_{p^2=1}^{q^2} v^2_{p^2} Z^2_{p^2k}} = \varphi$, $V_i = \varphi v_i (i=1,\ldots,m)$, and $W_{p^\alpha} = \varphi w^\alpha_{p^\alpha}(\alpha = 1,2, p^\alpha = 1, \ldots, q^\alpha)$, $U^\beta_{p^\beta} = \varphi u^\beta_{p^\beta}(\beta = 1,2, p^\beta = 1, \ldots, q^\beta)$. The fractional program is transformed into the following linear model:

$$
\begin{aligned}
E_k^{S1} = \max & \sum_{p^1=1}^{q^1} W_{p^1}^1 Z_{p^1k}^1 + \sum_{p^2=1}^{q^2} W_{p^2}^2 Z_{p^2k}^2 + \sum_{s^1=1}^{t^1} U_{s^1}^1 Y_{s^1k}^1 + \sum_{s^2=1}^{t^2} U_{s^2}^2 Y_{s^2k}^2 \\
s.t. & \sum_{p^1=1}^{q^1} W_{p^1}^1 Z_{p^1j}^1 + \sum_{p^2=1}^{q^2} W_{p^2}^2 Z_{p^2j}^2 + \sum_{s^1=1}^{t^1} U_{s^1}^1 Y_{s^1j}^1 + \sum_{s^2=1}^{t^2} U_{s^2}^2 Y_{s^2j}^2 - \sum_{i=1}^{m} V_i X_{ij} \\
& - \sum_{p^1=1}^{q^1} V_{p^1}^1 Z_{p^1j}^1 - \sum_{p^2=1}^{q^2} V_{p^2}^2 Z_{p^2j}^2 \le 0, j=1,\ldots,n, \\
& \sum_{p^1=1}^{q^1} W_{p^1}^1 Z_{p^1j}^1 + \sum_{p^2=1}^{q^2} W_{p^2}^2 Z_{p^2j}^2 - \sum_{i=1}^{m} V_i X_{ij} \le 0, j=1,\ldots,n, \\
& \sum_{s^1=1}^{t^1} U_{s^1}^1 Y_{s^1j}^1 - \sum_{p^1=1}^{q^1} V_{p^1}^1 Z_{p^1j}^1 \le 0, j=1,\ldots,n, \\
& \sum_{s^2=1}^{t^2} U_{s^2}^2 Y_{s^2j}^2 - \sum_{p^2=1}^{q^2} V_{p^2}^2 Z_{p^2j}^2 \le 0, j=1,\ldots,n, \\
& \sum_{p^1=1}^{q^1} W_{p^1}^1 Z_{p^1j}^1 \le \sum_{p^1=1}^{q^1} V_{p^1}^1 Z_{p^1j}^1, j=1,\ldots,n, \\
& \sum_{p^2=1}^{q^2} W_{p^2}^2 Z_{p^2j}^2 \le \sum_{p^2=1}^{q^2} V_{p^2}^2 Z_{p^2j}^2, j=1,\ldots,n, \\
& \sum_{i=1}^{m} V_i X_{ik} + \sum_{p^1=1}^{q^1} V_{p^1}^1 Z_{p^1k}^1 + \sum_{p^2=1}^{q^2} V_{p^2}^2 Z_{p^2k}^2 = 1, \\
& V_i, V_{p^1}^1, V_{p^2}^2, W_{p^1}^1, W_{p^2}^2, U_{s^1}^1, U_{s^2}^2 \ge \varepsilon.
\end{aligned}
\tag{7}
$$

The air route's system efficiency and three sub-functional efficiencies can be calculated using the following four equations:

