Evaluation of Coordinated Development of Beijing-Tianjin-Hebei Transportation Based on Super-efficiency DEA Model

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Abstract. We have developed and implemented Super-efficiency DEA (SE-DEA) model for evaluating the coordinated development of railway, highway and aviation in Beijing-Tianjin-Hebei (BTH) region compared with the traditional DEA (T-DEA) model. The evaluation of the internal and overall collaborative development of the transportation is carried out to verify that SE-DEA model can sort the efficient schemes. At the same time, within the way of transportation, the imbalance of input and output in the highway is serious. The overall coordinated development of the railway, highway and aviation is better, only appeared unbalance during the construction of Beijing-Tianjin high-speed railway. And the coordinated development in the latter period is declining, which is closely related to the slow economic development in Hebei Province, the near-saturation of the highway and the longer construction period of the railway.

Introduction

With the economic development of Beijing-Tianjin-Hebei (BTH) urban agglomeration, transportation has achieved a leap-forward development. However, it appeared "Beijing transfer", "broken road", "bottleneck section" and other issues for Beijing as the core of railway and highway. How to evaluate the current coordinated development of BTH transportation and provide an important reference direction for the future planning is an urgent problem.

The traditional DEA (T-DEA) method was proposed by Charnes, Cooper and Rhode in 1978 and it was designed to evaluate the relative efficiency of decision making units (DMUs) in the multiple input and multiple output mode. Andersen and Petersen (1993) proposed super-efficiency DEA (SE-DEA) model. Effective DMUs could be compared and ranked. Zhao et al. (2016) established the coordinated development T-DEA model of BTH. It is concluded that the coordinated development ability of BTH transportation system is not optimal. The T-DEA model was used to discuss the coordinated development of BTH regional economic complex system by Liu (2014). Yang et al. (2015) measured environmental efficiency by super-efficiency data envelopment analysis model.

At present, there are two main problems: First, there is few studies on the coordinated evaluation of BTH transportation. Second, the T-DEA model was used to evaluate mostly, but the T-DEA model cannot be further distinguish efficient DMUs. Based on the achievements, this paper introduces the construction of T-DEA and SE-DEA model firstly, then analyzes the model principle and characteristics, further more evaluates the coordinated development of BTH transportation by SE-DEA model, which can further distinguish the efficient DMUs and rank the degree of coordinated development of the transportation.

Model

T-DEA Model

Assuming that there are n DMUs and each one has m input indicators and s output indicators which are respectively denoted by $X_j = (x_{j1}, x_{j2}, \ldots, x_{jm})^T$ and $Y_j = (y_{j1}, y_{j2}, \ldots, y_{js})^T$, where $x_{ji}$ is the $i^{th}$ input index in the $j^{th}$ DMU; $y_{jr}$ is the $r^{th}$ output index in the $j^{th}$ DMU; $X_j$ and $Y_j$ are the known data.
The T-DEA model of the DMU can be obtained:

\[
\begin{align*}
\min \theta \\
\sum_{j=1}^{n} X_j \lambda_j \leq \theta X_0 \\
\text{st.} \quad \sum_{j=1}^{n} Y_j \lambda_j \geq Y_0 \\
\lambda_j \geq 0
\end{align*}
\]

(1)

The dual relaxation model is obtained by introducing the slack variable:

\[
\begin{align*}
\min z = \theta \\
\sum_{j=1}^{n} X_j \lambda_j + S^- = \theta X_0 \\
\text{st.} \quad \sum_{j=1}^{n} Y_j \lambda_j - S^+ = Y_0 \\
\lambda_j \geq 0, S^- \geq 0, S^+ \geq 0
\end{align*}
\]

(2)

(3)

Where:
- \( \varepsilon \) is Non-Archimedes infinitesimal, usually taken \( 10^{-5} - 10^{-6} \).
- \( \theta \) is the efficiency of the DMU.
- \( S^- \) is the slack variable corresponding to the input;
- \( S^+ \) is the residual variable corresponding to the output;
- \( \lambda_j \) is the input and output index coefficient;

**SE-DEA Model**

The T-DEA model can distinguish the DMU into two categories: efficient and inefficient, but it is difficult to further distinguish the efficient DMUs. In order to make up for this deficiency, the SE-DEA model is proposed, which can rank all DMUs including efficient and inefficient DMUs. The basic idea is: when evaluating the efficiency of a DMU, it is excluded first.

