REVISTA DE MÉTODOS CUANTITATIVOS PARA LA ECONOMÍA Y LA EMPRESA (29). Páginas 190-207.
Junio de 2020. ISSN: 1886-516X. D.L: SE-2927-06.
www.upo.es/revistas/index.php/RevMetCuant/article/view/2804

Effects of Inefficiency on Marginal Costs, Degree of Economies of Scale and Technical Change: A Theoretical Relationship. The Case of Spanish Port Authorities

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ABSTRACT

In this paper, a theoretical relationship is obtained to measure the effect that inefficiency has on marginal costs, degree of economies of scale and technical change. It is shown that when the relationship between inefficiency and output level is ignored, the estimation of marginal costs and the degree of economies of scale are incorrect. The measurement of technical change is also wrongly calculated if one does not consider the variation of inefficiency over time. This could lead to incorrect pricing decisions that would transfer inefficiency to the consumer via prices and non-optimal investments in productive capacity. In addition, the effect of technical change on costs could be erroneously estimated. The empirical application of this theoretical model to Spanish port authorities during the period 2008-2016 shows that marginal costs of port services were overestimated, the degree of economies of scale was underestimated and the time variations of the inefficiency were interpreted erroneously as technical change when the relationship between inefficiency and output and time is not considered.

Keywords: cost efficiency, marginal cost, degree of economies of scale, technical change, ports.
JEL classification: C13; C51; D24; L11; L25.
MSC2010: 91B38; 62H12.

Artículo recibido el 23 de octubre de 2017 y aceptado el 10 de mayo de 2019.

Efectos de la ineficiencia sobre los costes marginales, el grado de economías de escala y el cambio técnico: una relación teórica. El caso del sector estibador español

RESUMEN

En este trabajo se obtiene una relación teórica para medir el efecto que la ineficiencia tiene sobre los costes marginales, el grado de economías de escala y el cambio técnico. Se muestra que cuando se ignora la relación entre la ineficiencia y el nivel de producción, las estimaciones de los costes marginales y del grado de economías de escala son incorrectas. La medición del cambio técnico también es errónea si no se considera la variación temporal de la ineficiencia. Esto podría llevar a que se tomen decisiones de fijación de los precios que transferirían la ineficiencia al consumidor vía precios y a que las decisiones de inversión en capacidad productiva no fuesen óptimas. Además, el efecto del cambio técnico sobre los costes se podría valorar erróneamente.

La aplicación empírica de este modelo teórico a las autoridades portuarias españolas durante el periodo 2008-2016 muestra que los costes marginales de los servicios portuarios se sobreestimaron, el grado de economías de escala se infraestimó y las variaciones temporales de la ineficiencia se interpretaron erróneamente como cambio técnico cuando la relación entre la ineficiencia y los outputs y el tiempo no fue considerada.

Palabras clave: eficiencia en costes, coste marginal, grado de economías de escala, cambio técnico, puertos.
Clasificación JEL: C13; C51; D24; L11; L25.
MSC2010: 91B38; 62H12.

1. Introduction.

An accurate knowledge of costs is fundamental in economic policy and business management. This knowledge affects, at least, three key questions for firms and policy-makers: pricing policy, investment policy and assessment of technical progress. The estimation of the cost model allow underlying technology to be characterized as shown by duality theory (Shephard ,1953, 1970) and measure sources of change in productivity (Bauer, 1990). Another common aim of the cost model has been the measurement of firm´s efficiency through the estimation of a frontier that describes its optimum productive performance.

This paper is based on the hypothesis that to characterize correctly productive structure and measure suitably the impact of technical change is first required to isolate possible inefficiency cost, having into account that there is a relationship between inefficiency and output levels and time. If this relationship is ignored, the marginal costs, the degree of economies of scale and the rate of technical change will be wrongly estimated, and the decision based on them would be inadequate.

Although the presence of inefficiency always increases the total cost, its impact on marginal costs, degree of economies of scale and technical change rate is not clear. The problems of ignoring these relationships are serious. First, the over cost caused by inefficiency could be transferred to the users via prices, which would cause the loss of social welfare. Second, if the degree of economies of scale is distorted, the incorrect measurement of the minimum efficient scale could lead to investment decisions unjustified. For instance, if the biased estimates of the degree of economies scale shows diseconomies of scale but in fact is the opposite, then the firm would erroneously decide increase the productive capacity. Third, failure to consider the inefficiency that can vary over time could lead to confusing variations in inefficiency with technical change, what has important consequences in the evaluation of the sources of the productivity change.

For the main purpose of illustrating the application of this theoretical relation and showing the importance of the errors that could be committed, this paper shows an empirical study in Spanish Port Authorities sector for the period 2008-2016.

As Kumbhakar and Lovell (2000) point out, the analysis of productive efficiency has two fundamental tasks. The first is to identify a frontier that represents the optimizing behavior of the producer from the point of view of the transformation of inputs and outputs, minimization of costs and maximization of profit to measure its efficiency by comparing its observed behavior with this benchmarking. The second task is to study how a set of exogenous variables, which characterize either the producer or the environment where it operates, influence its efficiency.

From the seminal works of Aigner, Lovell and Schmidt (1977) and Meeusen and van den Broeck (1977), both the theoretical development and the empirical application of the stochastic frontier models have been extended to the achievement of the aforementioned objectives. This approach introduces "compound error term" which has two components: i) the one-sided error that captures the effect of inefficiency and ii) the two-sided "noise" component that reflects the effect of random shocks on producer. Kumbhakar and Lovell (2000) shows an exhaustive review of the theoretical developments and the econometric techniques to be used in the framework of stochastic frontier models, adapted to the use of cross-sectional data as well as data of panel.

