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Measuring the time-invariant and time-varying technical efficiency of ports in Tunisia: a stochastic frontier analysis

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Abstract

Purpose – In Tunisia, foreign commercial exchanges are predominantly maintained via ocean freight and accomplished through eight major ports. The latter play a critical role in the Tunisian economy, whereby nearly 30.7 million tons of goods were transited in 2018. Maintaining their efficiency therefore remains a very important objective to achieve. In this context, the present study is designed to investigate the technical efficiency of respective Tunisian ports over the 16-year period (2005–2020).
Design/methodology/approach – The stochastic frontier analysis (SFA) method is applied to measure the associated time-invariant and time-varying technical efficiency. Moreover, through technical inefficiency modeling, effects of both rail connectivity and private sector participation in handling activities on technical efficiency have also been accounted for.
Findings – The reached results turn out to reveal well that the Tunisian ports appear to operate below their production frontier, noticeably marked by persistent technical inefficiency. Additionally, the relevant estimates tend to confirm the berth variable associated importance in highlighting production related to Tunisian ports. More particularly, our analysis reveals that the private sector's participation proves to display a significantly negative association with technical efficiency, while the ports' rail connectivity turns out to demonstrate a significantly positive correlation with technical efficiency.
Practical implications – The findings of this study can provide port authorities and policymakers with insights into the technical efficiency of Tunisian ports by identifying best practices, the main factors influencing their efficiency (such as rail connectivity and private sector's participation) and areas for improvement in these ports.
Originality/value – The present study stands as a pioneering attempt to examine the efficiency dimension through the implementation of panel data estimation modeling frameworks, particularly the random-effects and the Battese and Coelli (1995) approaches, applied to measure the technical efficiency of the Tunisian port sector. Similarly, the present study also represents an effective attempt, whereby the effects of exogenous variables, notably the rail connectivity and private sector participation, are thoroughly considered in exploring the technical efficiency of Tunisian ports.

Keywords Time-invariant technical efficiency, Time-varying technical efficiency, Stochastic frontier analysis, Tunisian ports
Paper type Research paper

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1. Introduction

Nowadays, ports operate predominantly in a highly competitive environment. They play key roles in maintaining the global supply chain and international trade. In this respect, ports' associated effectiveness turns out to rely heavily on their efficiency levels, which makes the assessment of their respective efficiencies a significantly interesting procedure.

It is worth noting, in this respect, that remarkable progress has recently been perceived in measuring efficiency of decision-making units (DMUs). In this context, data envelopment analysis (DEA) and stochastic frontier analysis (SFA) have been intensively applied when analyzing the ports' productivity and efficiency. Yet, each of the DEA and SFA approaches turned out to display a number of strengths and weaknesses.

The parametric approach involves estimating inefficiency. However, it requires imposing assumptions regarding the functional form and error-term distribution. One of the most commonly used parametric methods is SFA, initially developed independently by Aigner *et al.* (1977) and Meeusen and van den Broeck (1977).

Contrary to the parametric approach, the non-parametric approach uses mathematic programming to estimate inefficiency. Hence, it does not suppose a given functional form of the production frontier or an error term. One of the most widely recognized techniques is the DEA, independently initiated by Charnes *et al.* (1978) and Farrell (1957).

In Tunisia, maritime transport plays a critical role in consolidating the country's economic activity. In fact, over 98% of the country's foreign trade is maintained by sea shipments (Ben Mabrouk *et al.*, 2022). As the first southern Mediterranean country to have signed a partnership and association agreement with the European Union (EU) for establishing a free trade area, Tunisia has constantly demonstrated a strong willingness to cooperate with the EU through promoting the transport sector as a fundamental pillar for maintaining its integration within its environment.

Owing to Tunisia's strategic geographical position, the volume of its cargo shipment exchanges with the outside world is entirely handled via its six major docks of Bizerte, Rades, Sousse, Sfax, Gabes and Zarzis, exclusively directed and managed by the Office of Merchant Marine and Ports (OMMP). Each of these ports involves an important industrial and commercial activity zone, and for some of them, such as the Zarzis port (including a free zone), it provides an attractive space for foreign investors (Ben Mabrouk *et al.*, 2022).

Accordingly, the Tunisian maritime transport and ports display promising areas of economic development capable of simultaneously sustaining the agricultural, industrial and trade sectors. Evaluating these ports relevant efficiency, therefore, seems like a procedure for promoting their value and contribution in maintaining the country's economic progress.

In this context, the present work is focused on measuring the six Tunisian commercial ports respective performance over the period from 2005 to 2020, conducting an empirical analysis of their associated technical efficiency. To this end, two stochastic production frontier models are considered, whereby the ports' efficiency scores could be effectively estimated and the technical-inefficiency explanatory factors can be accurately identified.

This study is intended to provide the relevant empirical literature with a twofold contribution. First, it provides a pioneering attempt to estimate the technical efficiency (time-invariant and time-varying) of the Tunisian port sector using random-effects (RE) and Battese and Coelli's (1995) approaches. Second, it explains the efficiency scores using some exogenous variables, i.e. the rail connectivity and the private sector participation in the handling activities.

The paper is organized as follows. Section 2 provides a review of the port-efficiency-related literature. Section 3 describes the adopted methodology. Section 4 is devoted to discussing our main results. As for Section 5, it presents the study's major reached conclusions.

2. Literature review

It is worth recalling that technical efficiency deals with measuring the ability of a DMU to produce a maximum output through the implementation of a certain amount of inputs. Technical inefficiency, however, corresponds to insufficient production compared to what is technically possible with a given, or available, level of inputs and is measured by means of deviation from the frontier.

