Abstract:

Maritime transport is a sector particularly affected by climatic conditions. Once a ship is in the port, ship manoeuvres and port operations can be hindered by the weather conditions related to wind, wave height, rain, fog, etc. Additionally, shipping can also be hindered by weather conditions which leading to demand variability. Therefore, the worse the weather, the greater also the necessity for some overcapacity, which will be used only during demand peaks, remaining unused during low-demand periods. Due to both their direct effect on productivity and their indirect effect through demand variability, weather variables can be important conditioning variables for port productivity. However, to the authors' knowledge, there has been no analysis published which deals with this effect. In this study, we analyse the effect of two weather variables, wind speed and wave height, on port productivity. In particular, a stochastic output distance function approach was used to assess the impact of wind and waves on the technical efficiency of Spanish ports. As in our sample wind and waves are positively correlated with the tidal amplitude, we also included this variable as a control variable. The impact of both weather variables and tidal amplitude were evaluated by means of some simulation analysis. The results confirm the significant influence of weather conditions on port technical efficiency. Moreover, during the sample period (1992-2016) it was found that weather conditions were responsible for a variation of 5.3% in the average technical efficiency of the whole sample.

Keywords: distance function; maritime transport; port; stochastic frontier; technical efficiency; weather conditions.

1. Introduction

Ports are a critical infrastructure for international trade. With more than 80% of the global volume of freight transported by sea (and more than 70% in terms of value) [1], the relevance of ports becomes clear. Their performance is of interest to all the stakeholders involved in the global supply chain because they act as a gateway and, consequently, their services are offered both to shipping lines and shippers. Their activity is also of interest to policy-makers as it influences transport costs and, hence, the competitiveness of the regions where their facilities are located. Therefore, the interest in improving port performance in a growing global trade situation is clear [2,3]. In particular, [4] shows the importance of improving port efficiency in order to reduce transportation costs.

From the port user's perspective, port efficiency is evaluated according to service characteristics provided within their facilities. For this, they tend to use partial performance indicators [5]. Specifically, rate and productivity of cranes, berths, yards, time required to enter and exit a port, dwell and turnaround times or tons/TEUs per hour are usually applied because they are simple in terms of both understanding and calculation [1,6,7]. Conversely, in the productivity literature, "the term (economic) *efficiency* refers to the comparison between the real –or observed– values of output(s) and input(s) with the optimal values of input(s) and output(s) used in a production process" [8] (p. 393). In terms of [9] (p. 50), it is understood as "the capacity of obtaining maximum amount of output from certain inputs (output orientation) or, alternatively, as the capacity of obtaining a given output level using the minimum amount of inputs (input orientation)".

Both meanings of efficiency should be positively related for a given demand of port services as the greater the efficiency (in terms of productivity literature), the greater the amount of services provided by the port in a given time. However, [10] observed a lack of correlation between average vessel turnaround and port efficiency estimations. This lack of correlation can be related with the variability of the demand for port services and the optimizing behaviour of the shipping companies. The demand for port services is characterized by its variability, which becomes enhanced as ship arrivals are commonly delayed[1]. Port facilities must be able to deal with the consequent demand peaks and possible disruptions of services to avoid traffic loss [11]. That is, port authorities have incentives to invest in their facilities to be ensured against high demand peaks and to

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[1] See [64].

prevent congestion, creating some *reserve capacity* [12]. This is particularly relevant nowadays because the increasing concentration within the shipping industry has contributed to intensify the inter-port competition and, consequently, port operators try to intensify the attractiveness of their facilities to maintain their market shares. In this context, the shorter the vessel turnaround, the more efficient a port will be considered by practitioners, but this quick service could result in a port overcapacity that will only be used during demand peaks (remaining unused during periods of low demand) and reducing the ports' efficiency from the productivity analysis perspective[2]. In fact, [13] observed that differences in demand variability cause differences in costs among ports, and concluded that the greater the demand variability of port services, the greater their cost-inefficiency.

Demand variability may arise from delays in arrivals due, for instance, to breakdowns or delays at previous ports, but also to adverse weather conditions. In this respect, port location is key. The weather conditions of the coastal facades can differ significantly and the hypothesis of this paper is that such differences influence port efficiency. This is of particular interest to policy-makers and regulators when port tariffs depend on the cost structure, even more so when these conditions are not static but evolve over time.

To verify the stated hypothesis, we focus on the wind and wave characteristics of a set of ports of a single port system (with the same regulations), but located in different coastal facades. The research presented here contributes to the literature by analysing the effect of such natural constraints on port efficiency, approached from the productivity analysis perspective. Two specific factors deserve attention as they condition port activity in several aspects. On the one hand, ship operations can be hampered by wind and waves [1]. Their empirical relevance on vessels manoeuvrability can be seen, for instance, in [14,15]. On the other hand, winds (and waves to a lesser extent) can also generate difficulties in terminal operations [1]. Particularly, high wind speed creates strong handling difficulties in crane operations due to the movement induced in load, the dispersion of solid bulk cargo as well as potential damage to port infrastructures. Therefore, these factors are also relevant from the standpoint of port users. Additionally, according to [16], bad weather at sea is a key factor in line-up schedule unreliability, increasing the demand variability and the need for a larger *reserve capacity* in order to be

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[2] As [65,66] highlighted, the higher the competition, the greater the pressure to over-invest in facilities and, thus, the probability of reducing port efficiency.

competitive. Hence, wind and waves have direct (difficulties in ship and terminal operations as well as their impact on infrastructures) and indirect effects (through their effect on demand uncertainty) on port efficiency.