In addition, incorporating exogenous influences on efficiency as an error component within a stochastic frontier framework, Kumbhakar and Lovell (2000) discuss how the literature evolves from the two-step approach by inefficiency and exogenous effect are identified sequentially to the more recent one-step approach where the exogenous effects are estimated simultaneously with the model´s other parameters. In both cases, the researcher chooses the exogenous variables to explain the inefficiency but the covariates of the cost model are often ignored. Thus, most of the literature assumes that its measurement is independent of output levels. This, therefore, implicitly means that an increase in output level only affects the value of marginal costs measured using the frontier, assuming that the measurement of inefficiency is unchanged respect to output variations. However, if this hypothesis of independence of inefficiency cost with respect to production were not true, this would mean that the estimation of the cost frontier would be inconsistent.

Other strategy has been proposed to model the inefficiency parametrically through the introduction additional parameters to be estimated rather than through error component of stochastic frontier. This alternative way called shadow price approach was initiated by Lau and Yotopoulos (1971) and Toda (1976). Following this shadow price approach, Atkinson and Halvorsen (1984) and Atkinson and Cornwell (1994) show that the effect of inefficiency on the cost depends on the input prices and output levels. Subsequently, Kumbhakar (1997) and Díaz-Hernández et al. (2008) adapted this proposal to the translog and quadratic functional forms, respectively. Moreover, they isolate the impact of inefficiency on cost depending of the covariates of the cost model. This parametric approach demonstrates that there is an exact theoretical relationship between the cost of inefficiency and output level, input prices and time. This is the starting point of this paper that leads us to study how changes in the explanatory variables of the cost frontier affect marginal costs, the degree of economies of scale and the rate of technical change.

This is a crucial point and it explains that if we ignore this relationship, the analysis of the underlying productive structure, decisions on economic policies and business management made from them would all be inadequate.

In section 2, for the marginal cost, the degree of economies of scale, and the rate of technical change, we obtain the theoretical relationships between the observed values (that is, they would be calculated from a model that does not consider that the inefficiency cost is related to output levels and time) and the optimal values estimated from a cost model that consider this relation. In section 3, we show the empirical application to the 27 Spanish Port Authorities over the period 2008-2016 for the sole purpose of illustrating the magnitude of the distortions caused and the serious consequences in the framework of cost-based pricing, investment decisions in new productive capacity and evaluation of technical change effects. Finally, the most relevant conclusions are drawn.

2. The model.

Below, the theoretical relationships between marginal costs, degree of economies of scale, technical change, and cost efficiency index are deduced.

2.1. Effect of inefficiency on marginal cost.

Cost efficiency index proposed by Farrell (1957), *CE,* is obtained by dividing the optimal cost, $C^*(Q,W,t)$, by the observed cost of the producer, $C^a(Q,W,t)$, given that outputs vector is Q and input prices vector is W and *t* is time trend, that is to say:

$$CE(Q,W,t) = \frac{C^*(Q,W,t)}{C^a(Q,W,t)}, \text{ where } CE) \leq 1, \tag{1}$$

Obviously, if $CE = 1$, the producer is efficient.

Isolating $C^a(Q,W,t)$ and deriving with respect to output *i*, the observed marginal cost of output Q_i, i.e., the observed increase in the total cost caused by the production of an additional unit, CMg_i^a, can be calculated as:

$$CMg_i^a = CMg_i^* \frac{1}{CE} - \frac{\partial CE}{\partial Q_i} \frac{C^*}{CE^2} \tag{2}$$

where CMg_i^* is the minimum (optimal) increase in costs required to produce an additional unit.

Equation (2) can be easily changed into:

$$CMg_i^a = CMg_i^* + CMg_i^* \left(\frac{1}{CE} - 1 \right) - \varepsilon_{CE,Q_i} \frac{CMg_i^*}{CE} \frac{C^*(Q,W)}{Q_i} \frac{1}{CMg_i^*} \tag{3}$$

with $\varepsilon_{CE,Qi}$ being the elasticity of the efficiency index with respect to output *i.*

Finally, we obtain:

$$\frac{CMg_i^a - CMg_i^*}{CMg_i^*} = \frac{1-CE}{CE} - \frac{\varepsilon_{CE,Q_i} / \varepsilon_{C^*,Q_i}}{CE} \tag{4}$$

The above expression shows that the difference between observed and optimal marginal cost has two components:

1. First, there is what we have called, the Pure Effect *(PE*), as it only depends on the cost efficiency index. If *CE(Q,W)*<1 then total costs are higher than the optimal ones and inefficiency is transferred to marginal cost as a percentage increase equal to $100\left(\frac{1-CE}{CE} \right)$. That is, producing an additional unit inefficiently causes observed marginal costs to exceed the optimal ones. Note that this effect is independent of whatever the product is whose quantity is being changed.
2. The second component, what we have called, the Elasticity Effect *(EE*), is related to the Elasticity of Efficiency Index with respect to output *i*, ($\varepsilon_{CE,Qi}$) which measures the effect that a percentage change in this output has on the cost efficiency index. Thus, if $\varepsilon_{CE,Qi}<0$, the increase in output *i* increases the inefficiency, and therefore the difference between observed and optimal marginal costs is greater, and vice versa if $\varepsilon_{CE,Qi}>0$. In the latter case, observed marginal costs could be lower than the optimal ones.

