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DEA-based Malmquist Productivity Index Measure of Operating Efficiencies: New Insights with an Application to Container Ports

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Abstract: To investigate the long-term operating efficiencies of container ports, we extend the work of previous researches to present a new systemic and improved method of data envelopment analysis (DEA)-based Malmquist productivity index (MPI) in this paper. An approach based on both panel data and multi-inputs/outputs is considered comprehensively, and aims at measuring the operating efficiencies of 10 leading container ports in China from 2001 to 2006 by applying this new systematic calculation method. The results illustrate that the main influence factor of total factor productivity change is the technology change, and the container transportation of these 10 ports is on the healthy development status and will recover and grow reposefully in the following years.
Key words: port operating efficiency, Malmquist productivity index (MPI), data envelopment analysis (DEA)
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Introduction

In recent years, the container port industry has received increasing attention, concomitant with containerized transportation coming to the forefront of the international shipping scene. The analysis of the operating efficiencies of container ports is of great importance for the survival and competitiveness of the industry. Such an analysis not only provides a powerful management tool for port operators, but also is important for informing regional and national transport/port planning and operations.

This research provides a systematic calculation method about data envelopment analysis (DEA)-based Malmquist productivity index (MPI) measure, and an application for operating efficiencies of 10 container ports in China from 2001 to 2006 is shown in this paper. The MPIs were first suggested by Malmquist as quantity indices for use in the analysis of consumption of inputs. This DEA-based MPI has proven itself to be a good tool for measuring the productivity change of decision making units (DMUs), e.g., changes in agricultural productivity in 18 developing countries[1], telecommunications productivity, technology catch-up and innovation in 74 countries[2], and evaluations in the changes of efficiency of 50 sea ports[3].

However, there are still some scarce with previous researches. First, multiple inputs and outputs lead multiple correlation problems, which make the information of DMUs overlap. But DEA requests that the selected indices are as independent as possible. Second, the efficiency score for DMU will be close to 1, when the index set is extended to some scale. There is an empirical law that the number of DMUs should be at lease twice as the sum of inputs and outputs[4]. Third, DEA is restricted within lack of information, e.g. time, energy, the collection of data and so on. On one hand, with a limited number of DMUs, if we reduce the index set to satisfy the constraint condition of DEA, the reliability and quality will be affected; on the other hand the efficiency score for DMU will be close to 1 with method of DEA directly, that will be disadvantage to gain different information from DMUs, and the evaluation of efficiency will be invalid.

This paper aims at filling these gaps. To investigate the long-term operating efficiencies of leading international container ports, an approach based on both panel data and multi-inputs/outputs should be considered comprehensively.

1 Methodology

In Ref. [5], using linear programming techniques, DEA provides a suitable way to estimate a multi-input/multi-output empirical efficient function as described. Given a set of DMUs with multi-input and multi-output, DEA determines a best-practice or efficient frontier without a priori information on tradeoffs among inputs and outputs. The DEA frontier DMUs are those with maximum output levels given by input levels or with minimum input levels given by output levels. DEA provides efficiency scores for individual units as their technical efficiency measure, with a score

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of one assigned to the efficient frontier units. Färe *et al*[6] constructed the DEA-based MPI, and they decomposed their Malmquist productivity index into two components; one measures the change in efficiency, and the other measures the change in the frontier technology. The frontier technology determined by the efficient frontier is estimated using DEA for a set of DMUs. However, the frontier technology for a particular DMU under evaluation is only represented by a section of the DEA frontier or a facet[7].

Suppose we have a production function in time period t as well as period $t+1$ Malmquist index, and calculation requires two single period and two mixed period measures. The two single period measures can be obtained by using the CCR (Charnes-Cooper-Rhodes) DEA model[5]:

$$\left.\begin{aligned} & d_k^t(x_k^t, y_k^t) = \min\theta \\ & \text{s.t.} \quad \sum_{j=1}^{n} \lambda_j x_{ij}^t \leqslant \theta x_{ik}^t \\ & \qquad i = 1, 2, \cdots, m; \quad k \in \{1, 2, \cdots, n\} \\ & \qquad \sum_{j=1}^{n} \lambda_j y_{rj}^t \geqslant y_{ik}^t, \quad r = 1, 2, \cdots, s \\ & \qquad \lambda_j \geqslant 0, \quad j = 1, 2, \cdots, n \end{aligned}\right\}, \tag{1}$$

where $d(\cdot)$ is a distance function, x_{ik}^t is the ith input and y_{rk}^t is the rth output for DMU_k in time period t. The efficiency ($d_k^t(x_k^t, y_k^t) = \theta_k^*$) determines the amount by which observed inputs can be proportionally reduced, while still producing the given output level. Instead of t for the above model, we get $d_k^{t+1}(x_k^{t+1}, y_k^{t+1})$, the technical efficiency score for DMU_k in time period $t+1$.