To the authors' knowledge, there is no study using the standard productivity analysis to assess the effect of weather conditions on port productivity. The purpose is to fill this gap by using an output distance function approach to evaluate the impact of wind and waves on the technical efficiency through a case study. The remainder of the paper is organised as follows: Section 2 provides the methodological proposal and introduces the case study, detailing the data sources and the evolution of waves and wind during the sample period. Section 3 presents the results of the analysis carried out and Section 4 is devoted to their discussion. Finally, Section 5 summarises the main conclusions drawn.

2. Materials and Methods

2.1 The model

In the productivity analysis literature, a firm is considered economically efficient when it takes full advantage of the technology to achieve some economic target (profit maximization or cost minimization). Therefore, economic efficiency could be split into technical, allocative and scale efficiency. Technical efficiency requires taking full advantage of the technology by extracting the maximum output from the input endowment (output-oriented efficiency) or by minimizing the input endowment used to produce some output (input-oriented efficiency). Allocative efficiency requires the use of the input mix that minimizes the cost of producing the output for a technically efficient firm. Finally, a firm is scale efficient if it minimizes the average cost of production. It is worth noting that the estimation of allocative and scale efficiency requires more data than the estimation of technical efficiency as data about input prices are necessary. It may be due to the lack of this kind of data, but most port efficiency analysis focuses on technical efficiency.

Technical efficiency can be analysed following parametric and non-parametric techniques. A deep study on the differences between both approaches applied to the port topic can be found in [17]. [18,19] provide a more recent literature review on this field. As can be seen there, the objectives of the studies carried out are vast, addressing a wide range of issues. In particular, during recent years, the main topics of interest remain the same: the consequences of regulatory and economic changes [20], the role of efficiency in port choice [10], methodological novelties [21,22] or particular case studies [7,20,23–

25]. However, even though it is known that poor natural conditions can greatly affect port competitiveness [26], to the authors’ knowledge, there is no study evaluating the effect of meteorological conditions on port efficiency.

Bad weather conditions may contribute to create a gap between the maximum potential services production and the actual production. This gap may appear due to both its direct effect on the services offered and its indirect effect through its influence on demand uncertainty, partially caused by bad weather conditions delaying ship arrivals. To assess this gap, the output□oriented distance function was applied [27,28], which is a tool frequently applied in the analysis of port efficiency [29–31]. In the stochastic frontier literature, the technical inefficiency degree associated to this gap is commonly associated with a suboptimal management. Nevertheless, in this study, it was considered that it includes both: the “wasted resources” due to a suboptimal management (i.e., “pure” technical inefficiency) and the direct and indirect effects of wind and waves.

The output distance function could be defined as:

$$D_O(x,y) = min\left\{\theta: \frac{y}{\theta}\ can\ be\ produced\ with\ x\right\} \qquad (1)$$

where y represents the output vector and x is the input vector. Therefore, $D_O(x,y)$ represents the technology frontier as it represents the maximum potential production attained with each input endowment. That is, each input endowment generates a transformation curve in the space of outputs and these transformation curves define the frontier of the technology. The distance magnitude, θ, refers to the expansion of outputs allowed by the technology within the production possibilities set while the input endowment is held constant [27,28]. [32] analyses the properties that the output oriented distance function must hold. In particular, $D_O(x,y)$ should be decreasing in x and non-decreasing and degree of one and homogeneous in y. In this sense, it is possible to rewrite (1) as:

$$\theta = y_1 \cdot D_O(x,y^*) \qquad (2)$$

where y^* is the output vector divided by y_1, which makes the distance function linearly homogenous in outputs. After rearranging and taking logarithms, it takes the following form:

$$-\ln y_1 = D_O(\ln x\,, \ln y^*) - ln\,\theta \tag{3}$$

To define a functional form for the distance function, an approximation to an arbitrary function is necessary since the true technology is unknown. Flexible functional forms [33] are typically used. The translog form, *D(·)*, one of the most commonly employed in the empirical literature, was applied here. Then, the distance function to be estimated becomes:

$$\begin{aligned} -\ln y_{1i} \; &= \alpha_0 + \sum_{j=1}^{4} \alpha_j \ln x_{jit} + \frac{1}{2}\sum_{j=1}^{4}\sum_{k=1}^{4} \alpha_{jk} \ln x_{jit} \ln x_{kit} + \sum_{l=2}^{5} \beta_l \ln y^*_{lit} \\ &+ \frac{1}{2}\sum_{l=2}^{5}\sum_{m=2}^{5} \beta_{lm} \ln y^*_{lit} \ln y^*_{mit} + \frac{1}{2}\sum_{j=1}^{4}\sum_{l=2}^{5} \gamma_{jl} \ln x_{jit} \ln y^*_{lit} + \alpha_{Tide} Tide_i \\ &+ \alpha_t t_{it} + \frac{1}{2}\alpha_{tt} t^2_{it} - v_{it} + u_{it} \end{aligned} \tag{4}$$

