

Liu, Siwei; Park, Sung-Hoon; Choi, Young-Seo; Yeo, Gi-Tae

Article

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Efficiency evaluation of major container terminals in the top three cities of the Pearl River Delta using SBM-DEA and undesirable DEA

Siwei Liu, Sung-Hoon Park, Young-Seo Choi, Gi-Tae Yeo*

Graduate School of Logistics, Incheon National University, Incheon 22012, South Korea

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ABSTRACT

As the three largest central hub cities in the Pearl River Delta (PRD) region, Hong Kong, Guangzhou, and Shenzhen have played critical roles in regional growth. Nevertheless, these ports face many challenges, such as port handling capacity, environmental problems, and the expansion of the complex transportation system owing to the large volume of goods. Therefore, this study used the slacks-based measure–data envelopment analysis (SBM-DEA) and DEA-undesirable models to evaluate the efficiency of the major container terminals in these three cities between 2018 and 2019. Based on the decision-making unit values of the terminals for the past two years, Yantian and Container Terminal 9 (South) were the most efficient, followed by container terminals 6 and 7. Moreover, the efficiency of the major container terminals in Guangzhou was less satisfactory than that of terminals in Shenzhen and Hong Kong. The results provide a reliable reference for future port investment, and regional development policy in the PRD region.

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1. Introduction

China is a major hub for the global container market. It is home to several large ports such as Shanghai, Shenzhen, Ningbo, Guangzhou, Qingdao, Hong Kong, and Tianjin. Qingdao Port has recently been developed as an unmanned, automated port that exhibits high-efficiency operation.

The advantages of Chinese ports include China's enormous production capacity, an ability to handle the large volume of goods in the Asian market, geographical location, and the transformation of ports into hubs.

The Chinese civilization developed around a delta formed by the stems of the Yellow River, Yangtze River, and Pearl River. The Shanghai Port and Ningbo Port are located on the Chang River Basin, and have developed into China's largest ports. The ports of Guangzhou, Shenzhen, and Hong Kong are located on the Pearl River Basin and are important external gateways to the Pearl River Delta region (Fig. 1).

Although these ports have a competitive geographical edge; they have played complementary roles, and consequently, each has developed into an important port. But, these ports face many challenges, such as port handling capacity, environmental problems, and the need to expand a complex transportation system owing to the large volume of goods.

In terms of gross domestic product, Hong Kong, Guangzhou, and Shenzhen are the top three cities in South China's Pearl River Delta (PRD) economic region. The PRD is a significant economic zone in South China, with a superior geographical position, large hinterland, and long history of foreign trade. China is a significant production, manufacturing, and export hub. In recent years, the Chinese government has proposed to develop the Guangdong–Hong Kong–Macao Greater Bay Area, a global economic region comparable to the San Francisco Bay Area, centered on the PRD Economic Zone and the two Special Administrative Regions of Hong Kong and Macao (Youlin, XinWei, ZhiSen, & ZhiTe, 2021). From a comprehensive perspective, the region's logistics industry development potential is promising (Chong & Pan, 2020). As the three largest central hub cities in the region, Hong Kong, Guangzhou, and Shenzhen have played critical roles in regional growth.

Therefore, we selected three major container terminals in Hong Kong, Guangzhou, and Shenzhen as the research subjects of this study and employed the data envelopment analysis (DEA) method to

* Corresponding author.

E-mail addresses: 13592659782@163.com (S. Liu), psh427@inu.ac.kr (S.-H. Park), youngseochoi@inu.ac.kr (Y.-S. Choi), ktyeo@inu.ac.kr (G.-T. Yeo).



Fig. 1. City map of the Pearl River Delta.

evaluate the efficiency of the container terminals. We used gross crane productivity (from the perspective of mechanical facilities), cranes intensity, berth depth, and berth length of the container terminals as input factors, calls, moves and finish as output factors. By doing so, we expect to provide a reference for future regional logistics development planning.

2. Overview of container terminals in the targeted areas

The “National Coastal Port Layout Plan,” issued by the State Council of China, divides the coast of China into five port groups based on the geographical advantages of each region, and its resource type and environment: the Bohai Rim Port Group, Yangtze River Delta Port Group, Southeast Coastal Region Port Group, Pearl River Delta Region Port Group, and Southwest Coastal Region Port Group. Each port group consists of several ports, and each port contains several container terminals. The distribution data of container throughput in China’s coastal areas were released by the Ministry of Communications in 2020. The container throughput of Guangdong province (located in the PRD) was 60.44 million TEU, the highest among China’s coastal areas (Fig. 2) (Hu, Sun, & Jiang, 2020).

According to the Analysis Report on the Operation Status and Development Prospects of China’s Container Logistics Industry in 2020–2026, China’s domestic and foreign container logistics markets are distinct, due to varied resource allocation and economic development levels across different regions of China. In northern China, grains such as soybeans and corn are the leading products. By contrast, industrial products such as electrical appliances, clothing, and building materials are the main products in southern China. Industrial products are an essential part of China’s foreign trade, and they are a crucial reason for the higher container throughput in the southern coastal regions, when compared to the northern coastal regions.

In 2021, the Guangdong Provincial Government developed Guangzhou and Shenzhen as a mega-hub core city as part of its plan to transform the two cities into world-class international shipping hubs, and use them as the core cities for first-class transportation hubs, to drive the development of other regions (Meng, Sun, & Zhao, 2020; Wang, Zhang, & Wang, 2019). From a geographical perspective, Guangzhou is the port transportation hub in the PRD region, and the railroad transportation hub of the Beijing–Guangzhou line, which runs from Beijing in the north to Guangzhou in the south via the north, central, and south China. It is a national Class I passenger and freight line. Most export goods are transported to Guangzhou Port via the Beijing–Guangzhou line, and then dispatched worldwide. Therefore, Guangzhou Port has a vast cargo transportation hinterland, and obvious geographical advantages. Shenzhen, next to Hong Kong, was China’s first open special economic zone (SEZ), and has developed rapidly since its establishment 40 years ago, based on exceptional economic policy support and a superior geographic location. The expansion of the Beijing–Guangzhou railroad to Shenzhen accelerated the development of the shipping industry on the Shenzhen Port. The Shenzhen Port has gradually become the largest port in the PRD region in terms of throughput (Chen & Lam, 2018; Gharehgozli, Zaerpour, & de Koster, 2019).