$$
\begin{aligned}
E_k^{S2} &= \frac{\sum_{p^1=1}^{q^1} W_{p^1}^{1\#} Z_{p^1k}^1 + \sum_{p^2=1}^{q^2} W_{p^2}^{2\#} Z_{p^2k}^2 + \sum_{s^1=1}^{t^1} U_{s^1}^{1\#} Y_{s^1k}^1 + \sum_{s^2=1}^{t^2} U_{s^2}^{2\#} Y_{s^2k}^2}{\sum_{i=1}^{m} V_i^{\#} X_{ik} + \sum_{p^1=1}^{q^1} V_{p^1}^{1\#} Z_{p^1k}^1 + \sum_{p^2=1}^{q^2} V_{p^2}^{2\#} Z_{p^2k}^2} \\
E_k^{A2} &= \frac{\sum_{p^1=1}^{q^1} W_{p^1}^{1\#} Z_{p^1k}^1 + \sum_{p^2=1}^{q^2} W_{p^2}^{2\#} Z_{p^2k}^2}{\sum_{i=1}^{m} V_i^{\#} X_{ik}} \\
E_k^{P2} &= \frac{\sum_{s^1=1}^{t^1} U_{s^1}^{1\#} Y_{s^1k}^1}{\sum_{p^1=1}^{q^1} V_{p^1}^{1\#} Z_{p^1k}^1} \\
E_k^{F2} &= \frac{\sum_{s^2=1}^{t^2} U_{s^2}^{2\#} Y_{s^2k}^2}{\sum_{p^2=1}^{q^2} V_{p^2}^{2\#} Z_{p^2k}^2}
\end{aligned}
\tag{8}
$$

where $V_i^{\#}, V_{p^1}^{1\#}, V_{p^2}^{2\#}, W_{p^1}^{1\#}, W_{p^2}^{2\#}, U_{s^1}^{1\#}, U_{s^2}^{2\#}$ represent the optimal multipliers of the mathematical model (3), and E^{S2},E^{A2},E^{P2}, and E^{F2} are air routes' ES, EA, EP, and EF scores, respectively.

Similarly, the system efficiency can be decomposed into a weighted average of the process efficiencies:

$$
E^{S2} = \omega_1^2 E^{A2} + \omega_2^2 E^{P2} + \omega_3^2 E^{F2} \tag{9}
$$

where $\omega_1^2 = \frac{\sum_{i=1}^{m} V_i^{\#} X_{ik}}{\sum_{i=1}^{m} V_i^{\#} X_{ik} + \sum_{p^1=1}^{q^1} W_{p^1}^{1\#} Z_{p^1k}^1 + \sum_{p^2=1}^{q^2} W_{p^2}^{2\#} Z_{p^2k}^2}$,
$\omega_2^2 = \frac{\sum_{i=1}^{m} W_{p^1}^{1\#} Z_{p^1k}^1}{\sum_{i=1}^{m} V_i^{\#} X_{ik} + \sum_{p^1=1}^{q^1} W_{p^1}^{1\#} Z_{p^1k}^1 + \sum_{p^2=1}^{q^2} W_{p^2}^{2\#} Z_{p^2k}^2}$,
$\omega_3^2 = \frac{\sum_{p^2=1}^{q^2} W_{p^2}^{2\#} Z_{p^2k}^2}{\sum_{i=1}^{m} V_i^{\#} X_{ik} + \sum_{p^1=1}^{q^1} W_{p^1}^{1\#} Z_{p^1k}^1 + \sum_{p^2=1}^{q^2} W_{p^2}^{2\#} Z_{p^2k}^2}$, and $\omega_1^2 + \omega_2^2 + \omega_3^2 = 1$. $\omega_h^2, h = 1, 2, 3$ is the relative weight of the h-th sub-function.

4. Data and results

4.1. Data

The data on 477 air stages in 2013 are employed to study the efficiency of the air route. Owing to the limited air route data, five variables are collected based on the public availability of the data. The input of the allocation stage is the total number of flights (hereafter referred to as AF, measured in 1000 flights), which can also reflect the operating expense of the air route. The available seats (AS, measured in 1000 seats) and the available tonnage (AT, measured in 1000 tons) are selected as the outputs of the allocation stage, which are also the inputs of the transport stage. The passenger throughput (PT, measured in 1000 persons) is selected as the output of the passenger transport sub-function, while the cargo and mail throughput (CMT, measured in 1000 tons) is the output of the freight transport function. All the data are collected from annual "From a Statistical Look at the Civil Aviation 2013". Table 2 shows the data description of the variables. The total passenger throughput and mail and cargo throughput of the 477 routes is 255.93 million persons and 3.27 million tons, which account for 78.17% and 80.37% of all domestic routes in China, respectively.

4.2. Efficiencies of air stages

In this section, to address the question of whether air route performance measures—ES, EA, EP, and EF—are different with different intermediate constraints, two network DEA models are used here to measure the performance of the 477 air routes after considering the internal activity. Table 3 presents the frequency distributions and summary statistics for ES, EA, PE, and FE, measures of the 477 air routes. The second to fifth columns are the efficiency scores of ES EA, EP, and EF using network DEA model 2, named ES1, EA1, EP1, and EF1, while the sixth to ninth columns are

Table 2
Description of input, intermediate, and output variables.