where subscript *i* refers to port and *t* to year; y^*_{lit} is the output y_{lit} divided by y_{1it}; t_{it} is a time trend. Then, the equation (4) allows for non-linear neutral technical change by permitting the frontier expansion along the sample periods. Additionally, $Tide_i$ was included as an environmental variable to deal with the influence of tidal amplitude on ports' production. Ports in the sample are placed in different seas, some of them with large tidal amplitude (Atlantic and Cantabrian ports) and others with very small tidal amplitude (Mediterranean ports). Then, as large tidal amplitude may generate the necessity of waiting until the tide allows access to the port for the larger ships, this could imply an important handicap in ports' production. α*'s*, β*'s* and γ*'s* are the parameters to be estimated. Symmetry restrictions are imposed before the estimation ($\alpha_{jk} = \alpha_{kj}$; $\beta_{lm} = \beta_{ml}$ and $\gamma_{jl} = \gamma_{lj}$). The distance from the observation to the production frontier possibilities is represented by $-u \equiv ln\,\theta$. In this study the normal/half-normal model [28,34,35] was used. On the one hand, that v is assumed to be a normally distributed error with mean zero. On the other hand, $u \geq 0$ is assumed to be a positive error term following a half-normal distribution, where $u \sim iid\; N^+(0, \sigma^2_u)$. Therefore, the error term u measures the proportion in which each output must increase to reach the frontier of the technology (associated to the maximum potential output represented by the frontier) in order to be technically efficient.

As the tidal amplitude may reduce the time span in which large ships may access and leave the port, this may reduce output variability. Therefore, tidal amplitude is also included as a conditioning variable of the variance of the *v* error component.

$$\ln \sigma_{v\,i}^2 = \mu_0 + \mu_{Tide}\, Tide_i \tag{5}$$

The variance of *u* was specified as $\sigma_u^2 = g(z;\delta)$. The explanatory variables are represented by *z* and a set of parameters to be estimated by δ [36]. Therefore, the greater the variance of the error term *u* the larger the expected distance to the frontier. The natural logarithm of this variance was modelled as a linear function:

$$\ln \sigma_{u\,it}^2 = \delta_0 + \delta_{GDP}\, \Delta GDP_{it} + \delta_{Wave}\, Wave_{it} + \delta_{Wind}\, Wind_{it} \tag{6}$$

ΔGDP_{it} being the percentage change in the gross domestic product of the province (NUTS 3), where the port is located. It is included to control for the effect of drops in demand caused by the two important crises that took place during the period covered by the sample data: the first at the beginning of 90's and the second starting in 2007/08. The weather conditions are included through the variables *Wave,* measuring the yearly average significant height of waves, and *Wind*, measuring the yearly average wind speed[3]. Then, it is supposed that apart from pure technical efficiency associated to suboptimal management, there are two other reasons that can lead the port away from its technical efficient frontier.

2.2 Data

The case study addressed in this paper is focused on the Spanish port sector for the period 1992-2016, during which competition between ports increased noticeably [37]. In Spain there are 28 port authorities, and in this paper only those ports with a volume of traffic above 500 thousand tons were considered. The sample comprises 15 port authorities, which managed 85% of total throughput of the Spanish port system in 2016.

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[3] More details about the construction of these variables will be found in Section 2.2.

The port authorities are Algeciras, Alicante, Barcelona, Bilbao, Cadiz, Cartagena, Castellon, Gijon, Las Palmas, Malaga, Santa Cruz de Tenerife, Seville, Tarragona, Valencia and Vigo.

Historical series of waves and winds are not public data and were provided by the Ente Público Puertos del Estado based on two sources: observation buoys and SIMAR points[4]. As an example, Figure 1 shows the buoys and SIMAR points in the Straits of Gibraltar, where red points indicate the position of buoys and the green indicate SIMAR points. Most of the ports have one or several observation buoys close to the mouth of the port and, then, data on waves and wind correspond to the buoy closest to it. In case there are no buoys near the mouth, as is the case with the ports of Cartagena and Castellon, wave and wind data proceed from the closest SIMAR points. The same occurs in short periods when a buoy did not collect data due to malfunction, damage, substitution, etc., in which case the closest SIMAR point was also used. The port of Seville also deserves special mention as it is not located on the coast but is inland. It is necessary to navigate around 90 km from the mouth of the river Guadalquivir to reach this port. Accordingly, data of this port correspond to the observation buoy closest to the Guadalquivir mouth.

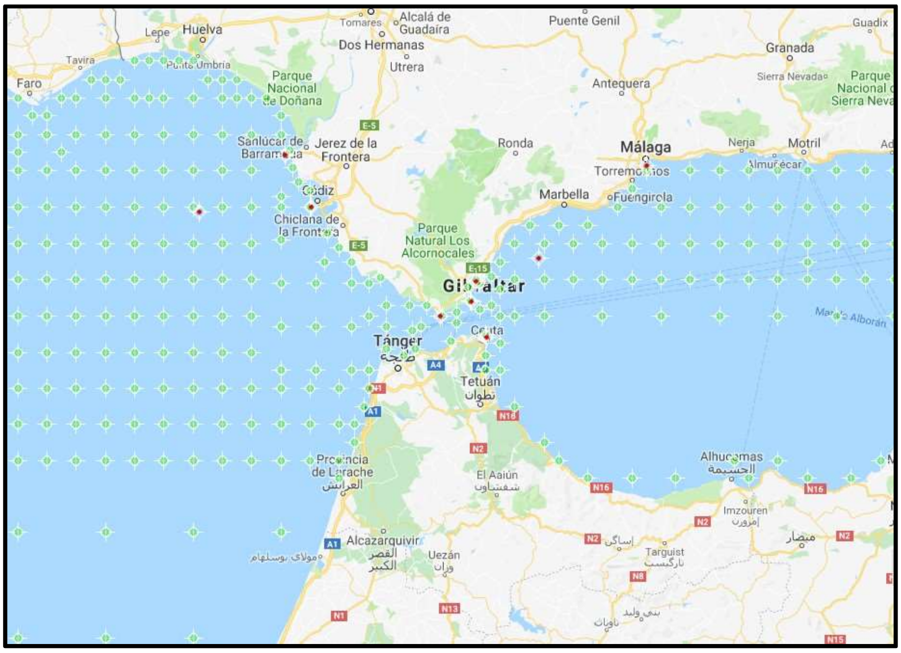

Figure 1. SIMAR points and buoys in the Straits of Gibraltar
Source: Ente Público Puertos del Estado.