The examination of the recently published literature highlights the existence of a significant number of empirical works dealing with analyzing ports' efficiency. In this context, our focus of interest is laid on two major study groups, namely those dealing with parametric approaches and those focused on non-parametric approaches. Among the relevant parametric analyses pertinent to our study subject, a major widely used approach turns out to be the SFA, which displays several advantages over the DEA method. Indeed, it helps in considering statistical noise, thereby enabling us to test the validity of certain hypotheses. Moreover, it allows for greater flexibility in specifying the appropriately fit production technology (functional form). In addition, it helps in modeling both the environmental and exogenous variable-related effects. In effect, the application of SFA in the port sector is relatively recent. It initially appeared in a study conducted by Liu (1995) to measure the efficiency of 28 UK-based public and private ports, regarding the period ranging from 1983 to 1990. The author was led to conclude that port ownership, as considered input, did not appear to display any significant impact on output (turnover). In addition to port ownership, the study also accounted for other variables such as labor and capital. Similarly, Tongzon and Heng (2005) applied the SFA approach to highlight the link between ownership and efficiency concerning 25 Asia- and Europe-sited ports, using container throughput as an output variable, while quay length, terminal area and number of quay cranes were considered as input variables. They found that the private sectors' involvement could help in improving the efficiency of ports' operations. In turn, Cullinane and Song (2003) documented that the efficiency of the UK and Korean port sectors was the introduction of private participation and deregulation policies. Their findings appeared to be rather robust in respect of those attained by Notteboom *et al.* (2000), who considered comparing the efficiency levels of 40 European and Asian container-specialized ports. However, they highlighted that private participation's positive effects on efficiency were discovered to depend highly on an effective regulation, clearly and transparently defining each agency or institution's respective legislative and institutional responsibilities (Marques and Fonseca, 2010).

As for Cullinane and Song (2006), who analyzed the technical efficiency of a number of European container ports' technical efficiency by means of a stochastic frontier model with cross-section data, they noted the persistence of a positive correlation between port size and efficiency. In this respect, and on applying SFA analysis with panel data to study the relationship between efficiency and container transshipment traffic, Sohn and Jung (2009) documented that the large Asian ports turned out to display greater efficiency and enjoyed a larger share of the container transshipment market than the small market restricted ports.

On undertaking to assess the evolution of the Spanish ports' efficiency, Coto-Millán *et al.* (2015) considered to analyze the technical efficiency of seven sub-sectors operating under the Spanish port system. Their study revealed well that the 2003 port reform helped bring about greater efficiency and promotion with respect to all port sectors. In this regard, González and Trujillo (2008) considered using a translog distance production function with panel data to investigate nine Spanish ports throughout the period ranging from 1990 to 2002 and concluded that the average technical efficiency proved to change only slightly.

On applying the SFA to analyze a set of 37 Africa-sited ports, using interactions between several input variables, Trujillo *et al.* (2013) concluded that landlord ports appeared to demonstrate the highest efficiency levels. Overall, the average port efficiency relevant to the review period turned out to be low, scoring a rate of 30%. Pagano *et al.* (2013) also used the stochastic frontier profit function to measure the associated time-invariant and time-varying efficiency and examined the effect of port privatization by comparing the effectiveness of Panama privatized ports with those of the United States of America ports, which exhibit varying degrees of privatization. The results of the study estimated the savings and effectiveness gains from privatization.

As to Chang and Tovar (2014), they applied the SFA method to evaluate the efficiency and performance of Peruvian and Chilean port terminals. On implementing a distance function on a sample of 14 port terminals from the period 2004 to 2010, their study revealed that the terminals tended to enhance their technical efficiency over the review period, with the Chilean terminals exhibited greater efficiency than the Peruvian ones. Worth citing, also, is the study conducted by Serebrisky *et al.* (2016) that investigated the determinants of technical efficiency of 63 container ports located in the Latin American and Caribbean area, observed over the period from 1999 to 2009. They used the SFA method, defining output as the number of containers handled and inputs as quay lengths, terminal areas and the number of cranes available. The study found that port privatization and the landlord model explain the higher gains of efficiency.

Concerning Coto-Millán *et al.* (2016), they considered analyzing the technical efficiency of 26 Spanish port authorities via the SFA method from the period 1986 to 2012 and concluded that privatization proved to positively affect port efficiency.

In the same vein of thought, López-Bermúdez *et al.* (2019) investigated the efficiency and productivity of 20 Brazilian ports' container terminals regarding the period lapsing between 2008 and 2017, using the SFA method and operational performance indicators. Their findings highlighted that terminals operated by private operators were discovered to be rather efficient. Regarding Pérez *et al.* (2020), they used the stochastic frontier method to measure the efficiency of 27 Spanish ports (2001–2011), wherein stevedores are used to measure labor input, and concluded that larger and more specialized ports proved to be more noticeably efficient. Finally, Andreas Tsakiridis *et al.* (2021) applied the SFA method to examine the efficiency shifts of sample Irish and North Atlantic Spanish ports during the period from 2000 to 2015. They identified two port clusters, wherein the estimated average technical efficiency of the first port's cluster proved to significantly exceed that of the second port's cluster. Table A1 reviews recent applications of the SFA method to port efficiency estimations.

Based on this literature review, one could well note that most studies measuring the port-sector efficiency have been focused on treating the container terminals' variables with respect to ports in European, Latin American and Asian countries. Hence, there is a need to go further with such an analysis to explore this dimension with regard to the Tunisian context, as no published studies have so far been perceived to examine the Tunisian ports' efficiency via the SFA method. The present study is therefore designed to measure the Tunisian ports' technical efficiency through implementation of the SFA methodology with the Cobb–Douglas production function for panel data. To our knowledge, the present study represents a pioneering attempt dedicated to treating the different factors likely to affect the Tunisian ports associated efficiency, including the private sector's presence and participation in the handling activities, along with the ports' rail connectivity dimension.

3. Methodology

3.1 Selected models

The SFA technique is associated with highlighting the parametric estimation of the efficiency frontier through considering the measurement errors and other statistical noise sources (Coelli *et al.*, 2005). In this respect, any deviation from the frontier could be due not only to inefficiency but also to data-associated errors and environmental factors (Bogetoft and Otto, 2011).

Owing to the abovementioned advantage it displays, we opt for applying the SFA method in this study, as it allows to disentangle inefficiency from other errors, i.e. environmental factors.

In the presence of panel data, several stochastic frontier estimation and technical efficiency measuring models can be used, where time-invariant and time-varying technical efficiencies could be distinguished. Regarding the present paper, the RE as well as the Battese and Coelli's (1995) models are applied to estimate the Tunisian ports' technical efficiency and apprehend the effect of the environmental factors on efficiency scores.

The technical efficiency average levels vary significantly in accordance not only with the estimation method but also with the functional form of the frontier used, e.g. translog versus Cobb–Douglas. Regarding our empirical work, the Cobb–Douglas [1] production function seems to be the most appropriate for the Tunisian ports' case, mainly due to data limitation.