The first of the mixed period measures, which is defined as $d_k^t(x_k^{t+1}, y_k^{t+1})$ for each DMU_k, $k \in \{1, 2, \cdots, n\}$, is computed as the optimal value to the following linear programming problem:

$$\left.\begin{aligned} & \min\theta \\ & \text{s.t.} \quad \sum_{j=1}^{n} \lambda_j x_{ij}^{t+1} \leqslant \theta x_{ik}^t, \quad i = 1, 2, \cdots, m \\ & \qquad \sum_{j=1}^{n} \lambda_j y_{rj}^{t+1} \geqslant y_{ik}^t, \quad r = 1, 2, \cdots, s \\ & \qquad \lambda_j \geqslant 0, \quad j = 1, 2, \cdots, n \end{aligned}\right\}. \tag{2}$$

Färe *et al*[6] specified an input-based total index change of a particular DMU_k, which also named as total factor productivity change (TFPCH_k):

$$\text{TFPCH}_k = \left[\frac{d_k^t(x_k^{t+1}, y_k^{t+1})}{d_k^t(x_k^t, y_k^t)} \cdot \frac{d_k^{t+1}(x_k^{t+1}, y_k^{t+1})}{d_k^{t+1}(x_k^t, y_k^t)}\right]^{1/2}. \tag{3}$$

TFPCH_k measures growth or declines of productivity over time. It can be seen that the above measure actually is the geometric mean of two MPIs. Thus, the following research defines that $\text{TFPCH}_k > 1$ indicates productivity gain, $\text{TFPCH}_k < 1$ indicates productivity loss, and $\text{TFPCH}_k = 1$ means no change in productivity from time t to $t+1$. Then the index was decomposed into two components:

$$\begin{aligned} & \text{TFPCH}_k = \\ & \left[\frac{d_k^t(x_k^{t+1}, y_k^{t+1})}{d_k^t(x_k^t, y_k^t)} \cdot \frac{d_k^{t+1}(x_k^{t+1}, y_k^{t+1})}{d_k^{t+1}(x_k^t, y_k^t)}\right]^{1/2} = \\ & \frac{d_k^{t+1}(x_k^{t+1}, y_k^{t+1})}{d_k^t(x_k^t, y_k^t)}\left[\frac{d_k^t(x_k^{t+1}, y_k^{t+1})}{d_k^{t+1}(x_k^{t+1}, y_k^{t+1})} \times \right. \\ & \left. \frac{d_k^t(x_k^t, y_k^t)}{d_k^{t+1}(x_k^t, y_k^t)}\right]^{1/2}. \end{aligned} \tag{4}$$

The first component technical efficiency change (EFFCH_k) is a ratio of two distance functions which measure the change in the technical efficiency between the periods of change:

$$\text{EFFCH}_k = \frac{d_k^t(x_k^{t+1}, y_k^{t+1})}{d_k^t(x_k^t, y_k^t)}. \tag{5}$$

The second component technology change (TECHCH_k) is a measure of the technological change in the production technology, an indicator of the distance covered by the efficient frontier from one period to another. It measures the technology frontier shifts between time t to $t+1$:

$$\text{TECHCH}_k = \left[\frac{d_k^t(x_k^{t+1}, y_k^{t+1})}{d_k^{t+1}(x_k^{t+1}, y_k^{t+1})} \cdot \frac{d_k^t(x_k^t, y_k^t)}{d_k^{t+1}(x_k^t, y_k^t)}\right]^{1/2}. \tag{6}$$

The above approach can be extended by decomposing the EFFCH_k into scale efficiency change (SECH_k) and pure technical efficiency change (PECH_k) components:

$$\begin{aligned} \text{TFPCH}_k = & \text{EFFCH}_k \cdot \text{TECHCH}_k = \\ & (\text{SECH}_k \cdot \text{PECH}_k)\text{TECHCH}_k. \end{aligned} \tag{7}$$

