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PRIMARY RESEARCH

Applying data envelopment analysis to evaluate of operational efficiency of the container terminals

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Abstract

Container transportation had become an important way for carrying cargo in the world because containers can be transported between ports and delivered to destinations conveniently by intermodal services. Container transportation is accomplished not only by ships but also by various handling operations at terminals and other vehicles such as trains and trucks. In the liner shipping industry, container terminals play important roles responsible for handling, storage, and loading/ unloading containers at the shipside. In response to handling the large number of containers brought by modern huge ships, most container terminals have been devoting to improve operating efficiency and the capacity of facilities and enhance the whole service quality to keep their competitiveness in the shipping industry. Therefore, the efficiency of terminal operations is crucial because the results can directly reflect the status of the terminal operation and indicate the direction for operators to take measures for improvement. This study intended to evaluate the efficiency of container terminals in the same port. The Data Envelopment Analysis (DEA) approach was used to measure the efficiency of CCR and BCC models to examine the relative efficiency and the scale efficiency. We defined container terminals in a Taiwanese port as the decision-making units (DMUs), and the items used in the models included six input items (number of berths, length of berth, design draft, number of gantry cranes, annual rental, and container terminal area) and five output items (container throughput, number of services, number of vessels in below 5500 TEU, number of vessels in 5500-10000TEU and number of vessels in more than 10,000 TEU) to estimate the efficiency of terminals. The result indicates useful information, which is helpful for terminal operators to adjust their input items for reducing waste and increase the output in an appropriate direction.

I. INTRODUCTION

A. Statement of the Problems

Liner shipping industry has been playing an important role in the international carriage of goods for more than 60 years [1, 2, 3]. Due to the containerization and globalization of services as well as development of intermodal services, it can easily place containers on ships, trucks and trains, and transfer them to different locations efficiently. Moreover, the supply chain management in many industries has been greatly extended due to the controllable schedules of liner shipping. In order to minimize the unit transportation cost and cooperate with others strategic alliances operation, carriers currently tend to deploy large container ships in the ocean-going market, resulting in the cascading effects in other markets. In response to this trend, it's a challenge for container terminals to handle a large number of goods brought by these large container ships. Running a container terminal needs large investment, including land, rent, gantry crane, equipment and fee, etc. Therefore, the efficiency of container terminals has been concerned by carriers and terminal operators, which is related to the time for handling ships. This study aims to evaluate the technical efficiency of 11 container terminals in a Taiwanese port using DEA, which can take into account of multiple inputs and outputs to measure the efficiency objectively.

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II. LITERATURE REVIEW

A. DEA Theory

DEA is a data analysis method aiming at the comparison of relative efficiency of DMUs. In recent years, DEA has been widely applied in the assessment of the operating efficiency in various industries and organizations. Also, there were a number of recent studies measured efficiency of ports and terminals by using DEA as a methodology. For example, [4] firstly applied DEA to measure the efficiency of 20 virtual ports with three input items (capital, cargo uniformity and manpower) and four output items (level of service, users' satisfaction, ship calls and cargo throughput). The results of empirical survey found the efficiency value of ports can be obtained better than others methods. Subsequently, [5] used DEA-CCR model to measure the efficiency of 19 container terminals from 12 countries in the Middle Eastern region. They selected five input items (total terminal area in hectares , quay length in meters, the number of quay gantry cranes, the number of pieces of yard equipment and maximum draft in meters) and one output item (container throughput).

The result indicated that only three terminals were efficient in the region, and the other terminals are inefficient. [6, 7] used the DEA-CCR, DEA-BCC and super efficiency models to evaluate the operational efficiency of 19 major container ports in Northeast Asia in 2004. There were four input items consisting of berth length, terminal area, number of quay cranes and number of yard equipment as well as one output item (container throughput). According to the result obtained from the BBC model, the inefficiency Ningbo, Tianjin and Keelung ports was due to their scale inefficiency, whereas the inefficiency of the other container ports was caused by their technical inefficiency. On the other hand, the container ports of Busan and Gwangyang in Korea, showed relatively low operational efficiency compared to their rival ports.

[8] used the DEA-CCR, Super Efficiency and BCC models to explore the efficiency of the container ports for 20 world's leading ports in 2009, including five input items (length of berth, number of gantry cranes, number of terminal cranes, Yard area and number of yard tractors) and one output items (Throughput per berth), The empirical results showed that there was a lot of waste in the production process of the world's top 20 container ports. Owing to DEA is a mathematical programming model, which can be adjusted to deal with different problems by revising objection function and constraints. For instance, [9, 10] mentioned that standard DEA models had been widely used to survey port efficiency. However, these models did not consider the internal structure relative to port operations. Therefore, [9] used a two-stage network DEA to evaluate 27 ports in Brazil in 2011 with three input items (number of berths, warehousing area, and yard area), two middle input and output items (solid bulk and containerized cargoes handled of certain shipment frequency per year) and two final output items (solid bulk and containerized cargoes handled). The results not only indicated that a private administration exerts a positive impact on physical infrastructure efficiency levels, but also pointed out the hinterland size had a positive impact on shipment consolidation efficiency level.