2.2. Effect of inefficiency on the degree of economies of scale.

First, the relation between observed and optimal cost-output elasticities from expression (2) must be calculated and transformed into the following elasticities:

$$\varepsilon_{C^a,Q_i} = \frac{1}{CE} \frac{Q_i}{C^a} (CMg_i^* - \frac{\partial CE}{\partial Q_i} \frac{C^*}{CE}) \tag{5}$$

From which the equation below is obtained, taking into account (1):

$$\varepsilon_{C^a,Q_i} = \varepsilon_{C^*,Q_i} - \varepsilon_{CE,Q_i} \tag{6}$$

From the previous result, working through $\varepsilon_{C^*,Qi}$, and adding all cost-product elasticities for *m* outputs, and dividing both sides of the previous equation by the term $\sum_{i=1}^{m} \varepsilon_{C^a,Q_i}$, we obtain the following expression:

$$\frac{\sum_{i=1}^{m} \varepsilon_{C^*,Q_i}}{\sum_{i=1}^{m} \varepsilon_{C^a,Q_i}} = 1 + \frac{\sum_{i=1}^{m} \varepsilon_{CE,Q_i}}{\sum_{i=1}^{m} \varepsilon_{C^a,Q_i}} \tag{7}$$

Bearing in mind that the degree of economies of scale, *S,* is the inverse of the sum of cost-output elasticities, we obtain the relationship between observed, S^a, and optimal, S^*, degrees of economies of scale:

$$\frac{S^a - S^*}{S^*} = \frac{S^* \sum_{i=1}^{m} \varepsilon_{CE,Q_i}}{1 - S^* \sum_{i=1}^{m} \varepsilon_{CE,Q_i}} \tag{8}$$

Expression (8) shows that if $\sum_{i=1}^{m} \varepsilon_{CE,Q_i} \neq 0$, then $S^a \neq S^*$. The difference between them will depend directly on the magnitude of S^*, and of the value and sign of $\sum_{i=1}^{m} \varepsilon_{CE,Q_i}$. Thus, S^a will be higher than S^* if the combined effect of the changes in output levels on the efficiency index is positive, $\sum_{i=1}^{m} \varepsilon_{CE,Q_i} > 0$. To the contrary, S^a will be lower than S^* if the combined effect of the changes in output levels on the efficiency index is negative, $\sum_{i=1}^{m} \varepsilon_{CE,Q_i} < 0$. These cases lead to the wrong interpretation of the changes in economies of scale. To sum up, a firm can actually be operating under diseconomies of scale and the observed degree would show economies of scale and vice versa; both cases can lead to erroneous investment decisions based on an incorrect assessment of the effect of output levels on the inefficiency.

2.3. Effect of inefficiency on the rate of technical change.

Starting from (1) and considering that $\overset{\circ}{TC^a} = -\frac{\partial C^a}{\partial t}\frac{1}{C^a}$ is the technical change rate estimated from a cost model that does consider the inefficiency is time varying:

$$\overset{\circ}{TC^a} = -\frac{\partial C^a}{\partial t}\frac{1}{C^a} = -\frac{\partial (C^* / CE)}{\partial t}\frac{CE}{C^*} = -\left[\frac{\partial C^*\!/\!\partial t\; CE - \partial CE\!/\!\partial t\; C^*}{CE^2}\right]\frac{CE}{C^*} = \overset{\circ}{TC^*} + \overset{\circ}{CE} \tag{9}$$

where $\overset{\circ}{TC^*}$ is the real technical change rate when inefficiency is time varying and $\overset{\circ}{CE}$ measures the cost inefficiency change. Finally,

$$\overset{\circ}{TC^a} - \overset{\circ}{TC^*} = \overset{\circ}{CE} \tag{10}$$

From (10), it can be deduced that if we ignore that the cost inefficiency is time varying, the observed technical change rate transforms efficiency variations into in technical change. In this case, the sources of the productivity changes are erroneously identified and the evaluation of the productive performance of the firm is not suitable.

3. Empirical application of the theoretical model to Spanish Port Authorities.

3.1. Data and sample.

A port can be understood as an economic agent that combines a set of inputs, such as infrastructure, labor, mechanical equipment, and intermediate inputs, in order to transfer goods between maritime and land transport. In ports, many actors perform a large number of functions and many of the functions link together in chains. The basic operations of a port are to create and manage port infrastructure for the berthing of vessels and for freight handling operations to transfer goods between land and sea and vice versa, as well as to move goods within the port itself. Many additional operations relate to the vessels themselves, their goods and crews (e.g., storage, ship repairs, provisioning, etc.). In addition, other auxiliary operations are provided to the large number of agents that operate within ports. For a more thorough overview of port agents and services and their interrelationships (see UNCTAD, 1975).

The Spanish Port System (*Sistema Portuario Español* in Spanish) is made up of the Spanish State Ports Authority (*Ente Público Puertos del Estado*), which bears responsibility for overall coordination and leadership, and the various port authorities, which are responsible within the sphere of each port. In total, Spain has 27 port authorities: A Coruña, Alicante, Almería-Motril, Avilés, Bahía de Algeciras, Bahía de Cádiz, Baleares, Barcelona, Bilbao, Cartagena, Castellón, Ceuta, Ferrol, Gijón, Huelva, Las Palmas, Málaga, Marín y Ría de Pontevedra, Melilla, Pasajes, Santa Cruz de Tenerife, Santander, Sevilla, Tarragona, Valencia, Vigo and Villagarcía. The functions of each port authority are to conduct planning for the port as a whole, coordinate and regulate its various activities, and establish competitive market conditions that prevent monopoly situations. By so doing, the port authorities become the core element of the port system and they are the focus of this application.

A database has been constructed using the 27 Spanish port authorities over the period 2008-2016 included. The information has been obtained from the management reports issued by the state-run port system (*Informes de Gestión del Sistema Portuario de Titularidad Estatal*), the annual reports prepared by the port authorities, and the statistical yearbooks on the state's ports (*Anuarios Estadísticos de Puertos del Estado*) published by the Spanish Ministry of Development.

