Journal of Ocean Engineering and Technology 39(1), 56-62, February, 2025
https://doi.org/10.26748/KSOE.2024.100
eISSN 2287-6715

Original Research Article

Efficiency Analysis of Container Ports in Vietnam Using Stochastic Frontier Analysis

Thanh Uyen Bui[1] and Gyu Sung Cho[2]

[1]*Graduate Student, Department of Port Logistic System, Tongmyong University, Busan, Korea*
[2]*Professor, Department of Port Logistic System, Tongmyong University, Busan, Korea*

KEYWORDS: Port efficiency, Stochastic frontier analysis, SFA method, Port industry, Vietnam

ABSTRACT: *This study compared the technical efficiency of container ports in Vietnam to pinpoint areas for improvement, enabling the ports to enhance their efficiency and competitiveness within the Vietnamese port industry. This analysis used cross-sectional data from 13 major container ports and terminals across the country, utilizing the variables related to port infrastructure, including the total quay length (in meters), maximum alongside depth (in meters), and total terminal area (in square meters). The output metric used was the cargo volume, measured in twenty-foot equivalent units (TEU) per year. The port efficiency was measured using stochastic frontier analysis (SFA), with the dataset sourced primarily from the official Vietnam Seaports Association website (www.vpa.org.vn). The methods were used to analyze the variations in port efficiency, including aspects such as distribution, rankings, identification of the best and worst ports, and determinants of the efficiency frontier. The results suggest that the port efficiency, as measured using the SFA models, enhances the technical efficiency scores of the container ports, with the collected scores generally being high among the 13 observations. This highlights the significance of the term error in container port production, showing that the seaport sector is an area where perception errors are highly developed. In addition, ports with higher throughput do not always have the highest efficiency scores. Therefore, the port authorities and managers responsible for port investment and management in Vietnam should consider using the SFA method to estimate and improve port efficiency.*

1. Introduction

Container port efficiency is an imperative indicator of the competitiveness and economic growth of a nation and region (Thai et al., 2015). Therefore, evaluating port efficiency is essential to port operators, investors, governments, and users because it helps to monitor the performance of the port and identify the critical factors that improve port efficiency and trade competitiveness. In particular, for developing countries, efficient port operations can enhance the economy, helping to transform it into a strong and developed nation. When assessing the development prospects of ports, researchers, and managers rely on the physical aspects of ports to measure and compare their efficiency. Hlali (2018) referenced the stochastic frontier analysis (SFA) method because it can deal with stochastic noise, highlighting the importance of the term error in container port production. Therefore, this study measured the efficiency of 13 Vietnamese container ports using the SFA method using the cross-sectional data. The results of the method were analyzed in two models (half-normal and truncated normal distribution) and compared to make the most appropriate comments.

The port industry in Vietnam provides a potential background to confirm the importance of evaluating port efficiency. First, Vietnam is a potential geographic location for shipping development and marine services. With a 3,260 km coastline, it borders the Pacific Ocean and South China Sea, which is an important economic transport route helping to transport goods from Asia to other parts of the world (Kuo et al., 2020). Second, Vietnam's seaport system currently has 286 ports, distributed in five groups of seaports, with a total wharf length of more than 96 km and infrastructure to meet the throughput of 24.7 million twenty-foot equivalent units (TEUs) in 2023. The recent Vietnamese seaport system has focused on investment with the current scale and technology that reaches internationally, with two seaports, Hai Phong and Cat Lai, in the top 50 largest container ports worldwide. In addition, Vietnam has attracted many direct foreign investments throughout the years (Dang and Yeo, 2018). The nation is considered a new low-cost option that provides cheap labor costs and offers a friendly environment and tax reduction to foreign firms (Kumar et al., 2009). Therefore, an analysis of the efficiency of these Vietnamese

Received 4 December 2024, revised 26 December 2024, accepted 26 December 2024
Corresponding author Gyu Sung Cho: +82-51-629-1466, gscho@tu.ac.kr

ports is essential to determine the improvement of their operation.

The key issue leading to this study is an empirical evaluation of the efficiency frontier. Based on this evaluation, this study examined whether the characteristics of infrastructure influence the efficiency of container ports and explored the relationship between the throughput volume and the efficiency scores of these ports. Another contribution of this study was to specify the locations of the most efficient container ports. Hence, the question as to why these container ports perform better has been raised. This paper emphasizes the preference for using the SFA method. Through this parametric technique, the results will provide an important foundation for port authorities and managers, helping them make more informed and confident decisions.