3.1.1 Time-invariant technical efficiency models. They are particularly fit for applications in cases where technical efficiency might vary from one port to another, while assumed to be constant over time for each port. Accordingly, a stochastic production frontier with time-invariant technical efficiency turns out to be:

$$\ln y_{it} = \beta_0 + \beta_1 ln\, x_{1it} + \beta_2 ln\, x_{2it} + \beta_3 ln\, x_{3it} + v_{it} - u_i \text{with i} = 1, 2, \ldots, 6;\ \text{t} = 1, 2, \ldots, 16 \quad (1)$$

Where y_{it} denotes the output of port « i » in year « t »; x_{1it}, x_{2it} and x_{3it} refer, respectively, to the total number of berths, the total number of gears and the total number of workers of port « i » in year « t »; β_0, β_1, β_2 et β_3 are unknown parameters to estimate; v_{it} is the symmetric random error variable assumed to be *i.i.d* $N\ (0,\ \sigma^2{}_v)$ and u_i is a non-negative error variable that designates the technical inefficiency of port « i ».

The parameters, along with technical efficiency, can be estimated through a variety of methods, particularly fixed-effects (FE) versus RE models.

3.1.1.1 Fixed-effect modeling. In the FE model, individual technical inefficiency is treated as an unknown fixed parameter to be estimated. Under the assumption that technical inefficiency is time-invariant, and following Schmidt and Sickles (1984), an FE production frontier model is generally formulated as follows:

$$\ln y_{it} = \beta_{0i} + \sum_{m=1}^{M} \beta_m ln\, x_{mit} + v_{it} \quad (2)$$

Where $\beta_{0i} = (\beta_0 - u_i)$; v_{it} is a random error term uncorrelated with the explanatory variables. In this case, no distributional assumptions are required for u_i, which is assumed to be correlated with the explanatory variables or with v_{it}. Consistent estimates of β are obtained by applying either the within estimator or the least square dummy variables. The individual time-invariant technical inefficiency is then obtained via the normalization provided by Schmidt and Sickles (1984), which ensures that $\widehat{u}_i \geq 0\ \forall i$. The technical efficiency estimates are then maintained by

$$TE_i = \exp(-\widehat{u}_i);\ \text{where}\ 0 \leq TE_i \leq 1 \quad (3)$$

3.1.1.2 Random-effects modeling. Unlike the FE model, in the RE model or composed error model, the u_i are assumed to be randomly distributed with constant mean and variance (μ, $\sigma^2{}_u$) but uncorrelated with the regressors (explanatory variables) and with v_{it}. In effect, the main advantage provided by the RE model resides in its ability to include time-invariant regressors (e.g. company activity sector) in the model. It is formulated as follows:

$$\ln y_{it} = [\beta_0 - E(u_i)] + \sum_{m=1}^{M} \beta_m ln\, x_{mit} + v_{it} - [u_i - E(u_i)] \tag{4}$$

Where $\beta_0^* = \beta_0 - E(u_i)$ and $u_i^* = u_i - E(u_i)$.

The model's associated parameters could be estimated through implementation of the generalized least squares (GLS) approach, and the firm-specific inefficiency estimate is attained via the equation:

$$\widehat{u}_i = \max\left(\widehat{u}_i^*\right) - \widehat{u}_i^* \tag{5}$$

At this level, we use the Hausman's (1978) test in order to pinpoint the most appropriate model that fits well our data, i.e. FE or RE model. Hence, under the null hypothesis, we accept the RE model.

3.1.2 Time-varying technical efficiency modeling. The assumption that technical efficiency remains unchanged over time is quite unrealistic, as managers and policymakers are generally expected to gain practical experience and are actually liable to boost efficiency levels over time. In this regard, Cornwell *et al.* (1990), Kumbhakar (1990) and Battese and Coelli (1992) are pioneers in suggesting the implementation of a stochastic production-frontier modeling with time-varying technical efficiency.

Accordingly, the Cobb–Douglas production-frontier function with a time-varying inefficiency model is formulated as follows:

$$\ln y_{it} = \beta_0 + \beta_1 ln\, x_{1it} + \beta_2 ln\, x_{2it} + \beta_3 ln\, x_{3it} + v_{it} - u_{it} \text{ with } \mathrm{i} = 1, 2, \ldots, 6;\ \mathrm{t} = 1, 2, \ldots, 16 \tag{6}$$

In effect, stochastic frontier modeling serves as a benchmark, whereby not only the ports' technical efficiency could be estimated but also the environmental factors' influence extent on port performance (Kumbhakar and Lovell, 2000).

To cope with this situation, Battese and Coelli (1995) devised a special panel data modeling scheme, where the technical inefficiency-related effects could be modeled in terms of a set of explanatory variables, namely:

$$u_{it} = Z_{it}\delta + W_{it} \tag{7}$$

Where Z_{it} designates a vector of variables likely to influence port efficiency, δ is a vector of scalar parameters to be estimated and W_{it} is an unobservable random variable, which is defined by the truncation of a normal distribution with zero mean and variance σ^2.

The parameters associated with the stochastic frontier model (β_0, β_1, β_2 et β_3) and those associated with the inefficiency effects model (δ_1 et δ_2) can be simultaneously estimated via the maximum likelihood method, whose variance parameters are as follows:

$$\sigma^2 = \sigma^2_{\mathrm{v}} + \sigma^2_{\mathrm{u}} \text{ and } \gamma = \sigma^2_{\mathrm{u}} / \left(\sigma^2_{\mathrm{v}} + \sigma^2_{\mathrm{u}}\right)$$

Where the parameter γ is a value comprised between 0 and 1. This parameter is used to determine whether the production frontier is stochastic or deterministic in nature, i.e. it highlights the technical inefficiency emanating from the production variation percentage. If γ proves to be too close to 0, it indicates that deviations from the frontier are mainly due to noise (v_{it}). However, a γ value that is too close to 1 implies that the inefficiency component (u_{it}) brings about a significant contribution to the production system (Battese and Corra, 1977 and Battese and Coelli, 1995).

The technical efficiency level (TE_{it}) is defined by Eq. (8):

$$ET_{it} = \exp(-Z_{it}\delta - W_{it}) = \exp(-u_{it}) \tag{8}$$

Prior to examining the estimation reached results, it seems important to test whether the hypothesis is relevant to the presence or absence of technical inefficiency effect on the Tunisian port industry. The null hypothesis ($\gamma = \delta_0 = \delta_1 = \delta_2 = 0$) denotes that the inefficiencies are not stochastic and that the effects of technical inefficiency are not present within the model. If the null hypothesis is not rejected, the stochastic frontier modeling could be reduced to the ordinary least squares (OLS) specification.