The Shantou Port and Zhanjiang Port are located in the western and eastern regions of Guangdong Province, respectively. They are the secondary core cities in the transportation development plan of Guangdong Province. The eastern and western regions take these two cities as the core to optimize the integration of resources and promote the intensive and large-scale development of ports in each region. The Hong Kong Port has a long history of development, and was once the world’s top port in terms of container throughput. However, after being overtaken by Singapore in 2005, it is ranking gradually fell. Nonetheless, it remains a critical container port in the PRD region, and in Asia. Therefore, the Guangdong Provincial Government is committed to transforming Guangzhou, Shenzhen,

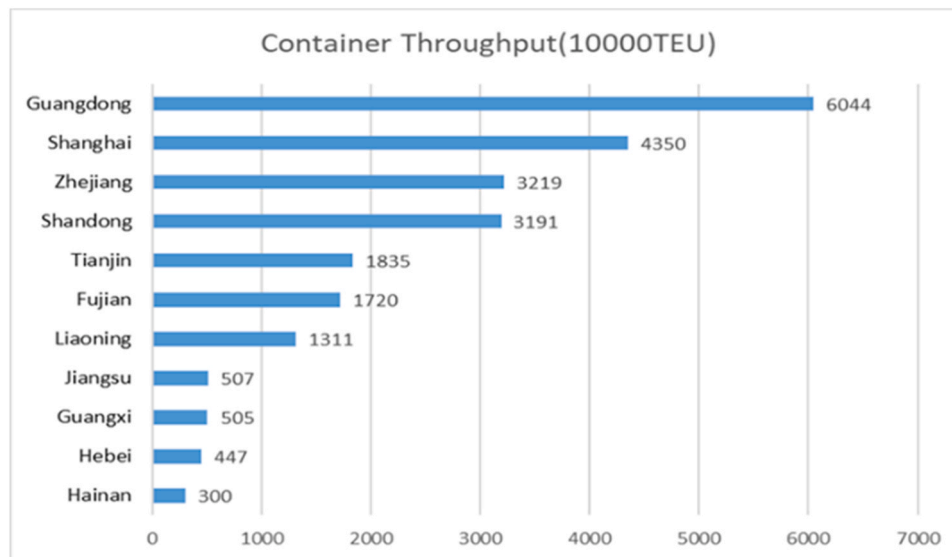


Fig. 2. Container throughput of China coastal areas in 2020.

and Hong Kong ports into the major international shipping hubs, and thereby creating a pattern of synergistic port development in the PRD region.

3. Literature review

3.1. Port efficiency of China

In general, the container transport industry in Chinese ports has progressed through four stages: initial, starting, rapid development, and comprehensive development. China's container transport industry was in its initial stages before reform and opening up (Cullinane, Fei, & Cullinane, 2004). The opening of the container line from Shanghai Port to Australia in September 1978 signalled the birth of China's port container transport industry (National Bureau of Statistics, 2008). Tianjin, China's first specialized container terminal, was built in December 1980. Since then, many Chinese ports involved in container transportation have increased (Wang, Notteboom, Lau, & Ng, 2017). From 1989 to 2001, the container transport industry experienced rapid growth. By 2001, the annual throughput of China's eight coastal ports of Shanghai, Shenzhen, Tianjin, Guangzhou, Qingdao, Dalian, Ningbo, and Xiamen surpassed one million TEU, and China's specialized container terminals gradually developed and expanded. In 2002, China's container transport industry entered an all-around developmental stage. China's container terminals have been progressing toward specialization and large-scale development to meet the requirements of large-scale ships and significantly improve loading and unloading efficiency. By the end of 2019, China's ports had 2520 berths belonging to the 10,000-ton class and above (Wang, Hu, Xu, Mei, & Wang, 2021). The development history of China's container ports from the initial stage to the present confirms China's steady economic development and the continuous improvement in Chinese port efficiency.

Chen et al. (2018) analyzed six standard free trade ports in China's coastal areas, and found that the free trade ports in the Yangtze River Delta and the Bohai Rim Economic Circle had outstanding performance. China's free trade ports are dependent on economic infrastructure and benign conditions, such as policy guidance and talent support. The establishment of free trade zones positively correlates with improvements in port efficiency (Liu, Wang, & Guo, 2021). In recent decades, nearly all coastal

cities in China have invested considerable human resources, materials, and financial capital in port construction (Yu, Lee, & Wang, 2017). Song and Cui (2014) investigated productivity changes in China's container terminals from 2006 to 2011, and discovered that the productivity growth was primarily due to technological advancements. Yuen, Zhang, and Cheung (2013) explored whether the participation of foreign owners in port competition could improve port efficiency, and found that, compared to foreign ownership, Chinese local ownership had a positive impact on port efficiency growth.

According to UNCTAD (2017), the global container fleet is increasing its load capacity and the degree of containerization in international trade. Improving port efficiency is a challenging task for many countries and regions (Turner, Windle, & Dresner, 2004). For many years, as an important manufacturing base, China has been an integral part of global supply chains. Maritime transport trade has stimulated the rapid development of China's coastal region ports. However, due to the regional competition between port hinterlands and the regions between ports, improving port efficiency is the top priority for port operators (Cullinane & Song, 2006). Yuen, Zhang, and Cheung (2012) analyzed all ports in China and its surrounding areas from users' perspective, and found that the Shenzhen Port ranks first in efficiency and competitiveness for freight forwarders because of its geographical location and hinterland connection. However, the shipping process is likely to cause environmental problems. Modern ports are transforming into green and low-carbon ports (Hua et al., 2020; Kong & Liu, 2021); therefore, the environmental efficiency of ports is also a critical evaluation indicator affecting port development. In assessing efficiency, an increasing number of academics have included harmful greenhouse gas emissions as a negative output. For example, Wu and Guo (2021) discovered that ports in East China have the highest efficiency when comparing the expected outputs under different particulate matter (PM) emission standards. Castellano, Ferretti, Musella, and Risitano (2020) estimated the relationship between the economic and environmental efficiencies of 24 Italian ports using the basic Charnes–Cooper–Rhodes (CCR) model. They concluded that port efficiency could be improved by paying attention to the impact of environmental factors. Gong, Wu, and Luo (2019) also conducted a study on China's publicly traded shipping companies to confirm the impact of environmental factors on port efficiency.