2. Literature Review

When considering some studies that focused on port efficiency, many empirical studies that focused on international container ports applied SFA as their research methodology but provided mixed results. In Vietnamese industry, however, limited quantitative studies have used this parametric methodology to compare the efficiency of domestic terminals.

Initially, Cullinane and Song (2003) used SFA to assess the technical efficiency of Korean ports and examine the impact of private sector ownership on efficiency, using cross-sectional and panel data. The results, based on various distribution assumptions, showed that private sector involvement and deregulation positively influence technical efficiency. This finding suggests that policies aimed at improving efficiency could also enhance the competitiveness of the port sector. Similarly, Tongzon and Heng (2005) applied SFA and reported that while privatization enhances terminal efficiency, it does not lead to significant improvements in overall efficiency. Some studies also compared two or more different methods to estimate the efficiency score. Nguyen et al. (2015) compared the results of SFA and standard data development analysis (DEA) with those of boost-strapped DEA to measure the efficiency of the 43 largest Vietnamese ports. Hlali (2018) also applied the SFA and DEA methods to assess the operating efficiencies of 26 international container ports. Both studies determined the efficiency scores from the SFA method to be the highest.

Table 1 provides a summary of previous studies measuring the efficiency of container ports or terminals using the SFA model. Cross-sectional data and panel data are the types of data that are commonly used in other studies. The majority of studies accepted the container throughput (TEUs) as the same output variable of efficiency measurement, but the input variables were different. The infrastructure or the superstructure factors, such as terminal area, quay length, and equipment number, were mostly selected as the input variables for the ports.

Table 1 Previous studies using SFA to measure the efficiency of container ports or terminals

Authors	Ports	Input	Output	Model	Data type
Cullinane and Song (2003)	Five Korean and UK container terminals	Labor Capital	Container throughput	SFA	Cross-sectional Panel
Cullinane et al. (2006)	74 European container ports with 2002 data	Terminal length Terminal area Equipment	Container throughput (TEU)	SFA	Cross-sectional
Barros (2005)	10 Portuguese port authorities, 1990–2000	Price of labor Price of capital	number of ships total cargo	SFA	Panel
Tongzon and Heng (2005)	25 container ports/terminals, 1999	Terminal quay length The terminal surface Number of quay cranes	total throughput (TEU)	SFA	Cross-sectional
González and Trujillo (2008)	Five Spanish port authorities, including 17 ports 1990–2002	Port authority Berths Number of labor	Cargo throughput Number of passengers.	SFA	Panel
Ro-kyung (2010)	Eight Korean container terminals for 3 years (2002,2003, 2004)	Number of Employees Quay Length Container Terminal Area Number of Gantry Crane	Container throughput	SFA	Cross-sectional
Nguyen et al. (2015)	Measuring port efficiency using bootstrapped DEA: the case of Vietnamese ports	berth length terminal areas warehouse capacity cargo handling equipment	Container throughput	SFA DEA bootstrapped DEA	Cross-sectional
Merkel (2018)	77 large European container ports	Total terminal area meters Total berth length Total number of quay cranes Stackers/front-end handlers	Container throughput	SFA	Panel
Hlali (2018)	26 world's major container ports in 2015	Total quay length The maximum alongside depth Total terminal area and the storage capacity	Container throughput	DEA-BCC SFA	Cross-sectional

3. Methodology

3.1 Stochastic Frontier Models Specification

SFA is a parametric method based on quantitative economy theory and is a very popular method for estimating efficiency. According to Farrell's (1957) theory of efficiency measurement, Aigner et al. (1977) and Meeusen and van den Broeck (1997) independently constructed an error structure of stochastic frontier analysis to measure the productive efficiency of firms.