To this end, we consider administering the likelihood ratio (LR) test, put forward by Coelli *et al.* (1998), to determine the effect of technical inefficiency (u_{it}) with respect to the null as well as alternative hypotheses. The LR test statistic takes the following form:

$$LR = -2[\ln\{L(H0)\}/\ln\{L(H1)\}] = -2[\ln\{L(H0)\} - \ln\{L(H1)\}]$$

Where ($H0$) and ($H1$) designate the likelihood function associated values under the null hypothesis H0: $\gamma = \sigma^2_u/(\sigma^2_v + \sigma^2_u) = 0$ and the alternative hypothesis H1: $\gamma > 0$, respectively. The administered test statistic reached a value that should be compared to the critical value of the chi-square distribution (χ^2), devised by Kodde and Palm (1986), with a tolerance threshold of 1%.

3.2 Data

In this work, the data used to measure technical efficiency are balanced panel data relating to six Tunisian ports, which is relevant to the period from 2005 to 2020. The study period was carefully selected in terms of data availability. The study investigated six ports located in different regions of Tunisia (Table 1 and Figure 1). The reasons behind the selection of these six ports lie in the fact that these ports, predominantly managed by the OMMP authority, constitute a set closely involving similar activities, while the La Goulette port is specialized mainly in passenger and cruise traffic, and the port of Skhira, primarily managed by the national oil company, is exclusively specialized in liquid bulk, namely, crude oil (Ben Mabrouk *et al.*, 2022).

It is worth noting that the commercial traffic of the Tunisian ports, including that maintained by the Skhira port, recorded an increase of 7.5%, with a trade volume increasing from 28.5 million tons by the end of 2017 to 30.7 million tons in 2018, demonstrating a significant resumption of their activities compared to the Tunisian revolution marking year (2011). Indeed, exchanges increased from over 30 million tons in 2010 to 30.7 million tons in

Ports	Missions	Regions
Bizerte	It is a multipurpose port, it mainly handles oil traffic	Bizerte
Rades	It mainly handles container and rolling unit traffic, as well as a portion of bulk traffic	Ben Arous
Sousse	It specializes in handling various goods as well as containers	Sousse
Sfax	It is a multipurpose port and its main traffic consists of sold bulk as well as containers	Sfax
Gabes	It is characterized by an industrial vocation, mainly deals with the bulk traffic	Gabès
Zarzis	It mainly handles bulk traffic and general cargo	Médenine

Source(s): Derived from OMMP

Table 1. The study selected Tunisian ports

Figure 1.
Location of the selected Tunisian ports

Source(s): World Port Source

2018 (OMMP, 2018). Each single port's associated traffic activities and types of goods are depicted in Table 2.

Collected physical data concerning the volume of import and export cargo handled have been selected as output, and the numbers of berths, gears and workers have been categorized as input with respect to the six investigated ports. Additionally, two extra explanatory variables have been introduced to explain the exogenous technical inefficiency at the port level. The output-related data have been drawn from the annual reports, which are available on the OMMP [2] special website. As regards inputs, relevant data were collected from the OMMP official website as well as the confidential documents of the port operators, including the handling groups of Zarzis (GMZ), handling groups of Sfax (GMS), handling groups of Gabes (GMGA), SOCIETE MARITIME TUNISIENNE (STUMAR), handling groups of the Center (GMC) and Tunisian Stevedoring and Handling Company (TSHC).

3.2.1 Study variables. Following a number of already conducted studies dealing with the port sector, as appearing in the relevant literature, we have selected a number of relevant variables to stand as output, input and exogenous factors.

Thus, we have opted for cargo throughput as an output factor for the present study. This variable serves to measure the total quantity of handled import and export goods (in 1,000

Table 2.
Traffic per port and types of goods in 2018 (in tons)

Type of goods	Goulette	Rades	Bizerte	Sousse	Sfax	Skhira	Gabes	Zarzis
Solid bulks	971,764	1,727,964	988,169	1,510,388	2,988,703	–	2,624,542	975,401
Liquid bulks	48,518	684,245	3,210,088	54,172	164,558	5,445,002	482,035	187,911
General cargo (non-unitized goods, containers	719,954	3,866,534	1,009,205	1,108,267	1,524,328	–	98,922	41,349
Total	1,740,236	6,278,725	5,207,462	2,672,827	4,677,589	5,445,002	3,205,499	1,204,661

Source(s): The data are collected from OMMP Stat Database (2018) tons). The choice factor as an output variable is justified by its widely common acceptance as a port production indicator. Actually, most of the port efficiency-focused studies have considered it as a production variable, which is closely related to the need for cargo handling facilities and other onshore services. Besides, it provides a basis on which ports can be compared in terms of respective size and activity level, and above all, it represents a major source of revenue generation. In effect, this limited choice of single output variable is mainly due to the SFA method's imposed prerequisite, highlighting the impossibility of simultaneously using several outputs within a production function.

As to the input variables, they include a wide range of resources used to produce the achieved output (e.g. land, labor and capital), as the relevant economic theory maintains well that an effective management of cargo volumes depends primarily on the efficient use of the port's available land, labor and capital (Dowd and Leschine, 1990). In port operations, the number of terminals, the total number or length of quays, the available surface area of land and the total number and/or area of warehouses, towing equipment (tugboat) and handling equipment (loading arms, gantry cranes, quay cranes, stackers, forklifts, etc.) are considered as possible input variables on accounting for port-maintained output. In effect, due to the unavailability of data concerning the entirety of these variables, only three variables have been considered in our study; more specifically, the number of berths was chosen to investigate the land factor, the number of gears to examine the capital factor and the number of workers employed by each port to control for the labor factor. The first variable involves the number of specialized berths as well as standard berths. The second variable concerns the number of gears provided for cargo handling operations in each port. As to the ultimate variable, it englobes the number of managers, supervisors and operatives exclusively associated with stevedoring activity (Ben Mabrouk *et al.*, 2022).

In the technical-inefficiency effect model, two binary variables are retained to explain the technical inefficiency associated variations noticeable among the selected Tunisian ports. The first variable RC_{it} is defined as the "presence of a direct rail link connecting the port inside to the national railway lines," which takes either the value 0 or the value 1. With regard to our study sample, four ports appear to enjoy direct rail connections, namely those of Bizerte, Rades, Sfax and Gabes. The second variable PSP_{it} helps in capturing the effect of the private sector's presence and participation in the port related handling activities. It takes the value one if the private sector's participation is present in the port activities and zero otherwise. In Tunisia, part of the port infrastructure (cargo loading and/or unloading and storage areas) has been transferred to private operation through leasing, under the law of 2008-23 of April 1, 2008 relevant to the ports' concessions regime. Even though the TSHC (public entity) in the port of Rades ensures the totality of the stevedoring and handling activity, there are five groups of private handling contractors operating alongside TSHC in the other ports.