Researches[1-2] display that the EFFCH_k obtained from a constant returns to scale (CRS) DEA has been decomposed into two components as variable returns to scale (VRS) situations, viz. SECH_k and PECH_k. Both SECH_k and PECH_k are components of EFFCH_k. The use of the CRS specification when not all DMUs are operating at the optimal scale will result in measures of EFFCH_k which are confounded by scale efficiencies. The use of the VRS specification will permit the calculation of technical efficiency devoid of these scale efficiencies effects. The SECH_k is the ratio of efficiency under constant return to scale and the same efficiency under variable return to scale, which means the efficiency change decided by the scale of DMU_k, and the PECH_k is a component of the technical efficiency change and obtained by re-computing efficiency change under the variable return to scale, which means the technical efficiency change measured between the periods for VRS situations. In VRS situations, the EFFCH_k is an integrative efficiency change decided both in scale factor and technical factor. All of the values of MPIs being higher than one indicate a positive improvement or technical progress, contrarily, a recessionary process, and the value being equal to one indicates no shift correspondingly.

2 Three Steps before DEA-based MPI

After the review of researches[8-11], to be in compliance with characteristic of consistency for this DEA-based MPI method, this paper adopts 5 outputs and 5 inputs for each DMU as shown in Table 1. The input and output indices selected for DEA-based MPI must be representative and have remarkable change from 2001 to 2006. We obtain results via comparison at different times. If the discrepancy of factor in these seven years is not obvious, it has a weak effect in this method, and the analysis of the factor is insignificant. Such as working days, which are decided by the climate condition, they are all almost 330 days and have little fluctuation. The highway connection conditions with port as a part of collecting and distributing system almost do not change in these seven years, nor do the water depths of berth. We all do not take the above mentioned factors into account. To be different from previous research on ports' efficiency, we adopt gross domestic product (GDP) of hinterland and secondary industry of hinterland to reflect the capacity to bring supply of goods containerized to transport from their hinterland.

In this paper, 10 leading container ports in China are selected as DMUs, and the data of ports are collected mainly from China Ports Yearbook (various issues), Report on Ports and Shipping Development of China (various issues), and the annual statistical data of various port authorities from 2001 to 2006. The flow chart of container ports evaluation is shown in Fig. 1.

A pretreatment is used by a multivariate statistical method-principal component analysis (PCA) before DEA-based MPI. PCA is a data reduction technique, combines new multiple measures defined by the inputs/outputs, which is used to identify a small set of indices that account for a large part of the total variance in the original indices[12].

Before evaluating the operating efficiency of container ports, there are certain questions of the application of PCA: during the process of PCA, in order to describe the object more integrally, the appraisers usually tend to select relative indices as comprehensive as possible. Then a wrong comprehension is formed: the PCA can eliminate multiple correlations of samples and

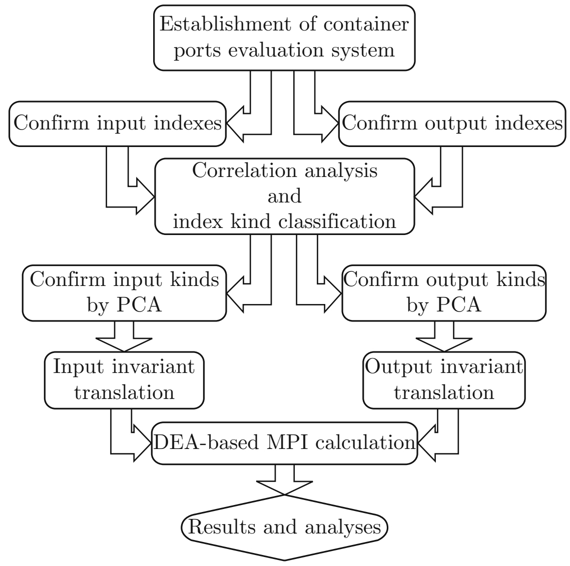

Fig. 1 The flow chart of container ports evaluation

the adverse effects of overlapping information among indices. During the course of establishing index system and selecting indices, researchers are inclined to adopt the viewpoint of "the more the better". But this viewpoint has failed to grasp the essence of PCA. In fact, the multiple correlations of indices inevitably distort the real data both from the direction and the quantity. The PCA can effectively transform an index system from high-dimensional to low-dimensional, and indices of the system do not correlate each other in the new index system. But the results of PCA can not eliminate the influence of overlapping information between the indices effectively, when adopting some meaningless correlative indices. According to the research by Zhang *et al*[13], it is necessary to establish the evaluation system to reflect port performance systematically before PCA, and make correlation analysis for the index sample. We can classify all the factors affecting the index system, and then calculate various kinds of inputs/outputs by PCA method. In this way, superposition of indices can be avoided effectively to some extent.