As shown in Jara-Díaz et al. (2006), the costs of transferring goods depend on the type of cargo, which can be categorized as containerized general cargo (CGS); non-containerized general cargo (NCGC), which includes a very heterogeneous group of goods (e.g., pallets, timber, paper reels, etc.); liquid bulk (LB) such as petroleum products, and solid bulk (SB). It is important to take into account that services for the four types of goods were not provided in all 27 ports every year. As a result, it has proved necessary to specify a defined functional form in the case of null values for certain outputs, and this has been done through the quadratic form employed in the application.

The application distinguishes three productive inputs in the provision of port services by port authorities: labor, capital and intermediate inputs. The price of the labor factor, W_L, has been obtained by dividing staff-related spending, including social security contributions, by the total number of full-time employees. Capital spending has been obtained by adding together the depreciation of tangible fixed assets, as an accounting cost, and the annual yield on a thirty-year bond, in order to obtain the economic cost. The price of capital, W_K, is the quotient obtained by dividing the preceding sum by the variable of linear meters of docks, which serves as a proxy for the stock of port infrastructure, according to the way in which the application calculates the economic cost of capital. Lastly, the price of intermediate inputs has been obtained by dividing any remaining costs that are neither staff-related spending nor depreciation by a proxy variable for intermediate inputs. In this application, the proxy variable is taken to be turnover. The intermediate inputs cover the rest of the resources needed to deliver services, including energy consumption, cleaning services, and other external services that are necessary for the normal performance of the activity. All costs have been indexed to the consumer price index to express costs in 2016 euros. Table 1 shows the main descriptive statistics of the sample.

Table 1. Descriptive Statistics.

Variable	Units	Mean	Std. Dev	Minimun	Maximun
Total cost (CT)	Euros	35223917	28194962	5586114	131880916
Labor Expenditure (LE)	Euros	9324585	6195365	2951335	36728655
Capital Expenditure (KE)	Euros	13715402	11887829	1466023	55720000
Intermediate Inputs Expenditure (IIE)	Euros	12183929	11002420	1106091	60626097
Containerized General Cargo (CGC)	Tons	5637406	13119535	0	60178589
No Containerized General Cargo (NCGC)	Tons	2164879	2691390	122587	10834853
Liquid Bulks (LB)	Tons	5761756	7809132	0	27344044
Solid Bulks (SB)	Tons	3231631	3429676	3425	18905283
Labor (L)	Number of workers	187	96	65	504
Capital (K)	Docks linear meters	8340	5976	105	26432
Intermediate Inputs (II)	Euros	38602452	36079318	4423308	180123536

Source: Own elaboration.

3.2. Specification of the stochastic cost frontier.

This section sets out the specification used to characterize the technology structure of Spanish ports based on an estimation of marginal costs, the degree of economies of scale, and the rate of technical change. In addition, cost inefficiencies will be measured using the index devised by Farrell (1957).

By following the stochastic frontier approach proposed by Aigner, Lovell, and Schmidt (1977) and Meeusen and van den Broeck (1977), the error term of the cost frontier has two components. The first component, v_{it}, is a random variable that is symmetrical and assumed to be identical, independent, and normally distributed with a null mean and a variance of σ^2_v. It represents both the statistical noise and all exogenous shocks to the producer that affect costs. By following the approach put forward by Battese and Coelli (1995), the second component of the error term, u_{it}, represents the effect of inefficiency on costs. It is defined as a non-negative random variable with a truncated normal distribution whose mean is equal to $z_{it}\,\delta$ and whose variance is equal to σ^2_u, where z_{it} is the set of explanatory variables for inefficiency and δ is the vector of the coefficients of these variables.

The normalization of the cost function is a procedure that introduces linear homogeneity in prices and ensures the flexibility of the selected functional form. Normalizing the cost function consists of dividing the cost level and the input prices by a price or by a linearly homogenous price function. In this application, the econometric model is a stochastic cost frontier with a normalized quadratic specification, which is a functional form that belongs to the so-called "flexible" functions and is particularly suitable in a multi-output approach, where some observations give null values for some of the explanatory variables. Hence, the estimation model is as follows:

$$c_{it} = C(W_{it}, Q_{it}, t) + v_{it} + u_{it} = \alpha_0 + \sum_{j-1} \alpha_j W_{jit} + \sum_m \alpha_m q_{mit} + \frac{1}{2} \sum_{j-1} \sum_{k-1} \alpha_{jk} W_{jit} W_{kit} + \frac{1}{2} \sum_m \sum_n \alpha_{mn} q_{mit} q_{nit} + \sum_{j-1} \sum_m \alpha_{jm} W_{jit} q_{mit} + \alpha_t t + \alpha_{tt} t^2 + \sum_{j-1} \alpha_{tj} W_{jit} t + \sum_m \alpha_{tm} q_{mit} t + v_{it} + u_{it} \qquad (11)$$

where W is the vector of normalized prices for j-1 inputs [$W=(W_1,...,Wj_{-1})$], with Wj being the price of the input used to normalize the input prices and the total observed cost (c_{it}). In addition, Q is a vector of the m-outputs that are produced [$Q=(q_1,....qm)$] and of the time trend that is used as a proxy variable for technical change. In the case of the explanatory variables for inefficiency, the application specifies the levels of outputs transferred in ports and the time trend. This makes it possible to study both how changes in production levels can affect cost inefficiencies and how cost inefficiencies vary over time.

3.3. Empirical results.

In this empirical application, the intermediate input price has been selected for use as the normalization term, so the cost level and the normalized input prices are obtained by dividing the cost and prices of labor and capital by the intermediate input price.