3.2. Port research in Hong Kong, Shenzhen, and Guangzhou

When evaluating port efficiency, terminal has each specific characteristics according to its geographical location and regional economy (Wu, Yan, & Liu, 2010). Owing to special historical reasons, Hong Kong was the only gateway to Mainland China in the southern part of China for an extended period. Mainland China's dependence on Hong Kong promoted the latter's prosperity (Wang, Ng, Lam, & Fu, 2012). The Hong Kong Port was the busiest port globally during 1990–2000 (Yap, Lam, & Notteboom, 2006). However, its market share was gradually eroded by its neighbors, the Shenzhen Port and Guangzhou Port due to the cost disadvantage and the increasing competition among ports in the PRD region.

Homosombat, Ng, and Fu (2016) showed that, with the economic development of the PRD region, the labor force and operating costs in the region were also gradually rising, harming regional ports. Since China acceded to the World Trade Organization in 2001, commercialization activities have been gradually developing. Regional ports increasingly exhibit regionalization (Notteboom & Rodrigue, 2005), such as the PRD, Yangtze River Delta, and Bohai Rim port groups. Increasing port regionalization is also one of the reasons why Hong Kong Port is facing pressure from regional shipping hubs. Based on the current port development situation, the Chinese government has made corresponding plans for regional port development. Therefore, it is necessary for Hong Kong to integrate into the development plan of the administrative regions in Mainland China to cope with port regionalization, and maintain its efficiency (Wang et al., 2012). Shipowners account for 9.6% of the world's merchant shipping deadweight tonnage, and the shipping industry plays a significant role in Hong Kong's economy (Hong Kong Bureau of Statistics). Therefore, one of the port strategies of the Hong Kong government is to improve the efficiency of its ports and enhance their competitiveness in the region.

Mainland China's economy has benefited immensely from the economic reform initiated in 1978. As the first SEZ, Shenzhen attracted significant foreign investment in the initial stage of construction, particularly in the manufacturing industry (Lin & Lin, 1997). As the only gateway to South China at the time, the Hong Kong Port benefited greatly from the high demand during the economic development stage of Mainland China. It is evident that the economic development of the PRD region and the prosperity of the Hong Kong Port complement each other. However, when the Shenzhen Port began to approach significant shipping corporations, the Hong Kong Port's momentum began to diminish. The Shenzhen Port developed rapidly with an increase in investment in infrastructure and construction, and the removal of certain management restrictions. In particular, the Yantian and Shekou terminals proliferated (Wang, Ng, & Olivier, 2004). Song (2002) believes that Hong Kong has been a critical trans-shipment port in Mainland China for a long time. However, with the rise of Shenzhen, Guangzhou, and other ports, seeking cooperation from the Shenzhen and Guangzhou ports is an excellent choice. With the development of local manufacturing and other industries, the Guangzhou Port also began to expand and tried to improve the efficiency of regional ports by setting up free trade ports to promote the development of port logistics (Chen et al., 2018). Currently, China has been actively investing in inland transportation construction. For example, it has built several railway transportation lines, and has actively enriched land transportation modes. The improvement of inland transportation efficiency in Mainland China can facilitate hinterland access to ports so that the inland transportation network in Mainland China is effectively integrated with the ports in the coastal areas. All of these contribute to the growth of Shenzhen Port and Guangzhou Port (Chi-Lok & Zhang, 2009). In terms of the transport cost value, Hong Kong still has a unique advantage in providing first-class customs clearance, which saves transit time and reduces unnecessary

complexities. In the process of improving its efficiency, the Hong Kong Port should continue to maintain this advantage.

3.3. Research gap

Many studies (Debie & Raimbault, 2016; Ducruet, 2017; Grobar, 2008; Tan, 2007) have evaluated port efficiency. Data envelopment analysis has been widely used in the efficiency analysis of ports worldwide. Scholars have used DEA to analyze and study various Chinese port models as well (Dan, Weixin, & Feng, 2013). Tongzon (1995) selected 23 international ports to measure port efficiency in terms of parameter variation, and applied a regression model to investigate the relationship between port input costs and port efficiency to understand the factors that played a decisive role in port efficiency. Tongzon (2001) compared four ports in Australia and 20 ports in other countries to demonstrate the impact of port inputs on port efficiency. Valentine and Gray (2001) compared the efficiency of various ports based on different types of organizational structures to determine whether a specific type of ownership promotes greater efficiency. The DEA model has been widely used since it was first introduced for port efficiency assessment (Roll & Hayuth, 1993). Among the many works on port efficiency assessment, there are studies based on ports and their relationship with the economy, trade, finance, industrial structure, human resources, and national and regional policies. With the rise of a low-carbon economy and a green economy development mode, several environmental factors have also been introduced to evaluate port efficiency development (Kuo & Lin, 2020; Wan, Zhang, Yan, & Yang, 2018).

However, comparative studies about the three most significant port cities in the PRD region, China's core container-handling region, are scarce. Therefore, 17 container terminals in these three cities were selected for this study. The slacks-based measure–data envelopment analysis (SBM-DEA) and undesirable DEA models were used to conduct a comparative analysis of the efficiency of the container terminals from the perspective of productivity. The purpose was to provide decision-making suggestions regarding productivity for implementing policies to improve port efficiency in this region, and to fill the gap in port efficiency assessment in this region. Accordingly, in this study, undesirable output is introduced as an influencing factor based on the SBM-DEA model. Thereafter, the efficiency of container terminals in these three regions was evaluated using an undesirable DEA analysis model.

In particular, this study uses Finish variables, which refer to the time of stay in the terminal; identifies the reasons for inefficiency; and provides implications that will serve as a reliable reference for future port investment and regional development policies.