Variables	Name	Mean	S.D.	Max	Min
Inputs of allocation stage					
Number of flights	X	4.66	4.19	34.35	0.76
Intermediate measures					
Available seats	Z^1	730.76	759.25	7851.41	0.02
Available tonnage	Z^2	83.37	103.71	1321.64	12.76
Output of passenger transport function					
Passenger throughput	Y^1	536.54	639.31	6730.22	101.41
Output of freight transport function					
Cargo and mail throughput	Y^2	6.85	15.41	180.84	0.003

Table 3
Frequency distribution of efficiency scores or air routes using different network DEA models.

	Network DEA model 2				Network DEA model 6			
	ES1	EA1	EP1	EF1	ES2	EA2	EP2	EF2
1	0	0	1	1	0	0	0	1
0.9–1.0	2	2	24	0	27	2	24	0
0.8–0.9	10	3	139	0	132	3	135	0
0.7–0.8	145	18	113	0	108	6	108	0
0.6–0.7	210	333	94	2	111	157	90	2
0.5–0.6	102	100	63	0	78	156	61	0
0.4–0.5	7	18	40	11	3	90	40	11
0.3–0.4	1	2	3	20	1	24	1	28
0.2–0.3	0	1	0	44	0	15	2	68
0.1–0.2	0	0	0	66	7	12	0	144
0–0.1	0	0	0	333	10	12	16	223
Means	0.6576	0.6219	0.7171	0.0857	0.7084	0.5261	0.6921	0.1304
Variance	0.0777	0.0666	0.1401	0.1228	0.1704	0.1457	0.1886	0.1194
Min	0.3091	0.2233	0.3612	0.000008	0.0012	0.0009	0.0005	0.000001
Max	0.9259	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

the efficiency scores of ES EA, EP, and EF using network DEA model 6, named ES2, EA2, EP2, and EF2. The majority efficiency score of ES, EA, EP, and EF fall within the range of 0.5–0.8(account for 95.81%), 0.5–0.7(90.78%), 0.5–0.9(85.74%), and 0–0.2(92.87%), respectively, with network DEA model 2, which mainly fall within the same range of 0.5–0.8 (account for 64.57%), 0.4–0.7 (81.55%), 0.6–0.9 (72.54%), and 0–0.3 (90.99%), respectively, using network DEA model 6.

For the sub-functional efficiency of the air routes, we find that most air routes' EA and EP are high, while most air routes' EF is rather low. The reason for this is that, on the one hand, the development strategy of China's civil aviation pays more attention on the passenger transport, while thinks little of freight transport, so the airlines' investment on the passenger transport is not enough. At present, the operation of China's freight transport can be divided into two modes: all-cargo plane and the passenger plane transporting cargo. In 2013, there are only seven all-cargo airlines, whose freight transport only account for 27.4% of the country's. Therefore, the passenger plane transporting cargo is main mode of the freight transport, while for this kind of model, the priority is to transport the passenger, resulting in the inefficiency of freight business. On the other hand, China's shipping industry is facing fierce competition. Although the air transport plays an important role in China's comprehensive transportation system, it also faces fierce competition from the ground freight logistics. With the implementation of "National Expressway Network Plan", "National Long-term Railway Network Plan", the highways, high-speed railway has made great progress, thus, they also provide the service of the cargo transport. For example, to provide service to the high-value freight, the Railway Express launched the business named Today Arrival, The Next Day Arrival, The Next Morning Arrival. At the same time, the limited cargo transport capacity and the high charge of the air aviation result in the air route's low freight efficiency. The result reminds the airport administration that they should make the best use their facilities, improve the airport's freight throughput, and further strengthen the air routes' freight transport management.

The last fourth row of Table 3 is the average efficiency of the 477 air routes. The average of ES, EA, EP, and EF of the 477 air routes is 0.6576, 0.6219, 0.7171, and 0.0857 with network DEA model 2, respectively, which is 0.7315, 0.5301, 0.7166, and 0.1401 using with network DEA model 6, respectively.