2.1 Correlation Analysis and Indices Classification

To confirm the correlation between selected inputs and outputs, this paper applies analysis of pearson correlation coefficients at 0.01 significant level (two-tailed). For Inputs Indices, X_1 isn't significant with other inputs, so we name it Input I. There are high correlations between indices of X_2 and X_3, and the Pearson correlation coefficient is 0.938, and we call them Input II; X_4 and X_5 also have high correlations, and the Pearson correlation coefficient is 0.994, and we name them Input III. The Inputs aren't significant among Input I, II and III, as shown in Table 1. For the outputs indices, there are also high correlations among indices of Y_1, Y_2, Y_3 and Y_4, and the Pearson correlation coefficients mean, the minimal and maximal values are 0.905, 0.848, 0.991 respectively, and they are belong to Output I. Y_5 isn't significant with the other outputs, so we name it Output II, as shown in Table 1.

Table 1 Description of initially selected input/output indices

Index	Unit	Description	Kind
Inputs	Proportion of more than 10^4 DWT* berth X_1 (%)	Proportion of more than 10^4 DWT berth number in all the port's berth number	Input I
	Container quay length X_2 (km)	Total length of container berth	Input II
	Container gantry cranes X_3 (units)	Number of container gantry cranes	
	GDP of hinterland X_4 (100 million)	Value of GDP of their hinterland	Input III
	Secondary Industry of hinterland X_5 (100 million)	Value of secondary industry of their hinterland	
Outputs	Container throughput Y_1 (10^4 TEUs**)	Annual container throughput	Output I
	Foreign trade of container throughput Y_2 (10^4 TEUs)	Annual container throughput due to foreign trade	
	Shipping lane Y_3 (units)	Number of shipping lane of containership	
	Foreign trade of shipping lane Y_4 (units)	Number of shipping lane of containership due to foreign trade	
	Density of liner ship Y_5 (units/ month)	Number of liner ships in and out the port	Output II

*DWT: dead weight tonnage

**TEU: twenty-foot equipment unit

From Table 1, we can see that the input and output indices selected are representative after Correlation Analysis and Index Classification. Input I can describe the overall strength and development potential of a container port; Input II expresses hardware equipment abilities; Input III shows the economic strength of port's hinterland. Output I and Output II are the descriptions of the achievement of ports which have low correlation.

2.2 Principal Components Analysis

SPSS Release 13.0 for Windows computer software is adopted for calculation of PCA to Inputs I, II, III and Outputs I, II. Because Input I and Output II both have only one value, and don't need to use PCA, so we adopt their original values in the calculation below. After the calculation of PCA, we have 3 kinds of inputs and 2 kinds of outputs. Previous rule is satisfied: the selected 10 ports are indeed equal or larger than twice of sums of 3 inputs and 2 outputs. The DEA-based MPI requests that the inputs and outputs must be more than zero, and the data after the calculation of PCA can't satisfy it, so we should modify them after PCA, namely, invariant translation.

2.3 Invariant Translation

Ali *et al*[14] undertook a revision and a generalization of the results on the matter of translation invariance by allowing inputs and outputs to take not only zero but also negative values. They proved that linear and nonlinear translation to some index couldn't change the differentiation among efficient, weak efficient and non-efficient solutions, and there is no change to the rank of DMUs. This broadens the field of application of the DEA methodology. Our translation is shown below:

$$X_{ij} = 0.1 + 0.9\frac{X'_{ij} - \min\limits_j\{X'_{ij}\}}{\max\limits_j\{X'_{ij}\} - \min\limits_j\{X'_{ij}\}}, \qquad (8)$$

where X_{ij} is the ith input (output) of the jth DMU after invariant translation; X'_{ij} is the ith input (output) of the jth DMU.

3 Empirical Application to Container Ports

3.1 Empirical Results

After the invariant translation, Coelli's DEAP Version 2.1 computer software[15] is adopted for calculation. Table 2 presents the results of DEA-based MPI. Five indices of 10 ports are shown below from 2001 to 2006. The data of 2000 are the base ones, because indices are calculated from the data compared with the ones of last year, so there is no index of 2000.

3.2 Analyses of Efficiency Scores

Dealing with the data of the last line of Table 2, total trend of operating efficiency of 10 ports is shown in Fig. 2 from 2001 to 2006.