4. Methodology

4.1. SBM model

Charnes, Cooper, and Rhodes (1978) developed DEA as a non-parametric approach for dealing with multi-input and multi-output problems. It is frequently used to evaluate and measure the efficiency of decision-making units (DMUs) with multiple influencing factors (Boussofiene, Dyson, & Thanassoulis, 1991). Generally, these factors are divided into input and output. Input factors include production (labor, money, machinery, and equipment), and materials, while output factors include output value, value added, and production (Halkos & Petrou, 2019). Once the effective range is determined in DEA, an inefficient DMU can improve performance and efficiency by lowering its current input level or increasing its current output level (Seiford & Zhu, 2002). Traditional radial models—CCR and Banker–Charnes–Cooper—rely on a fixed integral input of the DMU or integral calculation to obtain the efficiency ratio, proving relatively limited.

The SBM model is classified as a non-radial model. In the existing radial model, only one of the total input and output variables of the DMU is fixed, necessitating a decision regarding whether Model I or Model O should be used. In the case of the SBM model, efficiency is calculated by determining the surplus of the input or output from the unfixed side. The present study adopts this model for analysis. The SBM model considers the surplus of the input and the output, and deems a DMU as efficient when the surplus of both is zero. The reason why this study choose is, the model what used in this study, undesirable DEA analysis model was derived from SBM model, and to compare with this two model.

Relaxation variables may be used as factors in the assessment process to achieve a relatively accurate evaluation (Tone, 2001). The equation for the SBM model is as follows: The input factor is s_i^- in the following formula, and the inadequate portion of the output factor is s_r^+ . The efficiency value of the DMU in the SBM model is 1, and a DMU is deemed to be efficient when the values of s_i^- and s_r^+ are 0. A DMU is considered invalid or inefficient if the values of s_i^- and s_r^+ are greater than 0.

$$\text{Min}_{pk} = \frac{1 - \frac{1}{m} \sum_{i=1}^m (s_i^- / x_{ik})}{1 - \frac{1}{m} \sum_{r=1}^s (s_r^+ / y_{rk})}$$

$$\text{s. t. } x_{ik} = \sum_{k=1}^n x_{ik} \lambda_k + s_i^-,$$

$$y_{ik} = \sum_{k=1}^n y_{ik} \lambda_k + s_r^+,$$

$$\lambda_k, s_i^-, s_r^+ \geq 0, \forall k, i, r$$

4.2. Undesirable model

The DEA method is based on the assumption that inputs must be minimized, and outputs must be maximized. However, under certain circumstances, the assessment process may have undesirable inputs and performance. To improve the efficiency of low-efficiency DMUs, the desirable output factors should be increased, and the undesirable output factors should be reduced (Jahanshahloo, Lotfi, Shoja, Tohidi, & Razavyan, 2005; Rashidi & Saen, 2015).

Therefore, an undesirable model can be used to address undesirable variables. The undesirable model deals with the negative variables, called bad or undesirable outputs. There are several ways to deal with the negative variables.

First, negative variables can be addressed by treating the negative output variable as an input variable. In the process of applying weights, however, it is possible that an inappropriate weight may be applied because the weight is applied in comparison to the input variables.

Second, they can be addressed through an analysis that inserts only negative output variables without inserting other variables into the output variable. This method indicates that the lower the efficiency score, the more efficient the DMU. The limitations of this method are that the existing positive output variable cannot be used, and that the value of efficiency is contrary to the value of the existing efficiency evaluation, making it impossible to identify which DMU is the most inefficient.

Third, when dealing with undesirable variables, we can multiply a variable by “-1”. Similar to the first method, when multiplying by a random weight, it is necessary to consider the weight along with the positive output variables, creating the possibility of applying an inappropriate weight.

Fourth, based on the SBM model, an analysis can be performed by multiplying the negative output variable, as a negative value, by a weight that is a constant number. This approach is useful in

comparing efficiency fluctuations due to the insertion of a negative output variable. Since the benchmark is the excess, it is possible to derive the excess in the variables, and propose plans to improve efficiency (Rashidi & Saen, 2015; You & Yan, 2011). The formula used is as follows:

$$\rho = \min \frac{1 - \frac{1}{m} \sum_{i=1}^m s_i^- / x_{io}}{1 + \frac{1}{s} \left(\sum_{r=1}^s \frac{s_r^g}{y_{ro}^g} \right) + \left(\sum_{r=1}^s \frac{s_r^b}{y_{ro}^b} \right)}$$

$$\text{s. t. } x_0 = x\lambda + s^-$$

$$y_0^g = y\lambda - s^g$$

$$y_0^b = y\lambda - s^b$$

$$L \leq e\lambda \leq u$$

$$\lambda, s^-, s^g, s^b \geq 0$$

$$\lambda \geq 0$$

In this equation, y denotes the product, and 0 signifies the DMU, which is the subject of the evaluation. s^- , s^g , and s^b mean input excess, general output shortage, and negative output excess, respectively. This equation was used to calculate the optimal values of ρ , s^- , s^g , s^b , and λ .

5. Empirical analysis

5.1. Variable selection

The SBM model used gross crane productivity, crane intensity, berth length, and berth depth as input variables, and calls and moves as output variables (Table 1). In the undesirable model, the input variables were the same as in the SBM model, whereas the output variables were finish, calls, and moves (Table 2), where finish was an undesirable output. The details of the research objects and explanations of the DMUs are provided in Table 3.

5.2. Analysis result from the SBM-DEA model

This study collected the data of the subjects from 2018 to 2019, and analyzed them through the DEA-Solver program, using two analytical models.

Table 4 shows DMUs and corresponding terminals.

In the data inclusion analysis, when the value of the DMU is 1, the efficiency of the terminal is highest. According to the analysis results of the SBM model (Table 5), the DMU values of Container Terminal 9 (South) and Yantian Container Terminal were 1 from 2018 to 2019,

Table 1
Input and output variables in the SBM model.