To further examine the efficiency difference between the two network DEA models, Table 4 shows the results of the Wilcoxon signed-rank tests, in which the null hypotheses of three measures using are rejected, and the null hypotheses of PE is accepted, which is keeping with the distribution of the efficiency scores in Table 3. This suggests that based on different intermediate constraints, the evaluation of the air route performance may result in the different performance scores except the PE. In other words, different constraints on intermediate measure in network DEA models do affect the air route's efficiencies significantly different. Thus, in the following efficiency analysis, we focus on the efficiency scores of network DEA model 2.

To further examine the difference between the sub-functions of the air routes, we compute the Spearman correlation coefficients as shown in Table 5. The correlation coefficients between three substages and ES1 are high as they are part of ES1. The strongest correlation is obtained for EA1 and EP1, while EP1 and EF1 shows the weakest correlation. Based on the results, we construct the efficiency matrix in which the horizontal axis represents EP1 and the vertical axis EF1, where each air route is located as shown in Fig. 2. We can see that only one of the 477 air routes EF1 is higher than EP1, which is Shenzhen-Wuxi. Therefore, we can conclude that the air routes' EP is higher than EF.

4.3. Efficiency of airports

With the rapid development of China's economy, the demand for air service is growing. However, it has been difficult for airports in China to meet the increasing market demand. Consequently, the Civil Aviation Administration of China published the "12th Five-Year Plan for China's Civil Aviation" in 2011, which proposed that the total number of China's civil airports should reach 230, and cover most of its regions by 2015. At the same time, the plan required the airports to improve their resource allocation efficiency, optimize the utilization of infrastructure, and enhance the operating efficiency. To meet the needs of air transport, it is necessary to analyze the airport's system efficiency along with the different sub-functional efficiencies and provide suggestions to increase their efficiencies.

The air routes reflect the socioeconomic links between the airports involved as well as airport services. Therefore, it is necessary to calculate the efficiency of the connecting airports. The 477 air routes studied connect 82 airports.[2] Table 6 shows the frequency

[2] At present, only two city have two airport: Beijing and Shanghai. Since CAAC publishes only the civil aviation data of the air route, which not includes the information of the airports, in this study, the data of Beijing airport are the sum of those of the Beijing Capital International Airport and the Nanyuan International Airport, and the data of Shanghai airport are the sum of those of the Shanghai Pudong International Airport and the Shanghai Hongqiao International Airport.

Table 4
Summary of Wilcoxon signed-rank test results for measure effect.

	Wilcoxon signed-rank test
H0: ES1 = ES2; H1:ES1 ≠ ES2	P = −8.302, Z = 0.000
H0: EA1 = EA2; H1:EA1 ≠ EA2	P = 13.262, Z = 0.000
H0: EP1 = EP2; H1:EP1 ≠ EP2	P = 0.979, Z = 0.3276
H0: EF1 = EF2; H1:EF1 ≠ EF2	P = −7.77, Z = 0.000

Table 5
Spearman correlation coefficients between different sub-functions using different network DEA model.

	ES1	EA1	EP1	EF1
ES1	1			
EA1	0.6357*	1		
EP1	0.8763*	0.2635*	1	
EF1	0.3906*	0.2612*	0.3116*	1

Table 6
Frequency distribution of airport efficiency scores.

	ES1	EA1	EP1	EF1
1	0	0	0	0
0.9–1.0	0	0	0	0
0.8–0.9	0	0	15	0
0.7–0.8	11	0	32	0
0.6–0.7	58	55	30	0
0.5–0.6	13	21	5	0
0.4–0.5	0	6	0	0
0.3–0.4	0	0	0	0
0.2–0.3	0	0	0	2
0.1–0.2	0	0	0	14
0–0.1	0	0	0	66

distribution and summary statistics of each airport's average efficiency score. We find that the majority of airports fall within the range of 0.5–0.8, 0.5–0.7, 0.6–0.9, and 0–0.2 for ES, EA, EP, and EF using network DEA model 2, respectively, which are similar to the frequency distribution of the air routes.

To analyze the efficiency of airports with a large number air routes, we examine the efficiency of 36 airports with more than 10 air routes as shown in Table 7. These 36 airports have 834 air routes, accounting for 87.42% (834/954) of the total number of routes, and their total passenger and freight volumes account for 92.58% and 95.94% of the total volume of the country, respectively. Particularly in Beijing, Shanghai, and Guangzhou, their total passenger and freight volumes account for 30.26% and 46.26% of the total volume of airports, respectively. Table 7 shows the efficiencies of these 36 airports.