By following the procedure formulated by Battese and Coelli (1995) for panel data, the method of maximum likelihood is employed to carry out a simultaneous estimation of the parameters of the stochastic frontier and the model for the cost inefficiency effects. The likelihood function is expressed in terms of the variance parameters, $\sigma^2 = (\sigma^2_u + \sigma^2_v)$ and $\gamma = \sigma^2_u / \sigma^2$. Table 2 sets out the results from the estimation of the stochastic cost frontier and the explanatory variables for inefficiency, showing only the variables that are significant at the 95% confidence level.

The parameters of the cost frontier coefficients have the expected signs. The estimated coefficients of the explanatory variables for cost inefficiency clearly indicate that inefficiency rises with increased traffic in CGC, NCGC and SB, and falls with increased LB traffic. In addition, cost inefficiency is observed to diminish over time.

The estimate for the variance parameter, γ, is close to one, which indicates that the inefficiency effects are likely to be highly significant in the analysis of the costs of Spanish port authorities.

The null hypothesis which specifies that the inefficiency effects are absent from the model, [$\gamma = \delta\text{constant} = \delta_{CGC} = \delta_{NCGC} = \delta_{LB} = \delta_{SB} = \delta_T = \theta$], is strongly rejected. The second null hypothesis, which specifies that the inefficiency effects are not stochastic, [$\gamma = \theta$], is also strongly rejected.

Table 2. Estimates of stochastic normalized quadratic cost frontier.

Parameter	**Estimate**	**t- ratio**
α_0	1,33 D+8	15,01
α_{WL}	123,66	2,84
α_{WK}	2902,80	7,57
α_{CGC}	5,95	4,49
α_{NCGC}	22,99	7,38
α_{LB}	0,82	2,11
α_{SB}	2,72	3,54
α_T	-2,44 D+6	2,01
α_{TCGC}	0,09	2,16
α_{TNCGC}	-0,48	-2,17
α_{TWK}	633,57	3,95
α_{WKWK}	-0,035	-3,85
α_{WLWK}	0,01	4,39
α_{WLCGC}	0,96 D-5	3,23
α_{WLNCGC}	2891,80	2,32
α_{WLSB}	-0,99 D-5	-2,20
α_{WKCGC}	0,28 D-4	2,59
α_{WKNCGC}	0,05 D-3	3,89
α_{WKLB}	-0,82 D-4	-2,90
α_{WKSB}	0,69 D-4	2,65
α_{CGCCGC}	-0,15 D-6	-4,49
$\alpha_{CCGNCGC}$	0,27 D-6	2,61
α_{CGCSB}	-0,59 D-6	-2,53
α_{NCGCSB}	0,38 D-5	2,89
α_{SBSB}	0,27	2,24
Parameters in one side error (inefficiency error term)		
Parameter	**Estimate**	**t- ratio**
δconstant	-3,02 D+6	-3,76
δ_{CGC}	0,50	2,20
δ_{NCGC}	1,56	3,24
δ_{LB}	-0,39	-2,70
δ_{SB}	4,79	4,14
δ_T	-5,44 D+5	-3,20
$\sigma^2 = (\sigma^2_u + \sigma^2_v)$	1,91 D+7	6,90
$\gamma = \sigma^2_u / \sigma^2$	0,93	1,98

Source: Own elaboration.

Finally, the null hypothesis which specifies that the inefficiency effects are not a linear function of the output levels and time, [$\delta_{\mathrm{CGC}}=\delta_{\mathrm{NCGC}}=\delta_{\mathrm{LB}}=\delta_{\mathrm{SB}}=\delta_{\mathrm{T}} = 0$], is also rejected at the 5% level of significance. This indicates that the joint effects of outputs and time on cost inefficiencies are significant. In addition, the individual effects of all variables are statistically significant.

Next, the theoretical model developed in section 2 has been applied with the primary aim of showing the magnitude of errors caused by not considering the relationship between inefficiency and production levels and time. The objective is to calculate the errors that the presence of inefficiency can cause in marginal costs, the degree of economies of scale and the rate of technical change.

First, $\overset{\circ}{CE}$, ε_{CE,Q_i} and ε_{C^*,Q_i} have been calculated so that (4) can then be applied. The distortions produced by inefficiency on the degree of economies of scale and on the rate of technical change have been obtained using the exact relationships obtained in (8) and (10). Accordingly, the following values have been obtained for every port on the frontier: 1) marginal cost for the four outputs; 2) the degree of economies of scale, and 3) the rate of technical change. Moreover, the cost efficiency index has been calculated using CE_{it}, = $\exp(U_{it}) = \exp(z_{it}\,\delta + W_{it})$. The results appear in Table 3.

Broadly speaking, the largest ports in the Spanish Port System (Bahía de Algeciras, Barcelona, Bilbao, and Valencia) show the highest levels of efficiency. Their marginal costs have the expected relative values. Conventional general cargo is observed to have a higher cost than containerized cargo, confirming the advantages associated with the use of containers. Also, traffic in liquid bulk is found to be the least costly of the four types, which appears to be related to automation of the processes involved. These results are consistent with other applications carried out on the Spanish Port System (SPE), i.e. Jara-Díaz et al. (2002).

The average port in the SPE has a size that falls below minimum efficient scale. This is indicated by the fact that the degree of economies of scale is greater than 1 ($S^* = 1.20$). Indeed, with the exception of Bilbao, all ports in the SPE are observed to operate below minimum efficient scale. In addition, the average port in the SPE is found to have enjoyed an average annual rate of technical change equal to 1,14% over the period 2008-2016, although there is greater variability in the results at the port level. For instance, the ports of the Balearic Islands, Ceuta, Pasajes, and Santa Cruz de Tenerife show a technical retrogression, while other ports like Avilés, A Coruña, Bilbao, and Huelva show an average annual rate of technical change in excess of 2%.