To explain the SFA method, the deviation from the frontier has two components, noise (v) and inefficiency (u), which result in two cross-sectional models: half normal and truncated normal distribution, as defined in the following Eq. (1):

$$\ln(y_i) = \ln(x_i) + (V_i - U_i), \quad i = 1,\ 2,,n \tag{1}$$

Where,

$ln(y_i)$: the output obtained by i^{th} port (logarithm)

x_i: vector of (m+1), the first element is 1, the remaining elements are the quantities of the m inputs of the i^{th} port;

β: vector of the parameters to be estimated;

V_i: random variables representing statistic noise, $N(0, \sigma_v^2)$;

U_i: non-negative random variables representing technical inefficiency;

Random variables V_i include measurements of the noise and other random factors, along with the joint effects of input variables not specified in the production function. Aigner et al. (1977) assumed that V_i with normal random variables with a zero mean and constant variance σ_v^2, is independent and distributed identically. In addition, U_i is assumed to be an independent and identically distributed half-normal $N(0, \sigma_v^2)$ or truncations at zero of the $N(\mu, \sigma_v^2)$. Aigner et al. (1977) suggested the following "half-normal" and "truncated" models. The following Eqs. (2)–(4) were adapted from Greene (2008):

$$\lambda = \sigma_u \ / \ \sigma_v \tag{2}$$

$$\sigma^2 = \sigma_u^2 + \sigma_v^2 \tag{3}$$

$$\gamma = \sigma_u^2 \ / \ \left(\sigma_u^2 + \sigma_v^2\right) \tag{4}$$

Where,

v is the variance parameter of the noise term;

u is the variance parameter of the inefficiency term.

Gamma (γ) represents the proportion of the total variation in the error term ($V_i - U_i$) due to inefficiency (represented by U_i) versus random noise (represented by V_i). A γ value close to zero indicates that the deviations from the frontier are due primarily to noise, and there is no inefficiency in the model. If γ is close to one, it indicates that the deviations from the frontier are due mainly to technical inefficiency, meaning there is no random noise in the model.

Eq. (5) expresses the Likelihood Ratio test statistics recommended by Kumbhakar et al. (2015):

$$LR_Y = -2\left[L(H_0) - L(H_1)\right] \tag{5}$$

where $L\ (H_0)$ and $L\ (H_1)$ represent the log-likelihood values calculated from the restricted original least squares (OLS) model and the unrestricted stochastics frontier model, respectively, with one degree of freedom representing the imposed restriction. The critical values for the mixed distribution were obtained from Kodde and Palm (1986). The stochastic frontier model is appropriate to justify the efficiency if the number of restrictions corresponding to the degree of freedom is less than the 0.5% significant level. On the other hand, if the null hypothesis is rejected, then the term for efficiency should be removed from the model, and the model can be estimated using the OLS method. As $0 \leq \gamma \leq 1$, $\gamma = 1$ is the same as $\sigma_v^2 = 0$. Therefore, the stochastic frontier model is similar to the deterministic frontier model, meaning there are no random errors in the production function.

One of the key objectives of SFA is to measure the efficiency of each unit or firm relative to the frontier. The efficiency E_i for firm i was calculated using Eq. (6):

$$E_i = \frac{f(X_i,\ \beta) \ - \ U_i}{f(X_i,\ \beta)} \tag{6}$$

where

E_i is the efficiency score for firm i.

$f(X_i, \beta)$ is the best possible output given inputs for firm i.

U_i is the inefficiency term, which quantifies how much the firm falls short of the frontier.

An efficiency score of 1 means the firm is fully efficient, while values less than 1 indicate varying degrees of inefficiency.

3.2 Data Set

This study used cross-sectional data from 2023 collected from 13 Vietnamese ports and terminals. The data were obtained from official websites and several sources, including the Vietnam Seaport Association (VPA) website and the 2023 annual report of Cai Lai JSC. The output variable was the annual container throughput in TEUs. The input variables selected are related to the characteristics of port infrastructure, such as the total quay length (m), maximum alongside depth (m), and total terminal area (m^2). These variables were chosen based on the available data for the various container ports. Table 2 lists the cargo numbers for 2023, along with the details of the variables of each port. According to Table 2, Cat Lai Port ranked first with the largest total terminal area and a container throughput of approximately 5,332,128 TEU last year, while Hiep Phuoc Port had the lowest container volume, with only 130,477 TEU. The distribution of container throughput varied across different regions. Most ports,