The above review indicates that DEA models are suitable to measure the efficiency of container terminals. Accordingly, this study also applied the DEA approach to measure the operational efficiency of container terminals in a Taiwanese port. This study not only included the input and output items used in the related literature, but also considered more related items to evaluate the efficiency of container terminals. Namely, six input items (i.e., number of berths, length of berth, design draft, number of gantry cranes, annual rental, and container terminal area) and five output items (container throughput, number of services, number of vessels in below 5500 TEU, number of vessels in 5500-10000TEU and number of vessels in more than 10,000 TEU) were used in this study to measure the efficiency of container terminals.

III. RESEARCH METHODOLOGY

A. DEA Model Framework

The basic models for DEA are CCR and BCC models. The CCR model proposed by [11] assumed Constant Returns to Scale (CRS), whereas the BCC model proposed by [12] was developed under the assumption of Variable Returns to Scale (VRS) to measure efficiency scores. This study adopted the input-oriented CCR and BBC models to measure the efficiency of container terminals, which were explained as below.

B. Input-Oriented of CCR Model

The input-oriented CCR model considers n DMUs with m inputs and s outputs. Assume a set of n observed DMUs, DMU $_j$ (for each $j = 1, 2 \ldots, n$) is associated with input vector $i(i = 1, 2 \ldots, m)$ of $X_{ij} = \left(x_{1j}, \cdots, x_{mj} \right)$ and output vector $r(r = 1, 2 \ldots, s)$ of $Y_{rj} = (y_{1j} \ldots, y_{sj})$. Then, the efficiency score of the DMU o can be expressed by Equation (1).

$$\begin{aligned} &\text{Max .}\quad h_i = \frac{\sum_{\frac{r-1}{m}}^{s} u_r Y_v}{\sum_{i=1}^{m} v_i X_{ij}} \\ &\text{s.t. } \frac{\sum_{\frac{r=1}{m}}^{s} u_r Y_{vj}}{\sum_{i=1}^{m} v_i X_{ij}} \leq 1 \quad \forall j, \quad j = 1, 2, \ldots, n \\ &u_r, v_i \geq \varepsilon > 0, \quad r = 1, 2 \ldots, s \quad i = 1, 2 \ldots, m \end{aligned} \tag{1}$$

u_r: The r th output

v_i : The r th input

n : The number of the DMUs

m : The number of the inputs

s : The number of outputs

ε : A very small positive number, and is called Non-Archimedean

Number, usually set to 10^{-4} or 10^{-6} in practical application. Owing to the objective function of Equation (1) is fractional linear, which will result in computational difficulty and infinite number of solutions. To avoid this, the denominator in Equation (1) can be set to 1, then it can be converted into a linear programming form as shown in Equation (2):

$$\begin{aligned} &\text{Max}_{i_i} = \textstyle\sum_{r=1}^{s} u_r Y_{rj} \\ &\text{s.t.} \textstyle\sum_{i=1}^{m} v_i X_{ij} = 1 \\ &\textstyle\sum_{r=1}^{s} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \leq 0, \quad j = 1, 2, \ldots, n \\ &u_r, v_i \geq \varepsilon > 0, \quad r = 1, 2, \ldots, s \quad i = 1, 2, \ldots, m \end{aligned} \tag{2}$$

C. *Input-Oriented of BCC Model*

The input-oriented of BCC model considers n DMUs with m inputs and s outputs. Assume a set of n observed DMUs, DMU $_\mathrm{j}$ (for each $j = 1, 2 \ldots$, n) is associated with input vector $i(i = 1, 2 \ldots, m)$ of $X_{ij} = (x_{1j}, \ldots, x_{mj})$ and output vector $r(r = 1, 2 \ldots, s)$ of $\mathrm{Y_{rj}} = (\mathrm{y}_{1j}, \ldots, \mathrm{y_{sj}})$. Then, the efficiency score of the DMU$_0$ can be expressed by Equation (3).