Table 4 below shows the marginal costs of CGC, NCGC, LB, and SB at the port level as calculated on the frontier. In addition, Table 4 shows the pure effect and elasticity effect on the marginal costs of CGC, NCGC, SB, and LB, as well as the distortions caused by inefficiency. Column (a) shows that the first term of (4), the so-called PE, gives an average increase in marginal costs of 14,4% for the four outputs, which, as we have seen, is because the effect only depends on the cost efficiency index and is, therefore, independent of the kind of service provided. The PE is observed to be positive for all ports, which is consistent with the analysis done in section 3.1, whereas the elasticity effect can be either positive or negative. The total effect is positive for the ports and outputs as a whole.

If marginal costs are calculated using a model which ignores that the cost of inefficiency depends on output levels, they will be higher than those estimated using a cost model that takes this relationship into account. As can be seen in columns (f), (g), (h), and (i) in Table 4, the average increase in marginal costs is 16,9%, 15,7%, 13,8%, and 14,2% for CGC, NCGC, LB, and SB, respectively. These results show that if a researcher does not take into account that changes in production levels affect the cost efficiency index, marginal costs will be overestimated, and therefore cost-based pricing will shift inefficiency to the users of port services.

Table 3. The cost efficiency index, marginal costs, degree of economies of scale and rate of technical change.

Port	***Cost Efficiency Index (CE)***	***CMg^*_{CGC}* (€/Ton)**	***CMg^*_{NCGC}* *(€/Ton)***	***CMg^*_{LB}* (€/Ton)**	***CMg^*_{SB}* (€/Ton)**	***Degree of economies of scale (S*)***	***Rate of Technical Change (%)* ($\overset{\circ}{TC}^{*}$)**
A Coruña	0,833	6,25	8,39	1,41	1,82	1,201	2,32
Alicante	0,828	2,94	4,59	1,47	2,09	1,243	1,03
Almería-Motril	0,918	7,49	8,34	1,59	3,76	1,127	1,45
Avilés	0,896	6,28	7,60	1,28	3,54	1,089	2,11
Bahía de Algeciras	0,960	4,52	6,41	1,27	1,64	1,277	1,62
Bahía de Cádiz	0,915	2,88	4,44	1,48	1,68	1,292	0,90
Baleares	0,940	2,93	4,93	1,42	2,95	1,106	-1,20
Barcelona	0,946	2,38	4,58	1,13	2,20	1,295	1,11
Bilbao	0,960	3,43	5,82	1,39	4,64	0,828	2,03
Cartagena	0,877	3,61	5,05	1,32	4,14	1,284	1,53
Castellón	0,933	4,42	5,93	1,47	3,82	1,042	1,41
Ceuta	0,877	3,94	5,64	1,51	2,90	1,321	-1,52
Ferrol	0,926	4,35	6,25	1,24	3,95	1,354	1,88
Gijón	0,918	3,69	5,54	1,38	2,13	1,060	1,15
Huelva	0,898	4,35	6,33	1,10	2,50	1,097	2,09
Las Palmas	0,928	7,24	8,64	1,50	3,06	1,229	0,66
Málaga	0,910	2,91	4,47	1,58	2,39	1,292	1,69
Marín-Pontevedra	0,888	2,96	4,63	-	2,32	1,301	1,64
Melilla	0,911	3,80	5,33	1,42	2,52	1,340	1,89
Pasajes	0,899	3,06	5,25	-	3,13	1,059	-1,09
Sta. Cruz de Tenerife	0,938	6,53	7,32	1,57	5,86	1,085	-1,14
Santander	0,845	8,54	9,62	1,55	4,36	1,045	1,41
Sevilla	0,874	3,86	5,02	1,50	2,28	1,339	1,59
Tarragona	0,920	3,27	5,40	1,44	3,78	1,203	0,94
Valencia	0,935	4,67	5,49	1,24	3,94	1,349	1,74
Vigo	0,928	2,03	3,57	1,59	2,26	1,352	1,83
Villagarcía	0,881	2,06	3,75	1,69	2,68	1,174	1,78
Minimun	**0,828**	**2,03**	**3,57**	**1,10**	**1,64**	**0,83**	**-1,52**
Maximum	**0,960**	**8,54**	**9,62**	**1,69**	**5,86**	**1,35**	**2,32**
Mean	**0,907**	**4,24**	**5,86**	**1,32**	**3,05**	**1,20**	**1,14**
St. Dev.	**0,035**	**1,73**	**1,56**	**0,40**	**1,03**	**0,13**	**1,09**

Source: Own elaboration.

Table 4. Distortions produced by inefficiency on marginal costs.