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[4] SIMAR points conform a network of points where the sea conditions are simulated by computer.

The data from observation buoys and SIMAR points are provided on an hourly basis. In relation to wind, the information provided is the hourly average wind speed. With regard to waves, the concept of *significant wave height* is considered, which means that once the wave heights in an hour are recorded, only the highest one-third of these waves is used to determine the average value. From this information, the yearly average wind speed and wave height were calculated. Wave height is measured in meters and wind speed in meters per second. An additional and relevant characteristic of the wind and waves could be their direction regarding the direction of the port entrance. However, this information is not available for the whole set of ports considered in the sample.

Input and output data proceed from Statistical Yearbooks and Annual Reports, both of the Ente Público Puertos del Estado. The input variables considered were deposit surface (x_1), infrastructure and buildings (x_2), labour (x_3) and other expenses (x_4). Deposit surface represents the available storage in thousands of square meters at the port. The remaining inputs are measured in thousands of constant Euros of 2013. Infrastructure and buildings are measured by the value of the amortisation of tangible assets of the port authority. In turn, labour represents the cost of port authorities' employees. Other expenses are other operating costs that are not included in the other accounts. Additionally, the tidal amplitude (measured in meters) is also provided by the Ente Público Puertos del Estado and corresponds to the average tidal amplitude observed over a long period, but the initial and final years used to calculate this amplitude vary across ports. Finally, the GDP of provinces (NUTS 3) comes from [40]. The output is measured in physical units, and includes both the loading and unloading of cargo and the embarkation and disembarkation of passengers. Merchandise is measured in thousands of tonnes and classified in four types: liquid bulk cargo (y_1), solid bulk cargo (y_2), general cargo by container (y_3), general cargo non-containerized (y_4). Finally, the embarked and disembarked passengers (y_5) are measured in thousands of passengers.

Before proceeding with the estimation, in 19 observations where some output was zero, generally passengers, that value was substituted by 1. The dataset includes 375 observations, and the descriptive statistics of the variables are shown in Table 1. It shows the diversity of the different ports considered in the analysis. It is worth noting that differences between outputs are larger than those between inputs, as the standard deviations in outputs are always larger than the average value, while between the inputs the opposite occurs.

Variable	Mean	Std. Dev.	Min	Max
Liquid bulk cargo *(1000 Tons)*	7264	7511	34	27300
Solid bulk cargo *(1000 Tons)*	3645	3893	235	19700
General cargo by container *(1000 Tons)*	5962	10800	5	60200
General cargo non-containerized *(1000 Tons)*	2751	5790	77	55500
Passengers *(1000 passengers)*	950	1538	0	5618
Deposit surface *(1000 m^2)*	1289	1291	105	7957
Infrastructure and buildings *(1000 €)*	15561	10636	2697	56536
Labour *(1000 €)*	11392	6676	2762	37400
Other expenses *(1000 €)*	11800	9969	942	61733
Tide *(m)*	1.09	0.90	0.05	2.75
ΔGDP *(% variation)*	1.95	3.13	-6.58	9.30
Wave Height *(m)*	0.88	0.42	0.37	2.09
Wind Speed *(m/s)*	4.40	1.02	2.38	6.45

Table 1. Output, input and efficiency determinants statistics

Regarding the efficiency determinants, it is important to highlight that the economic crises have generated a large variation for Δ*GDP* values along the sample period. Therefore, the standard deviation is larger than the mean value. Wave and wind conditions are also quite different among the different observations. It should be noted that the ports are in different seas and that the sample period is long enough (25 years) to observe certain changes in the evolution of the weather variables, most likely due to the climate change that the planet is undergoing [41]. The amplitude of tides is also quite different from port to port, ranging from 0.05 meters in Alicante to 2.75 meters in Gijon.[5] The following section describes the observed evolution of wave and wind variables.

2.3 Wave and wind evolution during the sample period

The sample was divided into 5 zones, as displayed in Figure 2, in order to consider different evolutions of waves and winds. Zone 1 includes ports located in the northern part of Spain (Bilbao, Gijon and Vigo); Zone 2 refers to the ports in the Canary Islands (Las Palmas and Santa Cruz de Tenerife); in Zone 3, the ports are located in the south-western part of the peninsular Spain (Cadiz and Seville); in Zone 4, the ports are located

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[5] It is also worth noting that the maximum sea level difference in a port is significantly larger than the average provided in Table 1, as tidal amplitude depends on several factors. Accordingly, during the period 1996-2003, the highest tide registered in Gijon (which is the maximum average tidal amplitude in our sample) was 5.40 meters while the lowest tide was 0.16 meters, resulting in an observed difference between the maximum and the minimum sea level of 5.34 meters during the period [67], which is considerably larger than the average tidal amplitude (2.75 m) in this port. However, the difference between maximum and minimum registered sea level is approximately proportional to the average tidal amplitude.

in the Alboran Sea (western part of the Mediterranean Sea, including Algeciras and Malaga) and Zone 5 includes the rest of the Mediterranean ports (Tarragona, Barcelona, Castellon, Valencia, Alicante and Cartagena).