\[
\begin{align*}
\min z = \theta \\
\sum_{j=1}^{n} X_j \lambda_j + S^- = \theta X_0 \\
\text{st.} \quad \sum_{j=1}^{n} Y_j \lambda_j - S^+ = Y_0 \\
\lambda_j \geq 0, S^- \geq 0, S^+ \geq 0
\end{align*}
\]

(4)

(5)

Compared with T-DEA model, it's assumed that there are 4 DMUs: A, B, C, and D, in which A to C are efficient and D is inefficient by T-DEA model. Figure 1 shows the principle of evaluation with T-DEA model and SE-DEA model respectively described above.
As shown in Figure 1 (a), in the process of evaluating by T-DEA model, three efficient DMUs constitute the production frontier ABC. D is an inefficient one which is surrounded by production frontier. B₁ and D₁ are the intersections of OB and OD on the production frontier ABC, then the efficiency of DMU B is OB₁ / OB = 1. And the efficiency of DMU D is OD₁ / OD < 1. That is, the efficiency of DMU on the production frontier is 1, and that of inefficient DMU is less than 1.

The evaluation process by SE-DEA model is shown in Figure 1 (b). When the efficiency of DMU B is calculated, DMU B will be excluded from the reference set of the evaluation DMUs, and the production frontier ABC becomes to AC. The efficiency of DMU B becomes OB₁ / OB > 1, where BB₁ is called expandable ratio, which can be used to sort the DMUs. And the efficiency of the original inefficient DMU D is unchanged because the production frontier has not changed. Therefore, the efficiency of SE-DEA model is greater than 1 for efficient DMU, but for inefficient DMU, the efficiency is unchanged compared with T-DEA model.

The optimal solution of the model is \( \theta^*, s^- \) and \( s^- \), which can be used as following:

1) When \( \theta^* \geq 1 \), the evaluation scheme is efficient. We can further distinguish the efficient schemes according to \( \theta^* \). The larger the \( \theta^* \) value is, the better the scheme is.

2) When \( \theta^* < 1 \), the evaluation scheme is inefficient, and the projection onto the efficient production frontier can be calculated:

\[
X^*_0 = \sum_{j \in \mathcal{I}} X_j \lambda^*_j = \theta^* X_0 - S^- \\
Y^*_0 = \sum_{j \in \mathcal{I}} Y_j \lambda^*_j = Y_0 + S^- 
\]  
(7)  

(8)

**Evaluation Process**

The process of SE-DEA model is shown in Figure 2:

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When using the SE-DEA model, we need first determine the evaluation index according to purpose principle, scientific principle, representative principle and operability principle

Example Analysis

We select the traffic infrastructure investment and the number of employees as input indicators, freight traffic and passenger traffic as output indicators referring to the indicators (Zhao 2016) and evaluate coordinated development of BTH transportation in 2003-2012 by T-DEA and SE-DEA models according to the data in Hebei, Tianjin and Beijing Statistical Yearbook.

Evaluation of Coordinated Development of Railway, Highway and Aviation Interior Systems

T-DEA model and SE-DEA model were used to evaluate development of railway, highway and aviation interior respectively. The results were shown in Table 1.

It can be seen from Table 1 that when the evaluation scheme is inefficient, the efficiency of SE-DES model is consistent with that of T-DEA model. When the evaluation scheme is efficient, the efficiency of the SE-DEA model is greater than 1, while the efficiency of the T-DEA model is equal to 1. In this case, the efficient schemes can be sorted according to the efficiency of the SE-DEA model.

| year | railway T-DEA | railway SE-DEA | highway T-DEA | highway SE-DEA | aviation T-DEA | aviation SE-DEA |
|------|---------------|---------------|---------------|---------------|---------------|---------------|
| 2003 | 0.7871        | 0.7871        | 0.804         | 0.804         | 0.8215        | 0.8215        |
| 2004 | 0.8733        | 0.8733        | 1             | 1.0642        | 0.6983        | 0.6983        |
| 2005 | 1             | 1.9865        | 1             | 1.0357        | 0.7473        | 0.7473        |
| 2006 | 0.8988        | 0.8988        | 0.6344        | 0.6344        | 0.9179        | 0.9179        |
| 2007 | 0.926         | 0.926         | 0.6082        | 0.6082        | 0.9485        | 0.9485        |
| 2008 | 1             | 1.0777        | 0.8909        | 0.8909        | 0.7667        | 0.7667        |
| 2009 | 0.9592        | 0.9592        | 0.8201        | 0.8201        | 1             | 2.5589        |
| 2010 | 0.9116        | 0.9116        | 0.9673        | 0.9673        | 1             | 1.1849        |
| 2011 | 0.9398        | 0.9398        | 1             | 1.2866        | 0.7521        | 0.7521        |
| 2012 | 1             | 1.0706        | 0.8399        | 0.8399        | 0.69          | 0.69          |