$$\begin{aligned} &\text{Max } h_j = \frac{\sum_{r=1}^{s} u_r Y_{ij} - u_0}{\sum_{i=1}^{m} v_i X_{ij}} \\ &\text{s.t. } \frac{\sum_{r=1}^{s} u_r Y_{vj} - u_0}{\sum_{i=1}^{m} v_i X_{ij}} \leq 1, \quad j = 1, 2, \ldots, n \\ &u_r, v_i \geq \varepsilon > 0, \quad r = 1, 2, \ldots, s \quad i = 1, 2, \ldots, m \end{aligned} \tag{3}$$

u_0 may be positive or negative(or zero).

since the objective function of Equation (3) is similarly to a fiactional linear programming, which will result in computational difficulty and infinite number of solutions. To avoid this, the denominator in Equation (3) can be set to 1, then it can be convented into a linearprogramming form as shown in Equation (4).

$$\begin{aligned} &\text{Max}_{j_j} = \textstyle\sum_{r=1}^{s} u_r Y_{rj} - u_0 \\ &\text{s.t.} \textstyle\sum_{i=1}^{m} v_i X_{ij} = 1 \\ &\textstyle\sum_{r=1}^{s} u_r Y_{ij} - \sum_{i=1}^{m} v_i X_{ij} - u_0 \leq 0, \quad j = 1, 2, \ldots, n \\ &u_r, v_i \geq 0, \quad r = 1, 2, \ldots, s \quad i = 1, 2, \ldots, m \end{aligned}$$

(4)

u_0 may be positive or negative (or zero).

The BCC model differs from the CCR model only in the condition of ^{u_0}, which is an intercept of the production function. In addition, ${}^{nn}\lambda_j$ can also be used to determine whether the returns to scale is increasing or decreasing. $\sum_{j=1}^{n} \lambda_j < 1$ represents the return to scale is increasing. $\sum_{j=1}^{n} \lambda_j > 1$ indicates the return to scale is decreasing. $\sum_{j=1}^{n} \lambda_j = 1$ denotes the return to scale is constant.

D. *Scale Efficiency (SE)*

According to [11], the CCR model is to measure the technical efficiency (TE). And the BCC model proposed by [12] is to measure Pure Technical Efficiency (PTE). The ratio between the scores obtained from the CCR and BCC models is called SE, which is shown in Equation (5).

$$\begin{aligned} TE &= PTE \cdot SE \\ SE &= \tfrac{TE}{PTE} \end{aligned} \tag{5}$$

IV. EMPIRICAL ANALYSIS

A. *Selection of DMUs*

In terms of the selection of DMUs, the DMUs must be a homogeneous set of units. That is, the DMUs need to under the quite similar set of market conditions. In this study, we selected 11 container terminals in a Taiwanese port as the DMUs (see Table 1).

V. SELECTION OF INPUT AND OUTPUT ITEMS

Owing to the plenty of factors that might affect the efficiency of container terminals, the selection of input and output items should take into account the suitability and availability of data. Therefore, the items selected in this study consisted of six input items (number of berths, length of berth, design draft, number of gantry cranes, annual rental, and container terminal area) and five output items (container throughput, number of services, number of vessels in below 5500 TEU, number of vessels in 5500-10000TEU and number of vessels in more than 10,000 TEU). Table 2 presents the descriptive statistics on all input and output items of the 11 DMUs in this study.

TABLE 1
DMUS EVALUATED IN THIS STUDY

DMU	Number of Berths	Container Throughput (TEU)
1	2	206,000
2	2	1,022,000
3	2	1,397,000
4	2	1,184,000
5	1	479,000
6	3	779,000
7	3	1,893,000
8	3	1,409,000
9	2	385,000
10	2	10,000
11	4	1,488,000

TABLE 2
DESCRIPTIVE STATISTICS OF INPUT AND OUTPUT VARIABLES

Input Variable	Maximum	Minimum	Mean	Standard deviation
Number of Berths	4	1	2.3636	0.80904
Length of Berth	1500	320.57	746.7727	319.75435
Design Draft	17.6	10.5	14.1909	1.60825
Number of Gantry Cranes	12	3	6.4545	2.65946
Annual Rental	422,000,000	0	203,909,091	125,308,782
Container Teminal Area	750,000	0	300,818.182	199,752256
Output Variables				
Container Throughput	1893000	10000	932000	604400.695
Number of Services	51	22	37.5455	9.48012
Number of Vessels				
- < 5,500 TEU	459	63	281.5455	111.04626
- 500 – 10,000 TEU	805	0	281.8182	260.95778
- > 10,000 TEU	1516	0	282.2727	505.32546

Table 2 shows the descriptive statistics of the items used in the study. It reports the minimum and maximum value for each item, including the largest number of berths (i.e., 4 for DMU11), the largest length of berth (i.e.,1500 meters for DMU11), the largest depth of design draft (i.e., 17.6 meters for DMU11), the largest number of gantry cranes (i.e.,12 for DMU11), the largest annual rental (i.e., 422,000,000 for DMU7), the largest container terminal area (i.e.,750000 m^2 for DMU11), the largest throughput of container throughput (i.e.,1893000 TEUs for DMU7), the largest number of services (i.e.,51 for DMU7), the largest number of vessels (< 5,500 TEU) (i.e.,459 for DMU11), the largest number of vessels (500 – 10,000 TEU) (i.e.,805 for DMU11), the largest number of vessels (> 10,000 TEU) (i.e.,1516 for DMU11).