Input variables	Output variables
Gross Crane Productivity (I1)	Calls (O1)
Crane Intensity (I2)	Moves (O2)
Berth Length (m) (I3)	
Berth Depth (m) (I4)	

Table 2
Input and output variables in the undesirable model.

Input variables	Output variables
Gross Crane Productivity (I1)	Calls (O1)
Crane Intensity (I2)	Moves (O2)
Berth Length (m) (I3)	Finish (Bad Output)
Berth Depth (m) (I4)	

Table 3
Description of variables.

Title	Description
Gross Crane Productivity	Moves per hour. Total moves divided by total gross crane hours.
Crane Intensity	Average quantity of cranes deployed per ship call.
Berth Length (m)	The length of the berth.
Berth Depth (m)	The depth of the berth.
Calls	Stopping at a port for loading or discharging cargo, refueling or landing wounded crew.
Moves	Total container moves. Discharge + Restowage, Moves + Load. Excluding Hatch Covers, Gear-boxes, etc.
Finish	Total elapsed time between last container move, and all lines released.

Table 4
DMUs and corresponding terminals.

	Terminal Name	Location
DMU 1	Container Terminal 1	Hong Kong
DMU 2	Container Terminal 2	Hong Kong
DMU 3	Container Terminal 3	Hong Kong
DMU 4	Container Terminal 4	Hong Kong
DMU 5	Container Terminal 5	Hong Kong
DMU 6	Container Terminal 8 (East)	Hong Kong
DMU 7	Container Terminal 8 (West)	Hong Kong
DMU 8	Container Terminal 9 (North)	Hong Kong
DMU 9	Container Terminal 9 (South)	Hong Kong
DMU 10	Container Terminal 6 and 7	Hong Kong
DMU 11	Chiwan Container Terminal	Shenzhen
DMU 12	Dachan Bay Terminal	Shenzhen
DMU 13	Mawan Container Terminal	Shenzhen
DMU 14	Shekou Container Terminal	Shenzhen
DMU 15	Yantian Container Terminal	Shenzhen
DMU 16	Nansha Container Terminal	Guangzhou
DMU 17	Guangzhou South China Oceangate Container Terminal	Guangzhou

Table 5
Result of the SBM model.

DMU	2018		2019	
	Score	Rank	Score	Rank
DMU 1	0.000	17	0.001	17
DMU 2	0.083	10	0.200	6
DMU 3	0.064	11	0.005	15
DMU 4	0.154	6	0.302	5
DMU 5	0.089	9	0.056	9
DMU 6	0.029	12	0.033	11
DMU 7	0.006	16	0.004	16
DMU 8	0.009	15	0.011	14
DMU 9	1.000	1	1.000	1
DMU 10	1.000	1	0.543	3
DMU 11	0.112	7	0.198	7
DMU 12	0.019	13	0.026	12
DMU 13	0.093	8	0.055	10
DMU 14	0.356	4	0.347	4
DMU 15	1.000	1	1.000	1
DMU 16	0.011	14	0.013	13
DMU 17	0.267	5	0.181	8

ranking first among the research objects, indicating that these two terminals were the most efficient in the study.

Container Terminal 9 (South) is one of the deep-water terminals in Hong Kong, with a depth of over 15.5 m. Compared to the other terminals in Hong Kong, Container Terminal 9 (South) is the only one that can receive ships above 200,000 DWT and 20,000 TEU. This makes it the most efficient port for evaluation. This terminal recorded the highest moves (O2) among all Hong Kong terminals—2307,917 moves in 2018 and 2145,208 moves in 2019. In addition, regardless of its smaller calls (O1) compared to the Yantian Container Terminal, the efficiency score is the same for both the terminals.

The Yantian Container Terminal has 16 berths and 106 shipping routes. Most berths have a water depth of more than 16 m, and the

Table 6
Result of the DEA undesirable model.

Name of the terminal	2018		2019	
	Score	Rank	Score	Rank
DMU 1	0.000	17	0.004	17
DMU 2	0.287	9	0.236	6
DMU 3	0.241	10	0.021	14
DMU 4	0.469	4	0.293	5
DMU 5	0.302	8	0.219	8
DMU 6	0.081	12	0.028	13
DMU 7	0.019	15	0.013	15
DMU 8	0.034	13	0.040	11
DMU 9	1.000	1	1.000	1
DMU 10	0.605	3	0.466	3
DMU 11	0.125	11	0.207	9
DMU 12	0.023	14	0.030	12
DMU 13	0.332	6	0.206	10
DMU 14	0.377	5	0.374	4
DMU 15	1.000	1	1.000	1
DMU 16	0.009	16	0.010	16
DMU 17	0.325	7	0.233	7

deepest berths have a water depth of more than 17 m, and can accept 230,000 DWT and 23,000 TEU ships. The Yantian Container Terminal's berth no. 16 was officially inaugurated in 2017. The berth has a 886 m long shoreline, with a water depth of 17.6 m, and is equipped with eight shore cranes, making it capable of receiving the world's largest container ships. The Yantian Terminal successfully received 210,000 tons from the world's largest container ship in 2019. As a result, from the standpoint of infrastructure, the Yantian Container Terminal has the best configuration, best receiving capacity, and highest efficiency.

The Yantian Container Terminal seems to be attracting large ships through deep shipment depth, recording 3225 ships in 2018 and 2958 ships in 2019. In addition, high moves (O2) were recorded because large ships could be docked. The Terminal recorded the largest number of moves among the analysis targets—5432,436 in 2018 and 5220,050 in 2019. Similar to Hong Kong's Container Terminal 9 (South), it is possible to maintain a large number of fleets and process large volumes in the Yantian Container Terminal because of its large storage.