The second column of Table 7 shows the number of air routes for each airport. We can see that eight airports have more than 30 air routes, and Beijing has the most number of air routes. The allocation service efficiency is the highest for Sanya and Beijing airports, while it is the least for Xian and Hohhot airports (see third column). In the last column pertaining to system efficiency, Beijing airport has the highest efficiency, followed by Shanghai airport, reflecting that the air route resources of these two airports are utilized efficiently. Nowadays, these two airports are the busiest airports in China. According to the national civil aviation flights operating efficiency report of 2014, the average daily flights of 13 air routes were more than 500, which are mainly located in Beijing and Guangzhou areas. The busiest air stage is Beijing–Xi'an through Taiyuan, whose daily flights are more than 1100. Beijing airport enjoys unique political, economic, cultural, and geographical

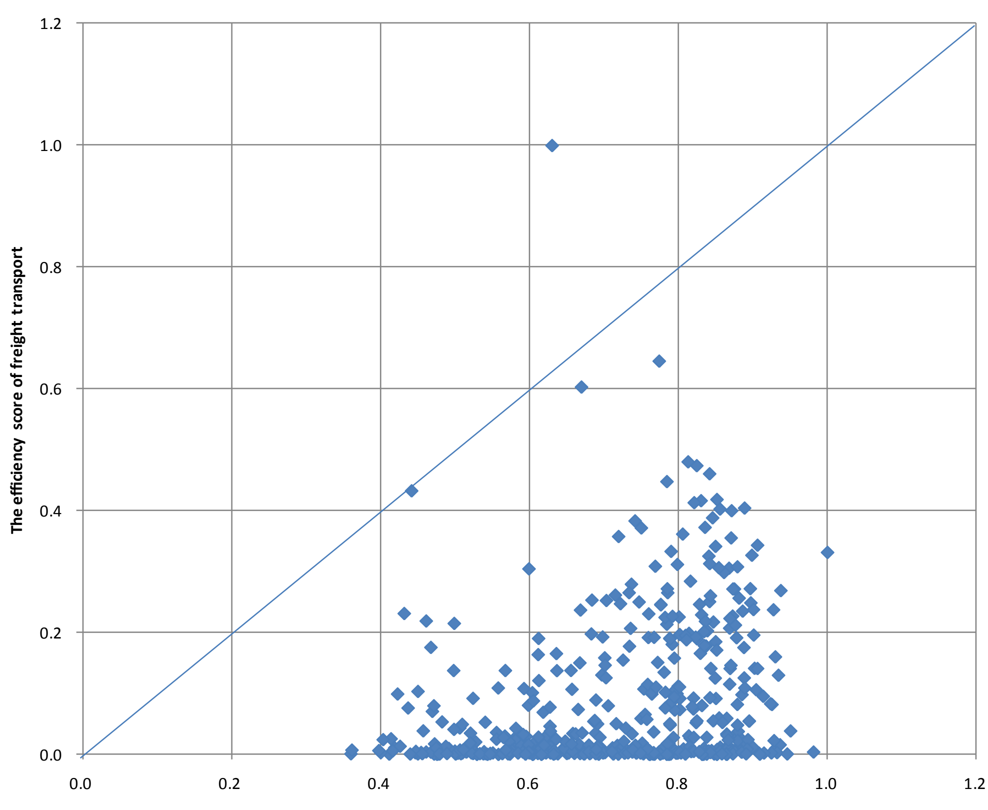

Fig. 2. EP1 (passenger) vs. EF1 (freight).

Table 7
Airports' system efficiency and sub-functional efficiency.