The TFPCH and TECHCH fluctuations have the same trend in Fig. 2(a). According to Eq. (7),

$$\text{TFPCH} = \text{TECHCH} \cdot \text{EFFCH}.$$

It means TECHCH is the main influence factor of TFPCH. These two indices all have two peak values in 2002 and 2004. It means the total development status and potential outputs are better than others relatively.

Table 2 Malmquist productivity index summary

Indices	Year	Port										mean
		Shenzhen	Guangzhou	Xiamen	Shanghai	Ningbo	Qingdao	Yantai	Tianjin	Dalian	Yingkou	
TFPCH	2001	1.053	1.031	0.922	1.166	0.974	1.002	0.936	0.928	0.967	0.960	0.991
	2002	1.370	1.118	1.284	0.918	0.966	0.890	1.081	1.140	0.969	0.883	1.050
	2003	1.119	0.964	1.217	0.664	0.885	1.023	0.987	0.950	0.855	0.946	0.950
	2004	1.070	1.061	1.455	1.359	1.167	0.963	1.054	0.786	1.033	0.970	1.077
	2005	0.932	0.931	0.959	1.220	1.214	0.955	0.980	1.136	1.054	1.098	1.043
	2006	1.003	1.007	0.971	0.926	1.046	0.942	0.805	0.952	0.993	1.061	0.968
EFFCH	2001	1.000	1.000	1.000	1.000	0.970	1.011	1.000	0.919	0.892	0.844	0.962
	2002	1.000	1.000	1.000	1.000	0.860	0.804	1.000	0.978	0.991	1.001	0.961
	2003	1.000	1.000	1.000	0.765	0.906	1.059	1.000	0.982	1.041	1.109	0.982
	2004	1.000	0.995	1.000	1.269	1.091	0.883	1.000	0.779	0.967	0.968	0.988
	2005	1.000	1.005	1.000	1.030	1.204	0.950	1.000	1.239	0.897	0.890	1.016
	2006	1.000	0.990	1.000	1.000	1.019	1.051	0.947	0.989	1.123	1.167	1.027
SECH	2001	1.000	1.000	1.000	1.000	0.877	1.014	1.000	0.919	0.892	0.844	0.953
	2002	1.000	1.000	1.000	1.000	0.907	1.003	1.000	0.978	0.991	1.043	0.992
	2003	1.000	1.000	1.000	0.992	1.026	1.021	1.000	0.982	1.041	1.065	1.013
	2004	1.000	0.995	1.000	1.001	1.129	1.004	1.000	0.779	0.967	1.154	0.998
	2005	1.000	1.005	1.000	1.007	0.982	0.989	1.000	1.327	0.897	0.893	1.004
	2006	1.000	0.990	1.000	1.000	0.918	0.875	0.947	0.962	1.123	1.072	0.986
PECH	2001	1.000	1.000	1.000	1.000	1.106	0.997	1.000	1.000	1.000	1.000	1.010
	2002	1.000	1.000	1.000	1.000	0.949	0.801	1.000	1.000	1.000	0.960	0.969
	2003	1.000	1.000	1.000	0.771	0.883	1.037	1.000	1.000	1.000	1.042	0.970
	2004	1.000	1.000	1.000	1.268	0.966	0.879	1.000	1.000	1.000	0.839	0.990
	2005	1.000	1.000	1.000	1.023	1.226	0.960	1.000	0.934	1.000	0.996	1.011
	2006	1.000	1.000	1.000	1.000	1.110	1.201	1.000	1.028	1.000	1.089	1.041
TECHCH	2001	1.053	1.031	0.922	1.166	1.004	0.991	0.936	1.011	1.084	1.137	1.031
	2002	1.370	1.118	1.284	0.918	1.122	1.107	1.081	1.165	0.978	0.881	1.093
	2003	1.119	0.964	1.217	0.868	0.978	0.966	0.987	0.967	0.821	0.853	0.968
	2004	1.070	1.066	1.455	1.071	1.069	1.091	1.054	1.009	1.069	1.002	1.090
	2005	0.932	0.926	0.959	1.185	1.009	1.006	0.980	0.917	1.175	1.234	1.026
	2006	1.003	1.017	0.971	0.926	1.027	0.897	0.850	0.962	0.884	0.909	0.943

They get in a low value because of the effect of severe acute respiratory syndrome (SARS) in 2003, and we can see an obvious rebound in 2004. After that, a stepwise decline trend has appeared, which is because the compatible coast line of these 10 ports used to build berth is limited, and also the ability of partial ports can adequately cope with current container transportation. So the development of container transportation becomes slow from 2004 to 2006. According to Eq. (7),

$$\mathrm{EFFCH} = \mathrm{SECH} \cdot \mathrm{PECH},$$

there are two main influence factors in two phases during these 6 years in Fig. 2(b). From 2001 to 2003, the main factor is SECH. It is due to the application of new berth with the investment additions of basic establishment; from 2004 to 2006, the main factor is PECH, and it can be interpreted as the application of new technology emerged by adding investment of basic establishment and reconstruction and betterment project in these years.