Table 2 Original data used in frontier analysis

No	Container port	Throughput (TEU)	Total quay length (m)	Max water depth (m)	Total terminal area (m^2)
1	Cat Lai Port	5,332,128	2,040	12.5	1,600,000
2	Hiep Phuoc Port	130,477	800	10.5	360,000
3	Cai Mep International Terminal (CMIT)	644,273	600	16.5	460,000
4	Dong Nai Port	570,215	1,131	12.0	817,526
5	Binh Duong Port	491,313	150	8.0	255,000
6	Can Tho Port	1,540,972	867	12.0	320,065
7	Cam Ranh Port	343,000	708	11.0	690,000
8	Thuan An Port	158,910	185	5.9	100,000
9	Da Nang Port	675,254	1,713	14.3	230,000
10	Vung Ang Port	2,829,000	1,500	11.0	1,083,000
11	Hai Phong Port	1,312,397	3,550	9.7	1,103,474
12	Nam Dinh Vu Port	897,224	440	8.5	202,149
13	Cam Pha Port	569,417	650	10.5	200,000

Table 3 Descriptive analysis data

Division	Throughput (TEU)	Total quay length (m)	Maximum water depth (m)	Total terminal area (m^2)
Mean	1,191,891	1,103	11.0	570,863
Maximum	5,332,128	3,550	16.5	1,600,000
Minimum	130,477	150	5.9	100,000
Standard deviation	1,437,322	928	2.72	457,432
Observations	13	13	13	13

particularly those associated with major centers and economic areas of the country, have developed into large seaports.

Table 3 lists the descriptive statistics for different variables used in the models of port efficiency. The minimum value and the maximum value of throughput (TEU) were 5,332,128 and 130,477, respectively, with a standard deviation of 1,437,322, suggesting that regional development is considerably unbalanced. The maximum and minimum variable total quay length were 3,550 and 150. The maximum alongside depth varied from 5.9 to 16.5. The total terminal area differed depending on the economic status of each area. The minimum and maximum total terminal area were 1,600,000 and 100,000, respectively, with a standard deviation of 457,432.

4. Results

Table 4 lists the results of the maximum likelihood estimation (MLE) analysis of domestic container terminals using SFA with cross-sectional data. The MLE results for the parameters of the production function were obtained using STATA 17 software. The parameters for the maximum water depth input were −0.036 and −0.104 for the half-normal and truncated normal distributions, respectively, indicating that the coefficient of the maximum water depth was insignificant for both distributions. On the other hand, the coefficients for the total quay length and total terminal area were significant in both distribution cases. Therefore, it can be associated directly with the observed performance in the container ports.

For both the half-normal and the truncated-normal distribution, the gamma $\gamma=\sigma_u^2/(\sigma_u^2+\sigma_v^2)$is the same estimated at 0.999 levels, which means 99% of random variations in both distributions in container port production are due to efficiency. Hence, the estimates of σ^2 were significant in both cases, with amounts of 0.527 and 0.034 for half vs. truncated normal distributions, respectively.

Mu (μ) refers to the mean of the inefficiency term (technical inefficiency) when the inefficiency term is assumed to have some specific distribution. In some formulations of SFA, the inefficiency term U_i was assumed to follow a truncated normal distribution, and Mu

Table 4 Maximum likelihood estimation of SFA

Variables/parameters	Half-normal	Truncated normal
Constant (β)	0.454	0.468
X_1	0.457	0.509
X_2	−0.036	−0.104
X_3	0.529	0.593
Sigma-squared (σ^2)	0.527	0.034
Gamma (γ)	0.999	0.999
Mu (μ)	0	−0.139
log-likelihood	0.6758	0.6848

(μ) represents the mean or expected value of this inefficiency term. The calculation of the μ (in Table 4) parameter was found to be negative (i.e., $\mu = -0.139$). The parameter μ was negative, indicating that the distribution of the inefficiency effects was concentrated at approximately zero compared to the half-normal distribution.

The values of the log-likelihood function for the two distribution production functions were 0.675 and 0.685, respectively. The generalized likelihood-ratio test statistic for the alternative hypothesis (H_1: $\gamma > 0$) of a technical inefficiency model with a half-normal distribution against the null hypothesis (H_0: $\gamma = 0$), where there is no technical inefficiency effect with a half-normal distribution, was 6.758. This value was greater than the critical value of 6.635 from the mixed chi-square distribution with six degrees of freedom at the 5% significance level, indicating the model significance. Therefore, the null hypothesis that there was no technical inefficiency effect with a half-normal distribution can be rejected, and the alternative hypothesis that such an effect exists was accepted. Hence, the traditional average response function, which does not consider technical inefficiency effects, does not adequately represent the data. In the truncated normal distribution, the estimate was 6.848, which is also significant because it exceeds the critical value of 6.635 from the mixed chi-square distribution with six degrees of freedom at the 0.5 significance level.