5.3. Analysis result of the DEA undesirable model

In reality, the input and output variables used in efficiency analysis are not always optimal, and undesirable variables are sometimes involved. Therefore, this study included undesirable output factors in the model for analysis. The undesirable DEA model also used gross crane productivity, crane intensity, berth length, and berth depth as input variables. However, here, “finish” was introduced as an undesirable output variable for analysis in the model. According to the analysis results (Table 6), the DMU value of the Yantian Container Terminal and Container Terminal 9 (South) from 2018 to 2019 is 1, indicating that these two terminals remain the most efficient. These results are consistent with those of the SBM. This indicates that the efficiency of these two terminals is not

affected even when undesirable output factors are considered. In considering undesirable outputs, except for the Yantian Container Terminal, Container Terminal 9 (South), and Container Terminals 6 and 7, the DMU value of all the terminals was lower than that in the SBM-DEA model. This result may be because the time required for “finish” in Container Terminals 6 and 7 is less than that in the other terminals. Thus, terminal efficiency improves with the addition of the undesirable output. The DMU values of Container Terminal 4 and Shekou in the SBM-DEA model decrease in the undesirable DEA model. Moreover, the ranking growth trend of both terminal is not as evident as in the SBM-DEA model. This indicates that, with the exception of the Yantian Container Terminal and Container Terminal 9 (South) with the best efficiency, and Container Terminals 6 and 7 with better efficiency owing to the time factor, the DMU values and the efficiency decreased for all the other terminals.

6. Conclusion

From the regional economic construction perspective, port development has a significant impact that cannot be ignored. Especially against a backdrop of increasing international trade, port container terminal development and efficiency deserve more attention. As one of the main means of international trade, the influence of container transport is undeniable (Yi, Yang, & Yu, 2021). In order to explore the efficiency of the major container terminals in the top three cities—Hong Kong, Shenzhen, and Guangzhou—in the PRD region of China over the last two years, the SBM-DEA and the DEA undesirable models were used. Based on the DMU values of the terminals in the two years, the Yantian Container Terminal and Container Terminal 9 (South) are undoubtedly the most efficient, and show the best development among all the research objects. Container Terminals 6 and 7 are next in performance. The Yantian Container Terminal is a natural deep-water terminal, with a container throughput of 13,069 thousand TEU in 2019, compared with Shenzhen Port's container throughput of 25,769 thousand TEU, or nearly half of Shenzhen Port's container throughput. Hence, the efficiency of the Yantian Container Terminal has a significant impact on the evaluation of Shenzhen Port's growth. In 1997, the Shenzhen Port had a container throughput of 1148 thousand TEU, ranking 35th in the world. By 2013, it had surpassed Hong Kong for the first time to rank third in the world, owing to rapid development. Coupled with its advantageous geographical location and policy advantage of being the first SEZ in Mainland China, its development potential should not be underestimated. The Hong Kong Kwai Tsing Container Terminal is Hong Kong's main container terminal, and prior to 2004, it was the world's busiest container terminal, with the world's largest container throughput. In 2005, first Singapore, and then Shanghai, surpassed the Kwai Tsing Container Terminal. However, the container throughput has been declining in recent years owing to a variety of factors. In 2019, it ranked eighth in the world.

In particular, the results of the study show that terminals in the PRD tend to have fewer calls and moves when the length of the berth is short or the depth of the berth is shallow. In the case of ports in this area, it is presumed that the length and depth of the berth greatly influence their ability to attract shipping business. When comparing the efficiencies in 2018 and 2019, the calls and moves of the terminals inaccessible to large ships fell, resulting in a decline in efficiency. This suggests that infrastructure should be expanded given with the recent increase in the number of large ships.

In addition, it was noted that inefficiency owing to undesirable variables is more prevalent in small terminals than in large ports. Target terminals require improvement in finish to eliminate inefficiency.

China's ports are growing in tandem with its economy. In particular, the rapid growth of the Shenzhen Port, which is also located in the PRD region, has intensified competition among ports in the

region. A coordination in port development is crucial for regional port development. Summarizing the main research findings, Kwai Tsing Terminal 9 and Yantian Terminal were ranked as the most effective terminals. Considering the continuous decline in the total throughput of the Kwai Tsing Terminal in recent years, preserving its efficiency of Kwai Tsing Terminal 9 is a top priority, as is considering the demand to increase the efficiency of the other terminals. In particular, the terminals at Kwai Tsing 6 and 7 have relative development potential, and can focus on the relevant options. In this study, the efficiency of the major container terminals in Guangzhou was less satisfactory than that of the major container terminals in Shenzhen and Hong Kong. Therefore, efforts should be made to improve the efficiency of the container terminals in the Guangzhou Port as part of regional container terminal development efforts. Guangzhou, Shenzhen, and Hong Kong are the three megacities in the PRD, as well as the central development cities in the Guangdong–Hong Kong–Macao Greater Bay Area development plan. Improving the terminal efficiency of these three cities will help accelerate the growth of the regional economy, and drive the development of the surrounding areas.

This study estimates terminal efficiency using terminal productivity as an input factor, which is a novel assessment perspective with limitations. Owing to the confidentiality of data, many other factors, such as economy, environment, and labor force, were not included in the efficiency evaluation of the terminal. Incorporating these influencing factors in a future evaluation study will provide a more comprehensive analysis of terminal development in this region.

Conflicts of Interest Statement

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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References

- Boussofiane, A., Dyson, R. G., & Thanassoulis, E. (1991). Applied data envelopment analysis. *European Journal of Operational Research*, 52(1), 1–15. [https://doi.org/10.1016/0377-2217\(91\)90331-0](https://doi.org/10.1016/0377-2217(91)90331-0)
- Castellano, R., Ferretti, M., Musella, G., & Risitano, M. (2020). Evaluating the economic and environmental efficiency of ports: Evidence from Italy. *Journal of Cleaner Production*, 271, Article 122560. <https://doi.org/10.1016/j.jclepro.2020.122560>
- Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research*, 2(6), 429–444. [https://doi.org/10.1016/0377-2217\(78\)90138-8](https://doi.org/10.1016/0377-2217(78)90138-8)
- Chen, C., & Lam, J. S. L. (2018). Sustainability and interactivity between cities and ports: A two-stage data envelopment analysis (DEA) approach. *Maritime Policy & Management*, 45(7), 944–961. <https://doi.org/10.1080/03088839.2018.1450528>
- Chen, J., Wan, Z., Zhang, F., Park, N. K., Zheng, A., & Zhao, J. (2018). Evaluation and comparison of the development performances of typical free trade port zones in China. *Transportation Research Part A: Policy and Practice*, 118, 506–526. <https://doi.org/10.1016/j.tra.2018.09.009>
- Chi-Lok, A. Y., & Zhang, A. (2009). Effects of competition and policy changes on Chinese airport productivity: An empirical investigation. *Journal of Air Transport Management*, 15(4), 166–174. <https://doi.org/10.1016/j.jairtraman.2008.09.003>
- Chong, Z., & Pan, S. (2020). Understanding the structure and determinants of city network through intra-firm service relationships: The case of Guangdong–Hong Kong–Macao Greater Bay Area. *Cities*, 103, Article 102738. <https://doi.org/10.1016/j.cities.2020.102738>