The descriptive statistics, relevant to these different variables, are depicted in Table 3 regarding the six samples constituting ports. The reached findings appear to reveal that the

Variables	Mean	SD	Min	Max
Cargo throughput	3702.104	1810.332	678	6,932
Number of berths	10.5	3.218368	6	15
Number of gears	40.85417	48.52975	3	184
Number of workers	180.9375	229.7537	12	813
Rail connectivity	0.67	0.474	0	1
Private sector participation	0.83	0.374	0	1

Source(s): Authors' computation based on data obtained from OMMP, THSC, STUMAR, GMC, GMS, GMGA and GMZ Stat Databases

Table 3. Variables' descriptive statistics

average port production turns out to be 3,702,104 tons for a set of 10 berths. The average labor size or number of workers relevant to the study sample, is estimated at 180 people, while the average number of machines used in the handling operations is of the rate of 40 machines. Table 4 highlights each of the applied port related variables' attained mean values regarding the time period from 2005 to 2020.

4. Results and discussion

In this section, the within and GLS estimators are used to estimate the FE and RE models' parameters, respectively, while the maximum likelihood method is used to simultaneously estimate both of the production-frontier modeling and technical-inefficiency effects modeling associated parameters. All the estimates have been implemented via STATA.13 software.

4.1 Tunisian ports' associated time-invariant technical efficiency

Prior to interpreting the parameter and technical efficiency-related estimates, we undertake to perform the Hausman test to select the appropriate modeling scheme fit for our applied data. Actually, the statistic attained value is discovered to be 3,24 (p-value = 01,978 > 0,05) regarding the difference between within and GLS estimates, denoting that the null hypothesis of no correlation between the specific effects and the regressors proves to be accepted. Hence, the RE model seems worth adopting and the GLS estimator is retained.

Then, we proceed with administering the Breusch–Pagan test to opt for the most optimally fit choice between the RE regression and the simple OLS regression. Accordingly, the test resultant null hypothesis indicates well that there are zero variances between the entities (ports), i.e. no significant differences appear to persist among the ports; thus, there is an absence of any panel effect. The null hypothesis (p-value = 0.000 < 0.05) is therefore rejected, and the RE model appears to be rather appropriately fit for implementation in this case. This implies well that there are significant differences in distinguishing these ports and that the RE regression with the GLS method is worth implementing.

Table 5 displays the GLS model achieved results, maintaining the assumption that technical efficiency is time-invariant.

The table reveals that the Wald statistic-associated probability is zero, highlighting well that the model's overall fit turns out to be effectively good and that the selected variables appear to provide a significant explanation of port production. As to the parameters respective significance, we consider comparing the p-value with the different thresholds (10% or 5% or 1%). Should the p-value be lower than the three stated thresholds, the coefficient will then prove to be significant. Hence, on examining Table 5, one could well note that the two variables ln x_1 (berths) and ln x_2 (gears) prove to be significant and that the variable ln x_3 (workers) does not seem to provide a significant explanatory power of port productivity.

Table 4.
Annual mean values for inputs and outputs by port (2005–2020)

Ports	Cargo throughput	Berths	Gears	Workers
Bizerte	5,073,375	13	30,5	86,562
Rades	6,040, 875	12	131,75	650,625
Sousse	2,129,187	7	19,312	101.312
Sfax	4,562,937	15	31,812	179,75
Gabes	3,391,937	10	19,437	65,125
Zarzis	1,014,312	6	12.312	22,25

Source(s): Authors' computation based on data obtained from OMMP, THSC, STUMAR, GMC, GMS, GMGA and GMZ Stat Databases

With respect to our modeling procedure, the estimated elasticities of ln x_1 and ln x_2, relevant to the number of berths and gears, turn out to be positive and statistically significant, indicating that the output tended to increase by means of such inputs. The greatest input elasticity corresponds to the berth, reaching 1,754. Noteworthy is that increasing the number of berths by 10% would lead to a noticeable increase in cargo throughput by 17.54%, which seems to be a statistically significant finding. Such a result highlights the importance of multiplying berths in boosting the productivity of Tunisian ports. The number of workers has a relatively lower and statistically insignificant impact on cargo throughput.

Based on Table 5 recorded parameters, we can also measure the time-invariant technical efficiency for each port, varying between 0 and 1, as depicted in the table below.

On average, only the Rades port was discovered to be the most efficiently operating port, displaying the highest average technical efficiency score of 100%. This result indicates that this port handled more container traffic, and it has a better infrastructure and benefits from a significant share of investment in technology by the port authorities. The remaining ports (Bizerte, Sousse, Sfax, Gabes and Zarzis) are inefficient, with average scores less than 1. This may be due to a lower annual throughput, the lack of adaptation of the ports to the characteristics of large vessels (draft, cranes, etc.) and also the non-use of modern equipment that facilitates handling operations (Table 6 and Figure 2).

Such a situation reflects well that Tunisian ports tend to operate at about 74.4% of their production capacity. Noteworthy, however, is that these ports are liable to increase their cargo throughput by almost 25.6% while deploying the same inputs.

4.2 Tunisian ports' time-varying technical efficiency

The already advanced model (RE) assumes that technical inefficiency is specific to each port and that it is invariable over time, suggesting that an inefficient port is never willing or prone

Variables	Coefficients	Std. Err	p-value
Constant	4.030***	0.826	0.000
lnxl	1.754***	0.364	0.000
lnx2	0.127**	0.058	0.031
lnx3	−0.095	0.067	0.153
Observations		96	
R^2	0.7675		
Wald $\chi^2(3)$	29.18		
Prob > χ^2	0.000		

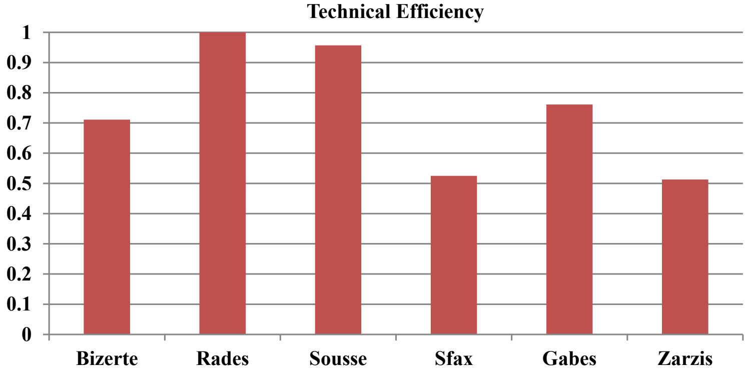
Note(s): *(10%); **(5%); ***(1%)
Source(s): Authors' estimations