Table 5 lists the descriptive statistics of the estimated efficiency scores to provide insight into the characteristics of all the models. The mean SFA efficiency score was 0.533 and 0.536 for the half-normal model and truncated normal model, respectively. The standard deviations of both SFA models were 0.338 and 0.341 because SFA is stochastic and involves the randomness of variables. These values do not appear to reflect the expected level of randomness as much as expected. In other words, SFA is unlikely to overestimate the actual efficiency scores.

The estimated efficiency scores of 13 observations showed that most of the observations were efficient (close to 1), as shown in Table 6. Cat Lai Port is the largest container port in Vietnam, handling around 5,332,128 TEU, approximately 50% of the market share nationwide in 2023. In this study, Cai Lai Port was also estimated to be the most efficient port, accompanied by Can Tho and Nam Dinh Vu Port. These ports achieved a scale efficiency of more than 0.9. On the other hand, despite being nominated in the top 50 port container volumes worldwide, Hai Phong port derived a very low efficiency score, only 0.230 and 0.218 for the half-normal and truncated normal, respectively.

Thuan An and Da Nang Ports delivered a discrepancy in the rankings between the two models. The results obtained from the half-normal distribution for Da Nang Port were higher than those for Thuan An Port, while the results from the truncated normal distribution for Thuan An Port exceeded those for Da Nang Port.

Table 5 Descriptive statistics of estimated efficiency

SFA	Half normal	Truncated normal
Mean	0.533	0.536
Maximum	0.999	0.998
Minimum	0.082	0.082
Standard deviation	0.338	0.341

Table 6 Efficiency estimates obtained from the SFA

No.	Container port	Half-normal	Truncated normal
1	Cat Lai Port	0.999	0.998
2	Hiep Phuoc Port	0.821	0.820
3	Cai Mep International Terminal (CMIT)	0.413	0.434
4	Dong Nai Port	0.200	0.202
5	Binh Duong Port	0.791	0.838
6	Can Tho Port	0.999	0.998
7	Cam Ranh Port	0.162	0.166
8	Thuan An Port	0.377	0.378
9	Da Nang Port	0.385	0.373
10	Vung Ang Port	0.747	0.745
11	Hai Phong Port	0.230	0.218
12	Nam Dinh Vu Port	0.999	0.998
13	Cam Pha Port	0.538	0.535

A comparison of the results with similar applications in the literature found that Nguyen et al. (2015) derived a great efficiency score under the SFA method, approximately 0.96 for the 43 largest container ports in Vietnam in 2015. The scores did not fluctuate significantly between the observations and were almost higher than the other methods used in the research. Hlali (2018) confirmed that the efficiency improved under the SFA models. The study revealed the best mean efficiency (0.876) among 26 major ports of the world since 2015, showing that the container ports were more efficient and could improve their infrastructure.

The relationship between the estimated efficiencies of the container ports and the number of cargo volumes showed that the port efficiency is associated with the quantities of container production. In this study, approximately half of the 13 ports investigated were efficient according to the SFA models. In particular, Hiep Phuoc Port showed higher operational efficiency than other ports, such as Dong Nai, Da Nang, and Hai Phong, despite the significant disparity in total cargo volumes produced. This suggests that ports with higher throughput do not necessarily achieve the highest efficiency scores in all cases.

The competitiveness of these ports is closely linked to the enhancement of their infrastructure, which in turn depends on the quality and efficiency of their hinterland connections. The SFA models showed that the selected sample of container ports generally has good access to infrastructure, positioning them among the most competitive container ports domestically. Prioritizing the expansion of existing infrastructure and initiating new construction plans is essential to fostering the development of an efficient container port.