Figure 2. Zones of the Spanish coast

Source: based on data from GISCO Ports 2013 dataset [42]

Figures A1 and A2 in the Appendix A show the global and the zonal averages of *Wave* and *Wind*. It becomes apparent that average wind speed increases along the sample period (even for the global sample or for each zone). This result is in line with the increase of wind speed in the Spanish latitude found in [41,43]. On the other hand, the significant wave height seems to increase along the sample period but not as clearly as the wind speed. To identify these time trends, the equations (7.a) and (7.b) were estimated:

$$Wave_{it} = \sum_{i=1}^{I} \beta_i D_i + \beta_t t + e_{it} \qquad (7.a)$$

$$Wind_{it} = \sum_{i=1}^{I} \beta_i D_i + \beta_t t + e_{it} \qquad (7.b)$$

where D_i are port dummies, e_{it} is the error term and β*'s* are the parameters to be estimated. The estimations were made for the total sample and for each zone separately. The set of estimations of the parameters β_t along with the R^2 statistics are included in Tables 2 and 3. Table 2 shows that only in Zone 2, Zone 3 and Zone 5 the trend for the evolution of the variable *Wave* becomes significant and positive, while in Zone 1 and Zone 4, no statistically significant trend was identified. Table 3 displays a statistically significant increase in the average wind speed in each zone. The trend of this variable varies ostensibly from one zone to another, but it is always positive and significant. Therefore, wave height and wind speed evolution is roughly consistent with the results provided by [43].

Wave height	**Coef.**	**Std. Err.**	**t-Stat.**	**R^2**
Global trend	0.0024	0.0006	3.90	0.960
Zone 1 trend	-0.0012	0.0020	-0.63	0.573
Zone 2 trend	0.0059	0.0019	3.18	0.837
Zone 3 trend	0.0041	0.0022	1.86	0.529
Zone 4 trend	-0.0015	0.0010	-1.54	0.795
Zone 5 trend	0.0038	0.0005	7.42	0.776

Table 2. Wave height trend

Wind speed	**Coef.**	**Std. Err.**	**t-Stat.**	**R^2**
Global trend	0.0684	0.0039	17.51	0.726
Zone 1 trend	0.1233	0.0106	11.63	0.693
Zone 2 trend	0.0955	0.0115	8.28	0.715
Zone 3 trend	0.0305	0.0088	3.47	0.571
Zone 4 trend	0.0710	0.0118	6.03	0.802
Zone 5 trend	0.0437	0.0031	13.99	0.783

Table 3. Wind speed trend

From this preliminary analysis it can be concluded that different zones show considerable variations in weather conditions. Even more importantly, the evolution of these conditions can have a strong influence on the evolution of the technical efficiency of ports.

3. Results

3.1 The estimation

Equation (4), including equations (5) and (6), was estimated in one step by maximum likelihood procedure using the econometric package Stata. Inputs and outputs were divided according to their respective geometric means. Then, first order coefficients could be understood as the corresponding output elasticities evaluated at the sample geometric mean. The production frontier estimation is reported in Table 4.

Variable	Coef.	Std. Err.	t-Stat.	Variable	Coef.	Std. Err.	t-Stat.
Const	0.273	0.080	-3.40	$\ln y_3^* \ln x_2$	0.036	0.073	0.49
$\ln y_2^*$ *(Solid bulk)*	0.519	0.020	25.63	$\ln y_3^* \ln x_3$	0.123	0.097	1.27
$\ln y_3^*$ *(Container)*	0.149	0.021	7.03	$\ln y_3^* \ln x_4$	-0.008	0.046	-0.18
$\ln y_4^*$ *(General)*	0.271	0.026	10.43	$\ln y_4^* \ln x_1$	-0.149	0.038	-3.92
$\ln y_5^*$ *(Passengers)*	0.077	0.010	8.13	$\ln y_4^* \ln x_2$	0.207	0.091	2.27
$\ln x_1$ *(Surface)*	-0.097	0.027	-3.52	$\ln y_4^* \ln x_3$	-0.106	0.107	-0.99
$\ln x_2$ *(Infrastruct.)*	-0.267	0.061	-4.35	$\ln y_4^* \ln x_4$	-0.032	0.060	-0.53
$\ln x_3$ *(Labor)*	-0.676	0.098	-6.92	$\ln y_5^* \ln x_1$	0.011	0.008	1.35
$\ln x_4$ *(Oth. Expens.)*	-0.210	0.061	-3.44	$\ln y_5^* \ln x_2$	-0.012	0.022	-0.55
$0.5 \ln y_2^{*2}$	-0.055	0.019	-2.91	$\ln y_5^* \ln x_3$	-0.040	0.027	-1.50
$\ln y_2^* \ln y_3^*$	0.003	0.012	0.26	$\ln y_5^* \ln x_4$	0.043	0.013	3.28
$\ln y_2^* \ln y_4^*$	-0.060	0.019	-3.15	$0.5 \ln x_1^2$	0.107	0.049	2.20
$\ln y_2^* \ln y_5^*$	0.006	0.004	1.49	$\ln x_1 \ln x_2$	-0.147	0.113	-1.31
$0.5 \ln y_3^{*2}$	0.044	0.021	2.15	$\ln x_1 \ln x_3$	-0.044	0.154	-0.28
$\ln y_3^* \ln y_4^*$	0.018	0.026	0.70	$\ln x_1 \ln x_4$	0.165	0.074	2.22
$\ln y_3^* \ln y_5^*$	-0.016	0.006	-2.62	$0.5 \ln x_2^2$	-0.038	0.338	-0.11
$0.5 \ln y_4^{*2}$	0.073	0.037	1.95	$\ln x_2 \ln x_3$	0.125	0.261	0.48
$\ln y_4^* \ln y_5^*$	0.006	0.007	0.82	$\ln x_2 \ln x_4$	-0.325	0.180	-1.80
$0.5 \ln y_5^{*2}$	0.010	0.002	4.96	$0.5 \ln x_3^2$	0.655	0.356	1.84
$\ln y_2^* \ln x_1$	0.060	0.023	2.59	$\ln x_3 \ln x_4$	-0.059	0.211	-0.28
$\ln y_2^* \ln x_2$	-0.264	0.059	-4.49	$0.5 \ln x_4^2$	0.162	0.180	0.90
$\ln y_2^* \ln x_3$	0.010	0.057	0.17	***Tide***	0.149	0.031	4.80
$\ln y_2^* \ln x_4$	-0.008	0.038	-0.21	t	-0.070	0.009	-7.70
$\ln y_3^* \ln x_1$	0.021	0.027	0.79	$0.5\, t^2$	0.002	0.000	6.07