	Number of air routes	EA1	EP1	EF1	ES1
Beijing	63	0.6656	0.8128	0.1174	0.7225
Shanghai	46	0.6594	0.8176	0.1192	0.7218
Guangzhou	44	0.6220	0.8329	0.1444	0.6999
Chengdu	42	0.6563	0.8227	0.1472	0.7206
Xi'an	38	0.5979	0.6984	0.0458	0.6349
Kunming	37	0.6100	0.7387	0.0842	0.6589
Chongqing	35	0.6081	0.7206	0.0448	0.6502
Shenzhen	35	0.6318	0.7949	0.2479	0.6964
Hangzhou	28	0.6010	0.6940	0.1486	0.6354
Xiamen	28	0.6425	0.6661	0.0703	0.6518
Wuhan	27	0.6205	0.6191	0.0577	0.6197
Changsha	27	0.6435	0.5966	0.0424	0.6249
Qingdao	24	0.6119	0.6016	0.0702	0.6082
Nanjing	23	0.6122	0.6625	0.1020	0.6309
Zhengzhou	23	0.6166	0.6294	0.0903	0.6211
Haikou	22	0.6254	0.7636	0.0830	0.6784
Guiyang	20	0.6059	0.6929	0.0494	0.6385
Fuzhou	18	0.6353	0.6356	0.0709	0.6347
Nanning	18	0.6008	0.6643	0.0800	0.6241
Sanya	18	0.6712	0.7793	0.0128	0.7145
Tianjin	18	0.6010	0.6863	0.0790	0.6331
Urumqi	18	0.6127	0.6501	0.0745	0.6224
Dalian	17	0.6018	0.6786	0.0378	0.6250
Ji'nan	17	0.6320	0.5943	0.0373	0.6175
Taiyuan	17	0.6108	0.6347	0.0363	0.6201
Shenyang	14	0.6424	0.6606	0.1142	0.6494
Wenzhou	14	0.6121	0.7405	0.1025	0.6611
Harbin	13	0.6483	0.6667	0.0680	0.6557
Hefei	12	0.6358	0.6567	0.0689	0.6442
Hohhot	12	0.5396	0.6360	0.0263	0.5720
Nanchang	12	0.6182	0.6969	0.0390	0.6483
Changchun	12	0.6329	0.6038	0.0890	0.6224
Guilin	11	0.6473	0.7745	0.0425	0.6971
Shijiazhuang	11	0.6020	0.7480	0.0390	0.6589
Lanzhou	10	0.6276	0.6523	0.0603	0.6377
Ningbo	10	0.6267	0.7308	0.1115	0.6654

Table 8
Correlation coefficients between the number of air routes and efficiency of different sub-functions.

EA1	EP1	EF1	ES1
0.5252***	0.282	0.5363***	0.4575***

Note: *** denotes significance level at 1%.

advantages. In 2012, the Beijing Capital International Airport (BCIA) passenger throughput was more than 81.93 million, which remained the world's second busiest airport in terms of passenger throughput. In the same year, the airport also devoted to improving its service quality and operating efficiency. It was the first domestic airport that constructed the first passenger service management platform. According to the passenger satisfaction survey of the International Airport Association (ACI), BCIA's global ranking rose from 62nd in 2006 to 3rd in 2013.

Table 8 shows the correlation coefficients of the airports' efficiency and their number of air routes. The correlation coefficients of 36 airports and their route numbers are all positive and significant at 1% level, except for EP1. This implies that the airport with a large number of air routes can also make good use of air aviation resources.

Among the 82 airports, 17 airports have only one air route and 15 airports have two air routes, while their passenger throughput and freight throughput account for only 1.69% and 0.46%, respectively. Among the 32 airports, 6 airports' ES is greater than 0.7, accounting for 54.55% (6/11) of the total airports in this range; 13 airports' EA is in the range of 0.5–0.6, accounting for 61.9% (13/21) of the total number of airports in the range, therefore, most airports EA is low. Eight airports' PE is in the range of 0.8–0.9, accounting for 53.33% (8/15) of the total airports in the range. While these airports have advantages in terms of passenger transport, affected by flight restrictions, and their efficiency in allocation of air route resource is low.

5. Conclusion

Compared with the traditional DEA model, the network DEA model can calculate the airport's system and sub-functional efficiencies. This paper proposed two network DEA models to analyze the system efficiency, allocation efficiency, passenger transport efficiency, and freight transport efficiency of 477 air routes in 2013. The results show that network DEA models can help us to find the reasons for the air route's inefficiency, and different constraints on intermediate measure in the network DEA models do affect the air route's efficiencies significantly. The results also show that most air route's efficiency of freight transport was much lower than its efficiency of passenger transport, and the airports with many air routes also have high efficiencies. So these results can help the governors to find the advantages and disadvantages of different functions of the airport.