5. Conclusions

This study examined the technical efficiency of major container ports in Vietnam using SFA models. In addition, it investigated the comparability of the efficiency rankings of these ports and compared the findings with the results from existing literature. The empirical results were highly satisfactory, with the following conclusions:

(1) The models were estimated using the error components model specification, which allows for the distinction between random error and technical inefficiency in the estimation of port efficiency. These results suggest that the input variables included in the technical efficiency analysis have a significant impact on the production abilities of container ports, with the terminal area emerging as a particularly important factor. Hence, larger terminal areas contribute to higher efficiency in port operations.

(2) The half-normal distribution closely resembles the truncated normal distribution when applied to the technical inefficiency effect and technical efficiency scores. This similarity suggests that the inefficiency effects across the ports follow a distribution that is well-captured by the chosen models, providing a strong basis for estimating the technical inefficiency.

(3) A comparison of the two stochastic models, which differ in their error term distributions (half-normal versus truncated normal distribution), provided valuable insights into the estimation of port efficiency. The half-normal distribution assumed a more straightforward form for the inefficiency term. In contrast, the truncated normal distribution allowed for more flexibility in modeling the inefficiency, especially when it was assumed that inefficiency cannot be negative. The results obtained from both models yielded similar conclusions regarding the relative efficiency of the ports.

(4) The two models may have different specifications, which can lead to variations in the rankings of the efficiency scores. In SFA, the choice of variables included in the model, as well as the functional form of the production or cost function, can significantly influence the estimated efficiency scores.

(5) On the other hand, the SFA models proved to be most relevant for evaluating the efficiency of container ports based on the empirical results and the overall performance of the models. The SFA models provided a robust framework for separating the effects of inefficiency from random noise and gave consistent, reliable estimates of technical efficiency across the ports. This reinforces the suitability of the SFA methodology in the context of port efficiency analysis, particularly when assessing the impact of operational variables and infrastructure on port performance. These results highlight the importance of selecting the appropriate model specification to capture accurately the nuances of technical inefficiency in port operations.

(6) A comparison of port efficiency revealed Cat Lai, Can Tho, and Nam Dinh Vu as the most efficient container ports in Vietnam based on both SFA models used for the evaluation. These ports exhibited the best infrastructure, which is reflected in their ability to handle a large volume of containers. The advanced facilities and efficient management practices at these ports enable them to maintain high levels of operational efficiency despite handling substantial throughput, positioning them as leaders in the competitive landscape of container ports.

(7) Receiving the lowest estimated efficiency score, the port of Hai Phong is now facing the problem of not fully utilizing its infrastructure; inputs such as total quay length, water depth, and terminal area are becoming redundant, proving the lack of accurate operation.

(8) These findings indicated a strong correlation between the estimated efficiencies of container ports and their throughput evaluations, showing that the efficiency of a port is closely related to the volume of container production. In other words, ports with higher throughput do not consistently achieve the highest efficiency scores in both cases.

In conclusion, Vietnam is emerging as an attractive location for many foreign investors where the port industry is considered as a potential factor. Nevertheless, a number of ports were found to be inefficient, indicating that Vietnamese ports have not yet made a substantial impact on improving Vietnam’s export competitiveness. Hence, a significant opportunity exists for these ports to enhance their operational efficiency, which could, in turn, boost Vietnam’s global competitiveness and trade performance. In a nation that relies heavily on trade, improving port efficiency is crucial for strengthening Vietnam’s export capabilities and fostering economic growth.

This study shows that SFA models are preferred when it comes to evaluating port efficiency. The container port sector is particularly susceptible to perception errors, where misjudgments or inaccurate assessments of operational performance are common. Such errors may arise from various factors, including inaccurate data, variability in management practices, or the complexity of port operations. Therefore, the port authority and managers responsible for port investment and management in Vietnam should perceive the importance of the term error and consider the SFA method to estimate and improve port efficiency.

Conflict of Interest

Gyu Sung Cho serves as a journal publication committee member of the Journal of Ocean Engineering and Technology, but he played no role in the decision to publish this article. The authors have no potential conflict of interest relevant to this article.

Funding

This research was supported by “Regional Innovation Strategy (RIS)” through the National Research Foundation of Korea (NRF), funded by the Ministry of Education (MOE) (2023RIS-007).

References

Aigner, D., Knox Lovell, C. A., & Schmidt, P. (1977). Formulation and estimation of stochastic frontier production function models.