Table 4. Output distance frontier estimation.

All the first order parameters show the theoretically expected sign. Then, first order parameters multiplying $\ln y_{lit}^*$ are positive and significant. On the one hand, it demonstrates that the distance to the frontier diminishes when an output increases (while the input vector remains constant), which, in turn, increments the technical efficiency degree of the port. On the other hand, first order parameters multiplying $\ln x_{jit}$ are negative and significant, which implies that, when the input endowment increases (while the output vector remains constant), the distance to the frontier becomes bigger, reducing the degree of technical efficiency. Scale elasticity at the sample geometric mean (calculated by changing the sign to the addition of the input first order parameters) is 1.25. The Wald test, used to test for constant returns to scale (scale elasticity equal to 1), takes a value of 19.37 and is significant at any standard significance level. The finding of increasing returns to scale in the Spanish port sector is usual in the literature [30,44]. However, diminishing returns to scale can also be found in the literature around the world [45–47]. The tidal amplitude reduces ports' productivity in a highly significant way. Therefore, as expected, the difficulties that low tides may create for large ship manoeuvres (which may impede access to the port until the tide reaches a certain level of security) affect their capacity to produce port services. Finally, the results show a positive but decreasing technical change along the sample period, as the parameter interacting with t is negative but that interacting with t^2 is positive. A similar pattern for technical change could be found in [47].

Table 5 shows the results of the estimation of the (log of the) variance of v. As expected, the difficulties associated to large tidal amplitude lower the variance of v, as the reduction of the number of hours in which large ships may access or leave the ports would limit the upper shocks of productivity.

Ln σ_v^2	**Coef.**	**Std. Err.**	**t-Stat.**
Const	-2.687	0.236	-11.39
Tide	-1.344	0.329	-4.08

Table 5. σ_v^2 heteroscedasticity estimation

Table 6 shows the estimation of the efficiency determinants. All the variables considered become significant and have the expected sign. The negative sign of ΔGDP shows that, when the GDP increases, the variance of u diminishes and the expected distance to the frontier and the degree of technical inefficiency reduce. Therefore, the economic crises observed during the sample period should have an important impact on port performance, as the drop in the demand for port services would decrease the technical efficiency score. *Wave* and *Wind* are also significant and show the expected sign. The obtained results indicate that the higher the waves and the faster the wind speed, the larger the distance to the frontier and the lower the degree of technical efficiency.

Ln σ_u^2	**Coef.**	**Std. Err.**	**t-Stat.**
Const	-5.025	0.928	-5.42
ΔGDP	-0.189	0.044	-4.30

Wave	1.020	0.370	2.75
Wind	0.392	0.138	2.85

Table 6. Efficiency determinants estimation

3.2 Effect of waves and wind

The negative effects of waves and wind on technical efficiency are evaluated through a simulation exercise. With the estimated parameters of equation (6), the conditional expectation of $\sigma_{u_{it}}$ was calculated by fixing the value of ΔGDP at its sample mean value. Then, the variability of $\sigma_{u_{it}}$ conditional expectation will depend exclusively on the wave and wind conditions registered for each observation. Once the conditional expectation of $\sigma_{u_{it}}$ was calculated, the conditional expectation of the degree of technical efficiency could be determined using equation (8) [28,48]:

$$E[\exp(-u_{it})] = 2\left[1 - \Phi\left(\sigma_{u_{it}}\right)\right] \exp\left(\frac{\sigma_{u_{it}}^2}{2}\right) \tag{8}$$

The global and zonal averages of the conditional expected values for the efficiency scores are shown in Figure B1 in the Appendix B. As could be expected, the evolution of the expected efficiency follows a similar pattern to that observed for *Wind,* since it is the weather variable that shows a clearer temporal evolution. It seems that the efficiency of the Spanish ports diminishes along the sample period, especially in Zones 1 and 2 where the variable *Wind* shows a greater increase. To verify the evolution of the expected efficiency, the equation (9) was estimated in a similar way to equations (7.a) and (7.b):

$$E[\exp(-u_{it}\ )\ ] = \sum_{i=1}^{I} \beta_i D_i + \beta_t t + e_{it} \tag{9}$$

The estimation of equation (9) was made again for the whole sample and for each zone separately. The obtained results are provided in Table 7.