The contribution of this paper to the existing literatures is embodied in the following two aspects. First, a two-stage network operating framework to evaluate the efficiency of the air route is proposed. Compared with existing papers, this study provides a new viewpoint for evaluating the performance of air route. Second, the efficiency of the main air route is discussed in several aspects, and the empirical results shed insight into the sources of inefficiency in the air route's operation, thus the relevant policy makers can use our research results to find the advantages and disadvantages of different functions of air routes and explore the reasons for their inefficiencies.

Acknowledgements

The paper acknowledges the funding from the National Natural Science Foundation of China (71573251, 71103177). We are grateful for the comments and suggestions from the editors and two reviewers.

References

Adler, N., Liebert, V., Yazhemsky, E., 2013. Benchmarking airports from a managerial perspective. Omega 41, 442–458.
Akther, S., Fukuyama, H., Weber, W.L., 2013. Estimating two-stage network slacks-based inefficiency: an application to Bangladesh banking. Omega Int. J. Manag. Sci. 41, 88–96.
Cao, Q., Lv, J., Zhang, J., 2015. Productivity efficiency analysis of the airlines in China after deregulation. J. Air Transp. Manag. 42, 135–140.
Cento, A., 2008. The Airline Industry: Challenges in the 21st Century. Springer Science & Business Media.
Charnes, A., Cooper, W.W., Rhodes, E., 1978. Measuring the efficiency of decision making units. Eur. J. Oper. Res. 2, 429–444.
Chen, Y., Du, J., David Sherman, H., Zhu, J., 2010. DEA model with shared resources and efficiency decomposition. Eur. J. Oper. Res. 207, 339–349.
Chiou, Y.-C., Chen, Y.-H., 2006. Route-based performance evaluation of Taiwanese domestic airlines using data envelopment analysis. Transp. Res. Part E Logist. Transp. Rev. 42, 116–127.
Cui, Q., Li, Y., 2015a. The change trend and influencing factors of civil aviation safety efficiency: the case of Chinese airline companies. Saf. Sci. 75, 56–63.
Cui, Q., Li, Y., 2015b. Evaluating energy efficiency for airlines: an application of VFB-DEA. J. Air Transp. Manag. 44, 34–41.
Fan, L., Wu, F., Zhou, P., 2014. Efficiency measurement of Chinese airports with flight delays by directional distance function. J. Air Transp. Manag. 34, 140–145.
Farrell, M.J., 1957. The measurement of productive efficiency. J. R. Stat. Soc. Ser. A General. 120, 253–290.
Fung, M.K.Y., Wan, K.K.H., Hui, Y.V., Law, J.S., 2008. Productivity changes in Chinese airports 1995–2004. Transp. Res. Part E Logist. Transp. Rev. 44, 521–542.

Kao, C., Hwang, S.-N., 2008. Efficiency decomposition in two-stage data envelopment analysis: an application to non-life insurance companies in Taiwan. Eur. J. Oper. Res. 185, 418–429.

Li, Y., Wang, Y.-z., Cui, Q., 2015. Evaluating airline efficiency: an application of virtual frontier network SBM. Transp. Res. Part E Logist. Transp. Rev. 81, 1–17.

Liang, L., Cook, W.D., Zhu, J., 2008. DEA models for two-stage processes: game approach and efficiency decomposition. Nav. Res. Logist. 55, 643–653.

Lu, W.M., Wang, W.K., Hung, S.W., Lu, E.T., 2012. The effects of corporate governance on airline performance: production and marketing efficiency perspectives. Transp. Res. Part E Logist. Transp. Rev. 48, 529–544.

Mallikarjun, S., 2015. Efficiency of US airlines: a strategic operating model. J. Air Transp. Manag. 43, 46–56.

Tavassoli, M., Faramarzi, G.R., Farzipoor Saen, R., 2014a. Efficiency and effectiveness in airline performance using a SBM-NDEA model in the presence of shared input. J. Air Transp. Manag. 34, 146–153.

Tavassoli, M., Faramarzi, G.R., Farzipoor Saen, R., 2014b. Efficiency and effectiveness in airline performance using a SBM-NDEA model in the presence of shared input. J. Air Transp. Manag. 34, 146–153.

Wang, J., Bonilla, D., Banister, D., 2016. Air deregulation in China and its impact on airline competition 1994–2012. J. Transp. Geography 50, 12–23.

Yu, M.-M., 2010. Assessment of airport performance using the SBM-NDEA model. Omega 38, 440–452.