Journal of Econometrics, 6(1), 21–37. https://doi.org/10.1016/0304-4076(77)90052-5

Barros, C. P. (2005). Decomposing growth in Portuguese seaports: A frontier cost approach. *Maritime Economics and Logistics, 7*(4), 297–315. https://doi.org/10.1057/palgrave.mel.9100140

Cullinane, K., Wang, T.-F., Song, D.-W., & Ji, P. (2006). The technical efficiency of container ports: Comparing data envelopment analysis and stochastic frontier analysis. *Transportation Research Part A: Policy and Practice, 40*(A): 354–374. https://doi.org/10.1016/j.tra.2005.07.003

Cullinane, K., & Song, D.-W. (2003). A stochastic frontier model of the productive efficiency of Korean container terminals. *Applied Economics, 35*(3), 251–267. https://doi.org/10.1080/00036840210139355

Dang, V. L., & Yeo, G. T. (2018). Weighting the key factors to improve Vietnam's logistics system. *Asian Journal of Shipping and Logistics, 34*(4), 308–316. https://doi.org/10.1016/j.ajsl.2018.12.004

Farrell, M. J. (1957). The measurement of productive efficiency. *Journal of the Royal Statistical Society: Series A (General), 120*(3), 253–281.

González, M. M., & Trujillo, L. (2008). Reforms and infrastructure efficiency in Spain's container ports. *Transportation Research Part A: Policy and Practice, 42*(1), 243–257. https://doi.org/10.1016/j.tra.2007.08.006

Greene, W. H. (2008). *Econometric analysis* (6th ed.). Pearson Education Inc.

Hlali, A. (2018). Efficiency analysis with different models: the case of container ports. *Journal of Marine Science: Research & Development, 8*(2), 250. https://doi.org/10.4172/2155-9910.1000250

Kodde, D. A., & Palm, F. C. (1986). Wald criteria for jointly testing equality and inequality restrictions. *Econometrica, 54*(5), 1243–1248. https://doi.org/10.2307/1912331

Kumar, S., Medina, J., & Nelson, M. (2009). Is the offshore outsourcing landscape for US manufacturers migrating away from China? *Supply Chain Management*, *14*(5), 342–348. https://doi.org/10.1108/13598540910980251

Kumbhakar, S. C., Wang, H., & Horncastle, A. (2015). *A practitioner's guide to stochastic frontier analysis using stata.* Cambridge University Press.

Kuo, K.-C., Lub, W.-M., & Le, M.-H. (2020). Exploring the performance and competitiveness of Vietnam port industry using DEA. *The Asian Journal of Shipping and Logistics, 36*(3), 136–144. https://doi.org/10.1016/j.ajsl.2020.01.002

Meeusen, W., & van den Broeck, J. (1977). Technical efficiency and dimension of the firm: some results on the use of Frontier production functions. *Empirical Economics, 2*(2), 109–122. https://doi.org/10.1007/BF01767476

Merkel, A. (2018). Competitive intensity and inefficiency in European container ports: An empirical investigation using SFA. *Maritime Business Review, 3*(2), 165–184. https://doi.org/10.1108/MABR-01-2018-0003

Nguyen, H.-O., Nguyen, H.-V., Chang, Y.-T., Chin, A. T. H., & Tongzon, J. (2015). Measuring port efficiency using bootstrapped DEA: the case of Vietnamese ports. *Maritime Policy & Management, 43*(5), 644–659. https://doi.org/10.1080/03088839.2015.1107922

Ro-kyung, P. (2010). A brief efficiency measurement way for the Korean container terminals using stochastic frontier analysis. *Journal of Korea Port Economic Association, 26*(4), 63–87

Tongzon, J. & Heng, W. (2005). Port privatization, efficiency and competitiveness: Some empirical evidence from container ports (terminals). *Transportation Research Part A: Policy and Practice*, *39*(5), 405–424. https://doi.org/10.1016/j.tra.2005.02.001

Thai, V. V., Yeo, G. T., & Pak, J. (2015). Comparative analysis of port competency requirements in Vietnam and Korea. *Maritime Policy & Management, 43*(5), 614–629. https://doi.org/10.1080/03088839.2015.1106017

Author ORCIDs

Author name	**ORCID**
Bui, Thanh Uyen	0009-0006-0591-8381
Cho, Gyu Sung	0000-0002-1289-4908