- Cullinane, K., Fei, W. T., & Cullinane, S. (2004). Container terminal development in Mainland China and its impact on the competitiveness of the port of Hong Kong. *Transport Reviews*, 24(1), 33–56.
- Cullinane, K., & Song, D. W. (2006). Estimating the relative efficiency of European container ports: A stochastic frontier analysis. *Research in Transportation Economics*, 16(1), 85–115.
- Dan, L. I., Weixin, L. U. A. N., & Feng, P. I. A. N. (2013). The efficiency measurement of coastal container terminals in China. *Journal of Transportation Systems Engineering and Information Technology*, 13(5), 10–15. [https://doi.org/10.1016/S1570-6672\(13\)60121-X](https://doi.org/10.1016/S1570-6672(13)60121-X)
- Debie, J., & Raimbault, N. (2016). The port–city relationships in two European inland ports: A geographical perspective on urban governance. *Cities*, 50(4), 180–187. <https://doi.org/10.1016/j.cities.2015.10.004>
- Ducruet, C. (2017). *A metageography of port-city relationships. Ports, cities, and global supply chains*. Routledge, 173–188.
- Gharehgozli, A., Zaeipour, N., & de Koster, R. (2019). Container terminal layout design: Transition and future. *Maritime Economics & Logistics*, 22(4), 610–639.
- Gong, X., Wu, X., & Luo, M. (2019). Company performance and environmental efficiency: A case study for shipping enterprises. *Transport Policy*, 82, 96–106. <https://doi.org/10.1016/j.tranpol.2018.04.008>
- Grobarr, L. M. (2008). The economic status of areas surrounding major US container ports: Evidence and policy issues. *Growth and Change*, 39(3), 497–516. <https://doi.org/10.1111/j.1468-2257.2008.00435.x>
- Halkos, G., & Petrou, K. N. (2019). Treating undesirable outputs in DEA: A critical review. *Economic Analysis and Policy*, 62, 97–104. <https://doi.org/10.1016/j.eap.2019.01.005>
- Homosombat, W., Ng, A. K., & Fu, X. (2016). Regional transformation and port cluster competition: The case of the Pearl River Delta in South China. *Growth and Change*, 47(3), 349–362. <https://doi.org/10.1111/grow.12128>
- Hu, G., Sun, W., & Jiang, J. (2020). Research on the current situation and development measures of rail-water intermodal transport in Guangzhou Port Group. *IOP Conference Series: Materials Science and Engineering*, 782(5), Article 052003. <https://doi.org/10.1088/1757-899X/782/5/052003>
- Hua, C., Chen, J., Wan, Z., Xu, L., Bai, Y., Zheng, T., & Fei, Y. (2020). Evaluation and governance of green development practice of port: A sea port case of China. *Journal of Cleaner Production*, 249, Article 119434. <https://doi.org/10.1016/j.jclepro.2019.119434>
- Jahanshahloo, G. R., Lotfi, F. H., Shoja, N., Tohidi, G., & Razavyan, S. (2005). Undesirable inputs and outputs in DEA models. *Applied Mathematics and Computation*, 169(2), 917–925. <https://doi.org/10.1016/j.amc.2004.09.069>
- Kong, Y., & Liu, J. (2021). Sustainable port cities with coupling coordination and environmental efficiency. *Ocean & Coastal Management*, 205, Article 105534. <https://doi.org/10.1016/j.ocecoaman.2021.105534>
- Kuo, S. Y., & Lin, P. C. (2020). Determinants of green performance in container terminal operations: A lean management. *Journal of Cleaner Production*, 275, Article 123105. <https://doi.org/10.1016/j.jclepro.2020.123105>
- Lin, C., & Lin, G. C. S. (1997). *Red capitalism in South China: Growth and development of the Pearl River Delta*, Vol. 2. University of British Columbia Press.
- Liu, J., Wang, X., & Guo, J. (2021). Port efficiency and its influencing factors in the context of pilot free trade zones. *Transport Policy*, 105(C), 67–79. <https://doi.org/10.1016/j.tranpol.2021.02.011>
- Meng, L., Sun, Y., & Zhao, S. (2020). Comparing the spatial and temporal dynamics of urban expansion in Guangzhou and Shenzhen from 1975 to 2015: A case study of pioneer cities in China's rapid urbanization. *Land Use Policy*, 97, Article 104753. <https://doi.org/10.1016/j.landusepol.2020.104753>
- National Bureau of Statistics (2008). Reform and Opening up 30 years report 12: transportation industry to achieve a variety of transport modes of leapfrog development.
- Notteboom, T. E., & Rodrigue, J. P. (2005). Port regionalization: Towards a new phase in port development. *Maritime Policy & Management*, 32(3), 297–313. <https://doi.org/10.1080/03088830500139885>
- Rashidi, K., & Saen, R. F. (2015). Measuring eco-efficiency based on green indicators and potentials in energy saving and undesirable output abatement. *Energy Economics*, 50(C), 18–26. <https://doi.org/10.1016/j.eneco.2015.04.018>
- Roll, Y., & Hayuth, Y. (1993). Port performance comparison applying data envelopment analysis (DEA). *Maritime Policy & Management*, 20(2), 153–161. <https://doi.org/10.1080/030888393000000025>
- Seiford, L. M., & Zhu, J. (2002). Modeling undesirable factors in efficiency evaluation. *European Journal of Operational Research*, 142(1), 16–20. [https://doi.org/10.1016/S0377-2217\(01\)00293-4](https://doi.org/10.1016/S0377-2217(01)00293-4)
- Song, B., & Cui, Y. (2014). Productivity changes in Chinese container terminals 2006–2011. *Transport Policy*, 35, 377–384. <https://doi.org/10.1016/j.tranpol.2014.04.011>