Table 5. Estimation of the stochastic frontier production via the GLS method

Ports/ Years	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average
Bizerte	0.711	0.711	0.711	0.711	0.711	0.711	0.711	0.711	0.711	0.711	0.711	0.711	0.711	0.711	0.711	0.711	*0.711*
Rades	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	*1.000*
Sousse	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957	*0.957*
Sfax	0.525	0.525	0.525	0.525	0.525	0.525	0.525	0.525	0.525	0.525	0.525	0.525	0.525	0.525	0.525	0.525	*0.525*
Gabes	0.761	0.761	0.761	0.761	0.761	0.761	0.761	0.761	0.761	0.761	0.761	0.761	0.761	0.761	0.761	0.761	*0.761*
Zarzis	0.513	0.513	0.513	0.513	0.513	0.513	0.513	0.513	0.513	0.513	0.513	0.513	0.513	0.513	0.513	0.513	*0.513*
Grand mean																	*0.744*

Source(s): Authors' estimations

Table 6. Time-invariant technical efficiency scores of Tunisian ports



Source(s): Authors' calculations

Figure 2. Time-invariant technical efficiency of Tunisian ports

to improve or progress over time. This is, for instance, true regarding some situations where inefficiency proves to be closely associated with management capacity, particularly in those port cases where no change in management has been introduced over the study period. To account for the assumption that the Tunisian ports' technical efficiency has changed over time, we consider implementing Battese and Coelli's (1995) advanced model as part of this section. This model also allows us to measure the technical efficiency levels of the investigated Tunisian ports and examine the relationship between port efficiency and some exogenous variables, such as rail connectivity and private sector participation in handling activities.

The computed LR test statistic turns out to be 47.98 within a freedom level of four degrees, which tends to exceed the critical chi-square value of 12.483 at the 1% level of significance (Table 7). Consequently, the null hypothesis stipulating the absence of any technical inefficiency effects within the data is rejected at the significance level of 1%. Hence, the average traditional production function (OLS) does not seem to provide a convenient representation of the Tunisian ports' analysis appropriate to our study case.

On the other hand, the parameter λ (σ_u/σ_v), which is highly significant at the 1%, provides an insight as to the relative variance of the two composite errors constituting the total variation. Apart from the λ parameter, two error components-associated variances indicate that the technical inefficiency component u_{it} tends to vary more widely than the uncontrollable random exogenous component v, denoting that the technical inefficiency u_{it} contributes rather significantly to our model's total error variability. Moreover, the estimated value of γ (0.99) reveals that about 99% of the difference recorded between the production observed and potential production of the ports under review turns out to emanate mainly from technical inefficiency under the control of the port operations, while the remainder of the variation (1%) appears to stem from random factors outside their control.

Regarding the parameter estimates relevant to the Tunisian ports' stochastic frontier modeling, as shown in Table 7, the number of berths and gears and associated coefficients tend to be significant, displaying the positive signs expected, thereby confirming the persistence of a positive relationship between these inputs and port output (cargo throughput). Still, even though the elasticity of port production with respect to workers seems positive, it remains insignificant. Their scored values turn out to be: 0.551, 0.051 and 0.042, respectively, noticeably inferior to the unit, indicating that an increase of 1% in each of these inputs would certainly lead to an increase of less than 1% in the volume of cargo throughput. Then, the returns-to-scale parameter for the Cobb–Douglas production frontier

Dependent variable lny *Independent Variables*	Coefficient	*p*-value
Constant	6.892***	0.000
ln x_1	0.551***	0.003
ln x_2	0.051*	0.094
ln x_3	0.042	0.122
Inefficiency model		
Constant	−0.783	0.430
RC (δ_1)	−1.024***	0.000
PSP (δ_2)	1.742*	0.082
Variance parameters		
σ_u	0.388***	0.000
σ_v	0.034	0.102
σ^2	0.152	
λ (lambda)	11.359***	0.000
γ (gamma)	0.99	
Log-likelihood function	15.1055	
LR test	47.98	
χ^2 (1%)	12.483	
Observations	96	

Note(s): *(10%); **(5%) and ***(1%)
Source(s): Authors' estimations

Table 7. Estimation results of the stochastic frontier and inefficiency parameters via the maximum likelihood method

has been computed by summing the three variables relating elasticities, which ends up highlighting that the Tunisian ports' returns to scale tend to be decreasing, as the sum of input elasticities turns out to be of the rate 0.644.

Regarding the rail connectivity relevant coefficient, it is relatively high, exhibiting a negative and statistically significant sign at the 1% level (−1,024), implicitly suggesting to display a positive effect on the Tunisian ports' technical efficiency, thereby corroborating the findings reached by Turner *et al.* (2004) and Wanke *et al.* (2011) in their published studies. Indeed, the availability of rail access could act as a scaling engine, allowing a better match between port inputs (available infrastructure) and outputs (demands). On the other hand, the coefficient associated with the presence of private sector participation appears to be significant, bearing a positive sign of 1.742 (contrary to the expectations), denoting that this parameter has a negative effect on the Tunisian ports' technical efficiency, i.e. technical efficiency tends to decrease with the private companies' increased participation in handling activities, thereby contradicting the findings released in several relevant research studies (e.g. Tongzon and Heng, 2005; Wanke and Barros, 2015; Coto-Millán *et al.*, 2016; López-Bermúdez *et al.*, 2019). This finding has its explanation in the fact that since the issue of the concession regulation, a superiority of the TSHC has been noticeable over the private stevedoring companies in compliance with the imposed competitive conditions, resulting in these companies' low share participation in the loading and unloading activities (each stevedoring group is not entitled to handle more than about 30% of the total volume of cargo throughput), in addition to the mismanagement of their limited resources and the non-introduction of modern equipment likely to enhance the handling operations, i.e. they did not devote important investments to renovate the used equipment.

The average annual estimates relevant to each port and to the entire port system are depicted in Table 8. The Jondrow *et al.* (1982) estimator has been applied to estimate the technical efficiency scores.