On the other hand, the minimum values included the minimum number of stevedoring berths (i.e., 1 for DMU5), the minimum length of berth (i.e.,320.57 meters for DMU5), the minimum depth of design draft (i.e., 10.5 meters for DMU1), the minimum number of gantry cranes (i.e.,1 for DMU1), the minimum annual rental is 0 for DMU10, because it belonged to the port authority. The minimum container terminal area (i.e., 0 m2 for DMU10), the minimum throughput (i.e.,10000 TEUs for DMU10), the minimum number of services (i.e.,22 for DMU10), the minimum number of vessels (< 5,500 TEU) (i.e.,63 for DMU10), the minimum number of vessels (500 – 10,000 TEU) (i.e.,0 for DMU1), the minimum number of vessels (> 10,000 TEU) (i.e.,0 for DMU1,2,4,5,6,7, and 10).

A. *The Scores of Efficiency for Each DMU*

The efficiency scores based on models CCR, BCC and SE are summarized in Table 3. In terms of the scores obtained from the CCR model, an efficiency score of 1 signifies a terminal is efficient. The scores less than 1 indicate the terminals could not utilize their inputs perfectly. The optimal scores of technology efficiency of seven terminals acquired from CCR model were all equal to 1 (DMU 1,2,3,5,7,10, and 11). The efficiency values of other terminal were less than 1, including DMU8 (0.943), DMU6 (0.929), DMU4 (0.856) and DMU9

(0.781). Moreover, the optimal scores of pure technical efficiency of eight terminals obtained from BCC model were all equal to 1(DMU 1,2,3,5,7,8, and 10), the other terminals had lower efficiency scores were DMU4 (0.949), DMU6 (0.932), and DMU9 (0.786). Lastly, the optimal scores of scale efficiency of all terminals were obtained using Eq. (3.5). Four terminals which did not conform to scale efficiency were DMU6 (0.997), DMU9 (0.994), DMU8 (0.943) and DMU4 (0.902). Although these four terminals did not conform to scale efficiency, their SE scores were all above 0.9.

TABLE 3
THE RESULT OF EFFICIENCY SCORES

DMU	CCR Technical Efficiency (TE)	BCC Pure Technical Efficiency (PTE)	SE
1	1.000	1.000	1.000
2	1.000	1.000	1.000
3	1.000	1.000	1.000
4	0.856	0.949	0.902
5	1.000	1.000	1.000
6	0.929	0.932	0.997
7	1.000	1.000	1.000
8	0.943	1.000	0.943
9	0.781	0.786	0.994
10	1.000	1.000	1.000
11	1.000	1.000	1.000

VI. CONCLUSION

In response to the increasing number of containers brought by large ships, most terminals are improving their ability by increasing handling capacity and modern equipment. Therefore, the efficiency and throughput of the terminal in a port are concerned by the authorities in order to increase the performance of the port. This forced terminal operators to operate their terminals actively by reducing the waste of inputs and increase their outputs. This study investigated the technical efficiency of 11 container terminals in a Taiwanese port using DEA. In terms of the scores obtained from CCR model, seven terminals got perfect scores, showing that they could fully utilize their input items. The efficiency scores of the other four terminals were less than one due to the waste of their inputs. The results of efficiency scores obtained from the BCC model reveals that most of terminals got perfect efficiency scores. Only three terminals were unable to get optimal efficiency. Even so, two of the inefficient terminals still got scores above 0.9. The scores of scale efficiency of all terminals were close to one, indicating that most terminals were running close to their economic scale. Lastly, some limitations and directions for future research are given as follows.

First, The results of this study were based on an empirical study which only considered a single time period. Therefore, future researchers may extend the research period by including data of multiple periods to observe the change of annual efficiency scores. Compared with the study with data of single period, using the data of multiple periods is helpful to explore more managerial implication. Second, due to the limitation of data availability, this study only chosen six input items and five output items to evaluate the efficiency. Therefore, the research scope in this study was unable to take complete operation situation of terminals into account and carry out comprehensive evaluation. Future researchers may collect more input and out put items, such as warehouse area, labor force, number of gantry cranes, straddle carriers, trucks etc.

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