- Song, D. W. (2002). Regional container port competition and co-operation: The case of Hong Kong and South China. *Journal of Transport Geography*, 10(2), 99–110. [https://doi.org/10.1016/S0966-6923\(02\)00003-0](https://doi.org/10.1016/S0966-6923(02)00003-0)
- Tan, T. Y. (2007). Port cities and hinterlands: A comparative study of Singapore and Calcutta. *Political Geography*, 26(7), 851–865. <https://doi.org/10.1016/j.polgeo.2007.06.008>
- Tone, K. (2001). A slacks-based measure of efficiency in data envelopment analysis. *European Journal of Operational Research*, 130(3), 498–509. [https://doi.org/10.1016/S0377-2217\(99\)00407-5](https://doi.org/10.1016/S0377-2217(99)00407-5)
- Tongzon, J. (2001). Efficiency measurement of selected Australian and other international ports using data envelopment analysis. *Transportation Research Part A: Policy and Practice*, 35(2), 107–122. [https://doi.org/10.1016/S0965-8564\(99\)00049-X](https://doi.org/10.1016/S0965-8564(99)00049-X)
- Tongzon, J. L. (1995). Determinants of port performance and efficiency. *Transportation Research Part A: Policy and Practice*, 29(3), 245–252. [https://doi.org/10.1016/0965-8564\(94\)00032-6](https://doi.org/10.1016/0965-8564(94)00032-6)
- Turner, H., Windle, R., & Dresner, M. (2004). North American container port productivity: 1984–1997. *Transportation Research Part E: Logistics and Transportation Review*, 40(4), 339–356. <https://doi.org/10.1016/j.tre.2003.06.001>
- UNCTAD (2017). Review of Maritime Transport 2017. UNCTAD/RMT/2017, New York and Geneva.
- Valentine, V. F., Gray, R. (2001). The measurement of port efficiency using data envelopment analysis. In: Proceedings of the 9th World Conference on Transport Research, 22, 27. South Korea: Seoul.
- Wan, C., Zhang, D., Yan, X., & Yang, Z. (2018). A novel model for the quantitative evaluation of green port development – A case study of major ports in China. *Transportation Research Part D: Transport and Environment*, 61(B), 431–443. <https://doi.org/10.1016/j.trd.2017.06.021>
- Wang, J., Zhang, M., Wang, S. (2019). Shenzhen Port competitiveness evaluation based on the construction of the Guangdong-Hong Kong-Macao Greater Bay Area. In: Proceedings of the 19th COTA International Conference of Transportation Professionals, 5450–5457. <https://doi.org/10.1061/9780784482292.469>
- Wang, J. J., Ng, A. K. Y., & Olivier, D. (2004). Port governance in China: A review of policies in an era of internationalizing port management practices. *Transport Policy*, 11(3), 237–250. <https://doi.org/10.1016/j.tranpol.2003.11.003>
- Wang, K., Ng, A. K., Lam, J. S. L., & Fu, X. (2012). Cooperation or competition? Factors and conditions affecting regional port governance in South China. *Maritime Economics & Logistics*, 14(3), 386–408. <https://doi.org/10.1057/mel.2012.13>
- Wang, L., Notteboom, T., Lau, Y. Y., & Ng, A. K. (2017). Functional differentiation and sustainability: A new stage of development in the Chinese container port system. *Sustainability*, 9(3), 328.
- Wang, P., Hu, Q., Xu, Y., Mei, Q., & Wang, F. (2021). Evaluation methods of port dominance: A critical review. *Ocean & Coastal Management*, 215, Article 105954.
- Wu, J., Yan, H., & Liu, J. (2010). DEA models for identifying sensitive performance measures in container port evaluation. *Maritime Economics & Logistics*, 12(3), 215–236. <https://doi.org/10.1057/mel.2010.6>
- Wu, X., & Guo, J. (2021). Efficiency evaluation and PM emission reallocation of China ports based on improved DEA models. *Economic impacts and emergency management of disasters in China*. Singapore: Springer, 607–640. https://doi.org/10.1007/978-981-16-1319-7_21
- Yap, W. Y., Lam, J. S., & Notteboom, T. (2006). Developments in container port competition in East Asia. *Transport Reviews*, 26(2), 167–188. <https://doi.org/10.1080/01441640500271117>
- Yi, Z., Yang, C., & Yu, M. (2021). Managing regional container terminal competition: The roles of information and government support. *Maritime Policy & Management*, 1–21. <https://doi.org/10.1080/03088839.2020.1864491>
- You, S., & Yan, H. (2011). A new approach in modelling undesirable output in DEA model. *Journal of the Operational Research Society*, 62(12), 2146–2156. <https://doi.org/10.1057/jors.2011.1>
- Youlin, L., XinWei, C., ZhiSen, H., & ZhiTe, W. (2021). Analysis of Shenzhen Port container development countermeasures under the background of Guangdong-Hong Kong-Macao Greater Bay Area. *IOP Conference Series: Earth and Environmental Science*, 638(1), Article 012019. <https://doi.org/10.1088/1755-1315/638/1/012019>
- Yu, M., Lee, C. Y., & Wang, J. J. (2017). The regional port competition with different terminal competition intensity. *Flexible Services and Manufacturing Journal*, 29(3), 659–688. <https://doi.org/10.1007/s10696-016-9254-6>
- Yuen, A. C. L., Zhang, A., & Cheung, W. (2013). Foreign participation and competition: A way to improve the container port efficiency in China? *Transportation Research Part A: Policy and Practice*, 49, 220–231. <https://doi.org/10.1016/j.tra.2013.01.026>
- Yuen, C. L. A., Zhang, A., & Cheung, W. (2012). Port competitiveness from the users' perspective: An analysis of major container ports in China and its neighboring countries. *Research in Transportation Economics*, 35(1), 34–40.