The technical efficiency levels drawn results reveal well that, between 2005 and 2020, the investigated ports appeared to operate at an average technical efficiency of 67.3%, i.e. they could have increased their production by 32.7% with the same amount of available inputs. Accordingly, both Rades and Bizerte ports have been discovered to perform most efficiently, followed by the ports of Gabes and Sfax, with the least efficient of all being the ports of Sousse and Zarzis. This result is similar to the result obtained by Ben Mabrouk *et al.* (2022). Our attained results also highlight that, on the one hand, the ports equipped with direct rail access lines (Bizerte, Rades, Sfax and Gabes) turn out to operate more efficiently than those void of rail access. On the other hand, the five ports (Bizerte, Sousse, Sfax, Gabes and Zarzis), alternately operated by private handling groups along with the public TSHC entity in terms of handling activities, are discovered to function less efficiently compared to the port of Rades, where the entirety of handling operations are exclusively handled by TSHC.

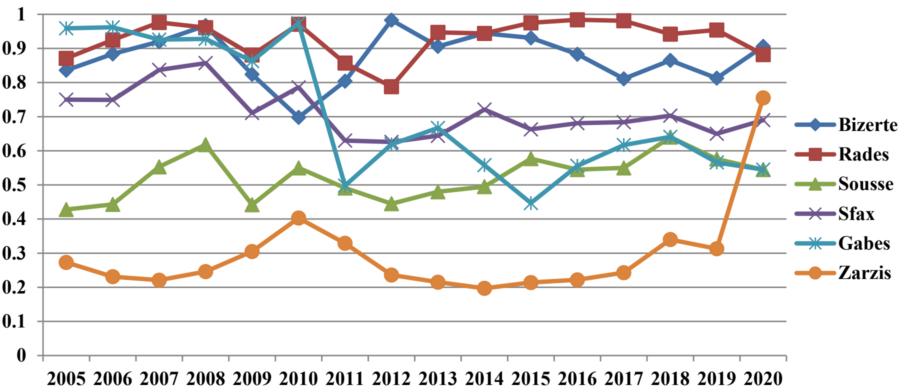
It is also worth noting that the relevant technical efficiency levels appear to be significantly affected by the recurrent financial and economic crises and, above all, the Tunisian Revolution event, as these two economic recession periods are characterized by relatively low technical efficiency levels. A possible explanation of this lies mainly in the decreased levels of international traffic and, therefrom, lower demand for port services (in 2010, for instance, the port of Zarzis handled 1,355,000 tons of cargoes, compared to only 776,000 tons in 2016) (Ben Mabrouk *et al.*, 2022).

As shown in Figure 3, relevant to the Tunisian ports' annual technical efficiency evolution, several fluctuations tend to persist in these ports recorded technical efficiency scores. Firstly, it has been found that throughout the period under review, both Rades and

Table 8.
Time-varying technical efficiency scores of Tunisian ports

Ports/ Years	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average
Bizerte	0.836	0.884	0.920	0.967	0.824	0.698	0.804	0.983	0.906	0.944	0.931	0.883	0.811	0.865	0.813	0.906	*0.873*
Rades	0.871	0.925	0.976	0.961	0.881	0.971	0.857	0.788	0.947	0.944	0.975	0.984	0.981	0.942	0.954	0.882	*0.927*
Sousse	0.428	0.443	0.553	0.618	0.442	0.550	0.491	0.445	0.480	0.495	0.577	0.545	0.550	0.640	0.576	0.545	*0.524*
Sfax	0.750	0.749	0.837	0.857	0.711	0.786	0.630	0.626	0.644	0.721	0.663	0.681	0.684	0.703	0.650	0.690	*0.711*
Gabes	0.959	0.962	0.926	0.928	0.863	0.974	0.498	0.619	0.667	0.558	0.447	0.556	0.617	0.641	0.566	0.545	*0.708*
Zarzis	0.273	0.231	0.221	0.246	0.305	0.403	0.329	0.236	0.215	0.197	0.214	0.222	0.243	0.340	0.313	0.755	*0.296*
Grand mean																	*0.673*

Source(s): Authors' estimations



Source(s): Authors' calculations

Figure 3.
Evolution of the Tunisian ports' technical efficiency (2005–2020)

Bizerte ports have been discovered to stand as the most efficient ports. Secondly, the port of Gabes has been discovered to record a technical efficiency of about 93.5% between 2005 and 2010, which tended to decrease in 2009 – more noticeably in 2011 and throughout the remainder of the review period. Specifically, the decrease in technical efficiency, noticeable in 2009 (with an annual GDP growth rate of 3.04%) and significantly persistent in 2011 (with an annual GDP growth rate of −1.92%), reflects the serious impact of the financial and economic crisis as well as the Tunisian Revolution event, which negatively affected trade relations and demand for port services, despite the recovery in technical efficiency noticeable in the year 2010 (with an annual GDP growth rate of 3.51%) immediately following the crisis span. Such a behavior, or trend, perceived in technical efficiency is mainly influenced by the overall growth rate of the country's economy as a whole, which displays a significant impact on demand for port services.

Following these achieved findings, a number of important implications could be drawn with regard to the determinants of technical efficiency. First, the major private stevedoring companies (STUMAR, GMC, GMS, GMGA and GMZ) should invest in modern handling equipment to speed up the loading/unloading operations. Second, attracting other private operators, notably the global handlers, to operate in Tunisia is a plausible measure likely to enable the Tunisian ports to enhance the cargo handling rates and draw valuable benefit from their know-how in terms of management, modernization or updates of information systems, along with maintaining provision sources of funds necessary for investment and maintenance of the available infrastructure. Finally, with regard to the ports without any rail network access (e.g. Sousse and Zarzis), the government should make greater efforts and reserve special investments to connect these ports to the rail network system, thereby promoting their accessibility to the hinterlands, enhancing their productivity output scale and boosting their efficiency.