Port	*PE* (%) *(a)*	*EE-CGC* *(b)*	*EE-NCGC* *(c)*	*EE-LB* *(d)*	*EE-SB* *(e)*	*Effect on* CMg^*_{CGC} (%) *(f)=(a)-(b)*	*Effect on* CMg^*_{NCGC} (%) *(g)=(a)-(c)*	*Effect on* CMg^*_{LB} (%) *(h)=(a)-(d)*	*Effect on* CMg^*_{SB} (%) *(i)= (a)-(e)*
A Coruña	22,60	-9,63	-4,31	3,40	2,19	32,22	26,91	19,20	20,41
Alicante	16,77	-10,26	13,21	3,91	-0,88	27,02	3,55	12,86	17,65
Almería-Motril	26,12	4,04	4,04	3,60	2,99	22,08	22,08	22,52	23,13
Avilés	10,01	-3,85	5,81	7,23	5,95	13,86	4,20	2,78	4,06
B. de Algeciras	4,04	-29,88	-1,68	-1,15	-5,60	33,92	5,73	5,19	9,64
B. de Cádiz	17,10	2,41	2,96	-0,34	7,51	14,70	14,14	17,44	9,59
Baleares	5,85	-17,34	-1,61	0,43	3,05	23,18	7,46	5,42	2,80
Barcelona	6,30	-4,05	4,93	-12,74	3,64	10,35	1,37	19,04	2,66
Bilbao	5,06	-7,41	-39,14	2,60	2,80	12,46	44,19	2,46	2,26
Cartagena	14,91	0,49	12,29	2,74	1,66	14,42	2,61	12,17	13,25
Castellón	3,45	-0,43	-0,41	-3,05	-0,59	3,88	3,86	6,49	4,04
Ceuta	30,64	4,10	-22,68	-3,38	-1,38	26,55	53,33	34,02	32,03
Ferrol	9,89	-3,01	-3,81	-1,58	-2,25	12,90	13,69	11,47	12,13
Gijón	14,46	-21,02	-2,13	2,79	-11,10	35,47	16,58	11,67	25,55
Huelva	19,71	0,00	11,74	0,61	13,32	19,71	7,97	19,10	6,39
Las Palmas	7,99	-3,45	1,08	2,39	-1,59	11,45	6,91	5,60	9,58
Málaga	28,12	-1,02	-28,31	-2,43	-1,91	29,14	56,44	30,56	30,03
Marín-Pontevedra	23,22	1,24	0,90	0,00	2,84	21,98	22,32	23,22	20,38
Melilla	7,09	0,85	1,53	4,45	-0,96	6,23	5,56	2,63	8,04
Pasajes	19,85	0,00	-10,36	5,17	1,14	19,85	30,21	14,69	18,71
Sta. Cruz de Tenerife	9,62	6,99	-13,99	2,49	2,70	2,63	23,61	7,13	6,93
Santander	29,58	18,73	1,67	-2,94	-1,96	10,85	27,91	32,52	31,54
Sevilla	12,68	5,09	24,26	4,06	-12,20	7,60	-11,58	8,62	24,88
Tarragona	13,00	1,10	7,60	4,43	-8,83	11,90	5,39	8,56	21,83
Valencia	4,22	-1,14	-1,22	1,92	0,44	5,35	5,44	2,30	3,77
Vigo	21,26	-3,38	0,66	-4,26	0,44	24,65	20,61	25,53	20,82
Villagarcía	4,10	-0,01	-0,18	-4,02	3,13	4,11	4,28	8,12	0,97
Minimun	**3,45**	**-29,88**	**-39,14**	**-12,74**	**-12,20**	**2,63**	**-11,58**	**2,30**	**0,97**
Maximum	**30,64**	**18,73**	**24,26**	**7,23**	**13,32**	**35,47**	**56,44**	**34,02**	**32,03**
Mean	**14,36**	**-2,62**	**-1,38**	**0,60**	**0,17**	**16,98**	**15,73**	**13,75**	**14,19**
St. Dev.	**8,57**	**9,27**	**12,93**	**4,11**	**5,34**	**9,70**	**16,22**	**9,52**	**9,84**

Source: Own elaboration.

Table 5 shows the distortion produced by inefficiency on the degree of economies of scale. On average, the distortion is 9,01%. In other words, the degree of economies of scale without taking inefficiency into account yields a value of 1,09; that is, an average port that is slightly undersized, whereas the frontier model shows a port that is clearly below its efficient scale, with a degree of economies of scale at 1,20.

Table 5. Distortion produced by inefficiency on the degree of economies of scale.

Port	*S**	*Effect on S* (%)*	S^a
A Coruña	1,201	-7,01	1,117
Alicante	1,243	-2,97	1,206
Almería-Motril	1,127	-16,53	0,941
Avilés	1,089	-12,18	0,956
B. de Algeciras	1,277	-7,04	1,187
B. de Cádiz	1,292	-19,35	1,042
Baleares	1,106	-3,55	1,067
Barcelona	1,295	-8,56	1,184
Bilbao	0,828	-8,12	0,761
Cartagena	1,284	-11,92	1,131
Castellón	1,042	-5,38	0,986
Ceuta	1,321	-8,76	1,205
Ferrol	1,354	-6,89	1,261
Gijón	1,060	-8,82	0,966
Huelva	1,097	-11,56	0,970
Las Palmas	1,229	-3,19	1,190
Málaga	1,292	-8,35	1,184
Marín-Pontevedra	1,301	-8,96	1,184
Melilla	1,340	-17,60	1,104
Pasajes	1,059	-9,26	0,961
S/ C de Tenerife	1,085	-14,13	0,932
Santander	1,045	-5,61	0,986
Sevilla	1,339	-9,78	1,208
Tarragona	1,203	-16,97	0,999
Valencia	1,349	-3,40	1,303
Vigo	1,352	-4,46	1,292
Villagarcía	1,174	-2,88	1,140
Minimun	**0,83**	**-19,35**	**0,76**
Maximum	**1,35**	**-2,88**	**1,30**
Mean	**1,20**	**-9,01**	**1,09**
St. Dev.	**0,13**	**4,73**	**0,13**

Source: Own elaboration.

The analysis at the port level, however, presents a number of severe distortions. For instance, for the ports of Almería, Avilés, Gijón, Huelva, Pasajes, Santa Cruz de Tenerife, and Santander, which are below efficient scale when measured by the frontier model, the failure to take inefficiency into account makes them appear oversized. In the case of Tarragona, the port is clearly undersized, yet it appears to be operating at efficient scale. These distortions can lead to investment decisions that seek to expand the scale of production when, in reality, this is misguided.