$[\exp(-u_{it})]$	**Coef.**	**Std. Err.**	**t-Stat.**	**R^2**
Global trend	-0.0022	0.0001	-15.22	0.841
Zone 1 trend	-0.0043	0.0005	-9.54	0.683
Zone 2 trend	-0.0034	0.0004	-7.79	0.798

Zone 3 trend	-0.0013	0.0004	-3.24	0.629
Zone 4 trend	-0.0017	0.0003	-5.17	0.824
Zone 5 trend	-0.0013	0.0001	-14.24	0.814

Table 7. Expected efficiency trend

As can be seen, on average, the degree of technical efficiency diminishes by 0.22% per year as the weather conditions (wind speed in particular) deteriorate over the sample period. Therefore, the evolution of the weather during the sample period generates a significant diminution on the efficiency of the Spanish ports. This evolution becomes especially important in Zone 1 (Bilbao, Gijon and Vigo) and in Zone 2 (Las Palmas and Santa Cruz de Tenerife). On the other hand, ports in Zone 3 (Cadiz and Seville), Zone 4 (Algeciras and Malaga) and Zone 5 (Tarragona, Barcelona, Castellon, Valencia, Alicante and Cartagena) suffer a significant reduction in their efficiency, but to a much lesser extent. The results are in line with [26], who found that the Mediterranean region is that with better natural conditions for the location of ports.

However, the expected evolution of wave height and wind speed around the Earth is found to depend on the geographical zone [49,50]. In particular, wave height and wind speed are predicted to decrease until the end of this century in the geographical zone analysed [49,50], in spite that both were found to increase during the sample period, but this period is climatically too short to reach valid conclusions. We then carried out a simulation analysis to assess the impact of a reduction in these variables in a range similar to that provided by [50], who predict a decrease in wave height of 10% by the end of XXI century. Therefore, we simulate the evolution of σ_u by fixing the value of ΔGDP at its sample mean value and taking into account the zonal average values of wave height and wind speed and simulating a decrease in those variables of up to 15%. The results are provided in Figure 2B in the Appendix B. Therefore, for a 10% decrease in wave height and wind speed the technical efficiency increases by 1.3% in Zone 4 (which is the most efficient zone, due to the better wave and wind conditions) and by 2.9% in Zone 1 (which is the least efficient zone). Then, the predicted improvement in wave and wind conditions would generate a convergence in port productivity.

3.3 Tidal amplitude effect

Finally, we analyse the effect of the tidal amplitude on the productivity of ports. In this case, we consider a firm characterized by the sample average of ΔGDP, wave height and wind speed. This firm would have an expected technical efficiency score equal to 82.8%. Taking into account the log-normal nature of the distribution of the efficient production of y_1 implied in equation (4), the efficient production of y_1 corresponding to a null tidal amplitude could be calculated by means of equation (10):

$$
\begin{aligned}
y_1^{eff} = \exp\Bigg[-\Bigg\{\alpha_0 + \sum_{j=1}^{4}\alpha_j \ln x_j + \frac{1}{2}\sum_{j=1}^{4}\sum_{k=1}^{4}\alpha_{jk}\ln x_j \ln x_k + \sum_{l=2}^{5}\beta_l \ln y_l^* \\
+ \frac{1}{2}\sum_{l=2}^{5}\sum_{m=2}^{5}\beta_{lm}\ln y_l^* \ln y_m^* + \frac{1}{2}\sum_{j=1}^{4}\sum_{l=2}^{5}\gamma_{jl}\ln x_j \ln y_l^* + \alpha_{Tide}Tide_i + \alpha_t t \\
+ \frac{1}{2}\alpha_{tt}t^2\Bigg\} + \frac{1}{2}\sigma_v^2(0)\Bigg] \qquad (10)
\end{aligned}
$$

where $\boldsymbol{y_1^{eff}}$ is the efficient production of output y_1 and $\boldsymbol{\sigma_v^2(0)}$ is the value of the variance of v if the tidal amplitude is null. Therefore, as the quotients of other outputs over y_1 are included as independent variables and the distribution of u is assumed to be independent of the variables included in equation (10), the quotient of the expected value of any output (given the observed tidal amplitude and the expected efficiency score) over its efficient value (assuming a null tidal amplitude) could be calculated using equation (11):

$$
\frac{E[y_{li}]}{y_l^{eff}} = \exp\left[-\alpha_{Tide}Tide_i + \frac{\sigma_v^2(Tide_i) - \sigma_v^2(0)}{2}\right] \times E[\exp(-\bar{u})] \qquad (11)
$$

where subscript i refers to port as usual, $E[y_{li}]$ is the expected value of any output y_l, $\sigma_v^2(Tide_i)$ is the variance of v which depends on tidal amplitude (see equation 5) and $E[\exp(-\bar{u})]$ is the expected technical efficiency value for the abovementioned firm of reference. The results obtained are shown in Figure 3.