5. Conclusion

The present work is designed to measure the technical efficiency of six Tunisian ports via SFA modeling, applied to the ports' balanced panel data over a 12-year time period (2005–2020). In this respect, a study of the effects of rail connectivity and private sector participation in handling activities on technical efficiency was also conducted. The executed analysis resulted in a number of important findings. In a first place, the berth-related variable turned out to display the strongest influence on port cargo throughput, demonstrating highly positive coefficients, thereby highlighting the importance of a sufficient number of berths for an effective mooring of ships. In a second place, the results from the Battese and Coelli (1995) model revealed that the vast majority of the residual variation was predominantly due to the inefficiency term (u) engendered effect and that the random error (v) value proved to be too close to zero, i.e. the estimated parameters are significantly different from zero, suggesting that the technical inefficiency equation is appropriately fit for estimating the production frontier. Moreover, it was found that the existence of rail network access proved to have a significant and positive impact on the Tunisian ports' technical efficiency. Hence, ports equipped with a direct rail link, such as those of Bizerte, Rades, Sfax and Gabes, appeared to demonstrate greater efficiency than those void of a rail network connection (Sousse and Zarzis). Additionally, the presence of the private sector and its participation in maintaining the stevedoring activities was discovered to have a negative effect on technical efficiency. Hence, ports operated alternately by private handling groups and the TSHC public entity in the handling process appeared to exhibit lower efficiency levels compared to the port of Rades where the entirety of handling operations are exclusively handled by the public TSHC. Finally, it has also been shown that technical efficiency levels appeared to be significantly affected by the financial and economic crisis along with the Tunisian Revolution event.

Indeed, it has been discovered that these two periods of striking economic recession were characterized by noticeably low levels of technical efficiency.

Like any research work, the present research is not void of any limitations. In effect, it should have incorporated more recent data, which are beyond our control, mainly due to the lack of data availability constraint. Moreover, the study applied inputs (berth and gear) turned out to be too limited to capture the ports' various physical configurations. Another limitation relates to the implementation of only two technical-efficiency-affecting exogenous variables, given the existence of other variables or determinants likely to affect these ports' efficiency. The last limitation is associated with the non-availability of port relating financial data allowing for an effective measurement of the relevant allocative and economic efficiency.

Ultimately, and as an extended research work, we consider accounting for extra inputs (e.g. land, hangar, warehousing, etc.) and additional outputs (e.g. number of ships), along with environmental factors considerations. With respect to the study idea and thought venue, a possible enrichment extension might well consist in implementing the parametric distance-function approach to effectively separate the multi-output nature of port activities. Another worthwhile research line would be to further explore and measure the allocative and economic efficiency of Tunisian ports, should financial information become available.

Notes

1. The Cobb–Douglas function is particularly suitable for limited databases because of its simplicity, robustness with few parameters and interpretable economic properties. On the other hand, the translog function, with its larger number of parameters, may require a larger data volume to obtain reliable estimates.
2. http://www.ommp.nat.tn

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Appendix

Authors	Data	Methods	Inputs	Outputs	Objectives
Liu (1995)	28 UK ports (1983–1990)	SFA	- Labor expenses - Capital	Annual earnings	To examine the effect of ownership or size on technical efficiency
Notteboom *et al.* (2000)	36 European and 4 Asian container terminals (1994)	SFA	- Terminal quay length - Terminal area - Number of gantry cranes - Average number of workers per crane	Container traffic	To investigate the efficiency of container ports
Cullinane and Song (2003)	5 ports Korean and UK (1978–1996)	SFA	- Labor expenses - Net tangible assets - Buildings and infrastructure	Annual earnings	To Asses the efficiency of Korea's port sector liberalization policy
Tongzon and Heng (2005)	25 International Terminals (1999)	SFA	- Quay length - Terminal area – number of quay cranes	Container throughput	To identify the relationship between ownership structure and port efficiency
Cullinane and Song (2006)	74 European container terminals (2002)	SFA	- Quay length - Terminal area number of pieces of cargo handling equipment	Container throughput	To analyze a number of European container ports' technical efficiencies
Sohn and Jung (2009)	16 major Asian ports (1995–2005)	SFA	- Berth length - Storage capacity of yard sector - Number of ship-shore gantries per berth length - Number of yard gantries	Container throughput	To test the viability of a port's strategy for a mega hub, in the context of international competition
González and Trujillo (2008)	9 Spanish ports (1990–2002)	SFA	- Labor - Berths - Surface	- Containers - Liquid bulk - Other cargo - Passengers	To analyze the effects of legislative reforms on technical efficiency
Trujillo *et al.* (2013)	37 African ports (1998–2007)	SFA	- Berths - Terminal area - Cranes	Container throughput	to measure the evolution of port efficiency during the port reform process and to estimate what factors affect perceived port quality
Pagano *et al.* (2013)	10 leading USA container ports (1997–2006)	SFA	- Average revenue per ton - Net investment in plant, property and equipment	- Profit per ton - Container traffic	To assess port efficiency during government operation and private sector operation
Chang and Tovar (2014)	14 port terminals in Chile and Peru (2004–2010)	SFA	- Berths - Workers - Net stock of fixed assets	- Container traffic - General and rolling freight - Bulk cargo	To evaluate the efficiency and performance of Peruvian and Chilean port terminals
Coto-Millán *et al.* (2015)	7 sub-sectors operating in Spanish ports (2011)	SFA	- Workers - Net tangible assets - Intermediate consumption	Annual earnings	To analyze the regulation, competition, crisis and technical efficiency of companies that operate in Spanish ports
Serebrisky *et al.* (2016)	63 container ports in Latin America and Caribbean (1999–2009)	SFA	- Quay lengths - Terminal area - Cranes	Container traffic	To investigate the determinants of technical efficiency

(*continued*)

Table A1.
Summary of previous studies applying SFA in the port sector

Authors	Data	Methods	Inputs	Outputs	Objectives
Coto-Millán *et al.* (2016)	26 Spanish port authorities (1986–2012)	SFA	- Workers - Net tangible assets - Berth length	- Solid bulk - Liquid bulk - Passengers - General merchandise not containerized - Merchandise containerized	To evaluate the impact of public regulation on the efficiency of the Spanish port system
López-Bermúdez *et al.* (2019)	20 Brazilian ports' container terminals (2008–2017)	SFA	- Frequency of calls - Gantry cranes - Mobile cranes	Container traffic	To measure the efficiency and productivity of the Brazilian ports and study the relationship between efficiency and private operation
Pérez *et al.* (2020)	27 Spanish ports (2001–2011)	SFA	- Stevedoring workers - Berth length - Cranes	- Total bulk cargo - Total tons of general merchandise	To analyze the effect of public regulation on the efficiency of the Spanish port system
Tsakiridis *et al.* (2021)	5 Irish and 10 North Atlantic Spanish ports	SFA	- Land - Labor - Capital	- Revenue - Total traffic	To examine the efficiency shifts of sample Irish and North Atlantic Spanish ports

Table A1.

Source(s): Authors' elaboration

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