For example, in the evaluation of railway interior system, the input and output are balanced in 2005 and 2008, but it is difficult to evaluate operation effect further for T-DEA model. The efficiency of SE-DEA model in 2005 and 2008, respectively, 1.9865, 1.0777, so it can be concluded that the coordinated development of railway interior system in 2005 is better than that in 2008.

The results of the table are summarized in Figure 3.

Figure 3. Comparison of T-DEA and SE-DEA Models within the way of transportation.
The efficiency of railway, highway and aviation in most years are distributed below the efficiency of 1, and the input and output are unbalanced. At the same time, through the results of SE-DEA model, the development of railway interior system is better than that in highway interior system, and the development of highway interior system is better than that in aviation interior system. The relatively short distance between BHT caused the input and output of aviation interior unbalanced.

**Evaluation of Integrated Coordinated Development among Railway, Highway and Aviation**

The T-DEA model and SE-DEA model were used to evaluate the integrated coordinated development among railway, highway and aviation. The results are shown in Table 2.

| YEAR | T-DEA | SE-DEA | YEAR | T-DEA | SE-DEA |
|------|-------|--------|------|-------|--------|
| 2003 | 1     | 1.1521 | 2008 | 0.984 | 0.984  |
| 2004 | 1     | 1.0392 | 2009 | 0.9164| 0.9164 |
| 2005 | 1     | 1.0273 | 2010 | 1     | 1.1246 |
| 2006 | 0.8026| 0.8026 | 2011 | 1     | 1.1416 |
| 2007 | 0.7633| 0.7633 | 2012 | 0.8091| 0.8091 |

The integrated coordinated development efficiency of the railway, highway and aviation shows the trend of decreasing first and then rising from 2003 to 2012. The demarcation point is in 2008 when Beijing-Tianjin high-speed railway opened. The nation accelerated the investment in the construction of high-speed railway and highway, which made the regional traffic develop rapidly. In 2006-2008, 2012, the degree of coordinated development was inefficient. Table 3 listed the redundant input indicators and deficient output indicators according to the results from SE-DEA model.

| year  | redundant input | output deficiency | number of employees | infrastructure investment | Freight /ten thousand tons | Passenger /ten thousand |
|-------|-----------------|-------------------|---------------------|--------------------------|---------------------------|------------------------|
| 2006  | 6.86952         | 47.00094          | 0                   | 66740                    |                           |
| 2007  | 8.26083         | 29.43359          | 0                   | 61371                    |                           |
| 2008  | 0.5792          | -95.0868          | 39742               | 0                        |                           |
| 2009  | 3.35236         | 22.73084          | 11614               | 0                        |                           |
| 2012  | 13.45845        | 60.8971           | 0                   | 3003                     |                           |

It can be seen, transportation infrastructure investment is over redundant, but passenger traffic is low, which may be due to preparing for the opening of the high-speed railway in 2006 and 2007. While the Beijing-Tianjin high-speed railway opened in 2008, the amount of redundancy has declined and there is sufficient passenger capacity in 2008-2009. In 2010-2011, the traffic coordination is better. But in 2012, there was a problem of excessive investment but insufficient passenger traffic.

**Conclusion**

In this paper, the SE-DEA model is used to evaluate coordinated development of railway, highway and aviation in BTH compared with T-DEA model, and draws the following conclusions:

1) It verifies the superiority of SE-DEA model in distinguishing the efficiency, and can sort the DMUs, which gives the real development trend of the internal and whole of the transportations.

2) In the internal transportation, the input and output of highway is unbalanced seriously.

3) The overall coordinated development of railway, highway and aviation is balanced except the unbalance during the construction of Beijing-Tianjin high-speed railway regardless of internal transportation problems. And the degree of coordinated development have declined, which may have a great relationship with the slow economic development of Hebei Province and the longer railway construction period.
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