Finally, Table 6 below shows the effect of inefficiency on the rate of technical change.

Table 6. Distortion produced by inefficiency on the rate of technical change.

Port	$\overset{o}{(TC^{*})}$	***Efficiency Change* (%)** ($\overset{o}{CE}$)	$\overset{o}{(TC^{a})}$
A Coruña	2,32	-2,38	-0,07
Alicante	1,03	-1,59	-0,56
Almería-Motril	1,45	2,27	3,71
Avilés	2,11	0,78	2,89
B. de Algeciras	1,62	-2,68	-1,07
B. de Cádiz	0,90	-1,96	-1,07
Baleares	-1,20	-2,69	-3,89
Barcelona	1,11	-0,28	0,82
Bilbao	2,03	0,86	2,89
Cartagena	1,53	1,39	2,92
Castellón	1,41	-1,86	-0,45
Ceuta	-1,52	-1,14	-2,66
Ferrol	1,88	-1,98	-0,10
Gijón	1,15	1,92	3,06
Huelva	2,09	1,06	3,15
Las Palmas	0,66	2,77	3,42
Málaga	1,69	-2,16	-0,46
Marín	1,64	-1,50	0,14
Melilla	1,89	-1,71	0,18
Pasajes	-1,09	-2,52	-3,61
Sta. Cruz de Tenerife	-1,14	-1,02	-2,16
Santander	1,41	-2,79	-1,38
Sevilla	1,59	2,23	3,82
Tarragona	0,94	-1,44	-0,50
Valencia	1,74	1,78	3,52
Vigo	1,83	-0,79	1,04
Vilagarcía	1,78	-1,73	0,06
Minimun	**-1,52**	**-2,79**	**-3,89**
Maximum	**2,32**	**2,77**	**3,82**
Mean	**1,14**	**-0,63**	**0,51**
St. Dev.	**1,09**	**1,80**	**2,30**

Source: Own elaboration.

It can be observed that when efficiency improves over time, i.e. when $\overset{o}{CE}$ has a positive sign, the model that ignores the relationship between inefficiency and time overestimates the rate of technical change by confusing the improvement in efficiency with technical change. In our empirical application, this occurs for the ports of Almería-Motril, Bilbao, Cartagena, Gijón, Huelva, Las Palmas, Seville, and Valencia. In these cases, the reduction in costs observed over time is attributed entirely to technical change. To the extent that this component of productivity is overestimated, it could persuade port management to increase changes in productive technology, when the real reason is the reduction in inefficiency.

By contrast, when efficiency worsens over time, i.e. when $\overset{o}{CE}$ has a negative sign, the model that ignores the relationship between inefficiency and time underestimates the rate of technical change. By ignoring the variation of efficiency over time, a rise in costs resulting from increased inefficiency will partly offset the effects of technical progress, leading to a mistaken perception that the rate of technical change is actually lower than it is in reality.

For the average port, given the decline in efficiency over the analyzed period, the model that ignores the variation in inefficiency over time will underestimate the actual value of technical change by 0,63 percentage points. That is, it will appear to be 55,3% lower than the real rate of technical change. This could lead to attention being focused on the improvement of productive technology instead of the elimination of inefficiency.

4. Conclusions.

While inefficiency means that production costs are higher than strictly necessary, this study has shown that the effect of inefficiency on marginal costs, on the degree of economies of scale, and on the rate of technical change is ambiguous, that is, not predictable. Assuming that the cost efficiency index depends on output levels and time, we obtain theoretical relationships that show how marginal costs, the degree of economies of scale, and the rate of technical change can become distorted when these relationships are ignored. The obtained theoretical relationships have a general character, i.e. they do not depend on the selected functional form.

With the main purpose of illustrating the application of these theoretical relationships and showing the importance of the potential errors, this paper sets out an empirical study of Spanish port authorities. If a researcher does not take into account that changes in output levels affect the cost efficiency index, then marginal costs will be overestimated and any pricing based on marginal costs will transfer inefficiency to the users of port services through prices. This situation could be generalized to all sectors with market power. Similarly, in the presence of inefficiency that depends on output levels, investment decisions aimed at modifying the productive scale could be misguided. Finally, the model that ignores how inefficiency varies over time will overestimate or underestimate the rate of technical change by confusing changes in efficiency with changes in technical change. This could lead to attention being focused on the improvement of productive technology instead of the elimination of inefficiency. In a preliminary version of this paper presented at the XVIII Pan-American Congress of Traffic, Transport and Logistics Engineering (PANAM 2014), we shown another empirical application for the Spanish stevedoring sector during the period 1990-1998. After contrasting the existence of a relation between inefficiency and levels of production and time, the magnitudes and the sense of the distortions in the marginal costs, the degree of economies of scale and the rate of technical change in Spanish stevedoring sector were calculated. These other results show the consistency of the theoretical model presented in this paper. This other empirical application to Spanish stevedoring sector using outdated data is available and will be sent to the interested reader if required.

In summary, it is necessary to estimate a cost model that recognizes that inefficiency depends on output levels and time in order to avoid errors in estimating marginal costs, the degree of economies of scale, and the rate of technical change. If this is not done, the result may be incorrect decisions on pricing and on investment in productive capacity. In addition, the valuation of the effect of technical change could be wrong.

Acknowledgements

The authors are grateful for the constructive comments of the reviewers and the editor, as well as the help of Professor Lourdes Trujillo (University of Las Palmas de Gran Canaria) and the public entity *Puertos del Estado* in the compilation of the data used in this paper.

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