The EFFCH has a weak influence on TFPCH, and the rise trend is not obvious. That fact can be explained because the reconstruction and betterment construction period of port project is long and affects the operation of original establishment. Otherwise, the fall of TFPCH is due to the economic level of their hinterland,

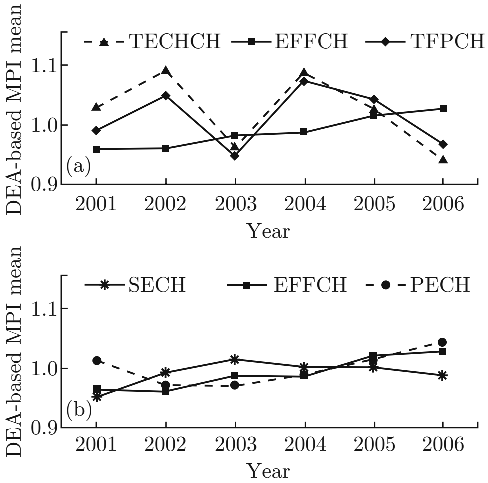

Fig. 2 Malmquist indices summary of annual means

so EFFCH can't add with the investment of ports. From Fig. 2(b), the SECH is falling, but the PECH is rising and so is the EFFCH. Although the TFPCH is declining because of the reasons mentioned above, the trend of EFFCH is developing well, and the container transportation is on the healthy development status and will recover and grow reposefully in the following years. We must pay more attention to increase the ability of technique and the capacity to bring supply of goods containerized to transport from their hinterland. There are two ways to increase operating efficiency of port: one is the function of macroscopic readjustment and control in resource of ports that adjusted by government, and the other is assorting the relationship of ports with others in one area, which can give impetus to development of ports for each other.

The analysis above is introduced about total MPIs of 10 ports from 2001 to 2006. So we can analyze the MPIs of any port in past years as the way of analysis, and find out improving method.

Classified by geographical location, the MPIs are shown in Table 3. The MPIs efficiency score of the delta of the Pearl River area ports and the delta of the Yangtze River area ones match themselves in actual strength, and the Circum-Bohai-Sea region isn't good enough because of the weaker economic vitality of their hinterland.

All analyses above are based on the conclusions gained from this research. In fact, operating efficiency of container ports is restricted by statistical data, which may be delayed or be not objective enough.

Table 3 Malmquist index summary of firm means

Indices	The delta of Pearl River area		The delta of Yangtze River area		Circum-Bohai-Sea region				
	Shenzhen	Guangzhou	Shanghai	Ningbo	Qingdao	Yantai	Tianjin	Dalian	Yingkou
TFPCH	1.083	1.017	1.014	1.036	0.962	0.970	0.974	0.976	0.984
EFFCH	1.000	0.998	1.000	1.002	0.955	0.991	0.972	0.982	0.990
SECH	1.000	0.998	1.000	0.969	0.983	0.991	0.979	0.982	1.006
PECH	1.000	1.000	1.000	1.033	0.971	1.000	0.993	1.000	0.984
TECHCH	1.083	1.019	1.014	1.034	1.007	0.978	1.002	0.994	0.993

4 Conclusion

This paper aims at providing an efficiency measure of container ports in China by a new systemic calculation method of MPI, and the results reflect the operating efficiency of these 10 ports. There are three conclusions:

(1) The main influence factor of TFPCH is the TECHCH.

(2) The trend of EFFCH is developing well, and the container transportation is on the healthy development status and will recover and grow reposefully in the following years.

(3) The MPIs efficiency scores of the delta of the Pearl River area ports and the delta of the Yangtze River area ones match themselves in actual strength, and the Circum-Bohai-Sea region is not good enough.

The analyses provide a powerful management tool for port operators. This technique can be applied and extended to further study other relative fields. We can apply the current approach to further research about more components, and lucubrate in the operating efficiency for the future research. The appraisal method in this research provides reference for managing and planning departments in other fields, which has wide applicability.

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