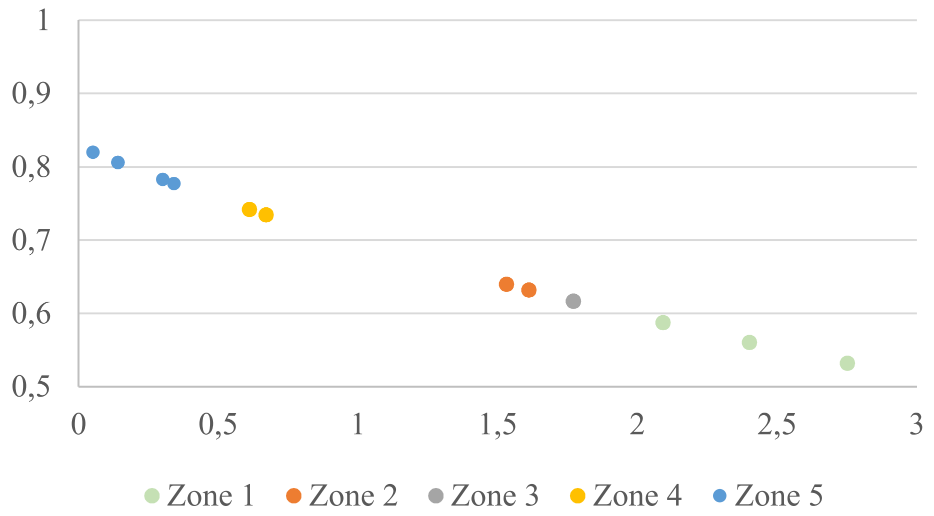

Figure 3. Productivity effect of tides
Source: own elaboration

Then, the expected production for the port with the lowest tidal amplitude (Castellon, with a tidal amplitude of 0.05 m) is 82% of the efficient production if the tidal amplitude is null. On the other hand, the port with the highest tidal amplitude (Gijon, 2.75 m) is expected to produce only 54% of the efficient production if the tidal amplitude is null. Therefore, tidal amplitude seems to be an important variable conditioning port productivity as a reduction of 28% in productivity is observed from the minimum to the maximum tidal amplitude in our sample.

4. Discussion

The climate change the planet is undergoing [51] has motivated the advent of several studies dealing with the effect of weather on the productivity of some sectors particularly influenced by meteorology such as agriculture [52–54] or energy [55–57]. However, research in this regard on the transport sector is limited, despite being one of the economic activities expected to be most affected by weather conditions [58–60][6].

As [61] pointed out, ports are exposed to the effects of climate change, such as rising sea levels, strong winds and, particularly, changes in the intensity and direction of waves. These phenomena can cause changes both in the patterns of shipping traffic and the navigability of the port access channels, and even increase flooding. [62] identified

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[6] An exhaustive review on the impact of climate change on the port sector can be found in [3], and [60,61] summarized the major climate variability and change direct impacts on ports by climatic factor. Furthermore, indirect impacts are also expected since climate change effects on trade will likely alter demand for port services.

two different strategies for addressing these threats: mitigation (which implies articulating initiatives to reduce emissions in order to reduce the strength of the climatic change) and adaptation (which deals with the problem in order to build resilience). They also observed that the former has received much more attention, i.e. that port managers are already adopting cleaner and greener processes [62], while the adaptation planning has scarcely been initiated, despite being aware that strong winds and storms are expected to increase due to climate change[7] [63], although in some zones of the Earth the expected evolution could be the opposite, as in the Northern Atlantic [49,50].

The analysis carried out here, as it confirms the existence of a relationship between the technical efficiency of ports and weather conditions, contributes to help understand some initiatives involving overcapacity as resilience strategies to face natural constraints. In short, the trade-off between overcapacity and congestion faced by port managers is more difficult the wider the variability in demand, which increases the worse the natural conditions of the port location.

The results can be of interest to both port managers and policy-makers concerning both the assessment of the current infrastructure endowment and their investment strategies to face climate change. It is interesting for the former as the effect of forecasted weather evolution on the technical efficiency should be an additional factor to be taken into account when deciding on new investments and service scheduling, and of interest to the latter as weather evolution may differ depending on the geographical locations, which is particularly important for countries with ports on different coastlines, as in the Spanish case. This circumstance should be considered when planning the country's transport infrastructure. It is convenient to realise that the reinforcement of the inland corridors linked to the most efficient ports is not necessarily the right option when the observed inefficiency (overcapacity) results from a competitive rational response to weather conditions. In short, the location of ports is relevant concerning the main economic poles, but also because it imposes natural constraints that, in turn, influence the technical efficiency of their facilities.

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[7] Some authors, such as [68] linked this fact to the decreasing atmospheric stability caused by the warmer sea-surface temperature (due to increases within atmospheric CO2 concentration). However, authors like [50] point out that the wide range of methodologies used to assess climate change generates uncertainty about the existing projections. In this sense, [69] concluded that the observed trends could be explained by both global warming and natural variability, although there is general agreement that climate change will have an impact on the sea (see, for instance, [43] or[49]).

For the particular case of the Spanish port system, there is an additional reason for policy-makers to keep in mind that adverse natural conditions hamper port competitiveness as port tariffs depend on their cost structure. Law 33/2010 states that ports have to be self-financing. Therefore, their cost structure determines the tariffs the port managers have to charge. As [13] highlight, the greater the variability of the demand, the greater the probability of inefficiency in terms of costs and, consequently, the greater the difficulty to achieve profitability targets because the extent to which they can modify port tariffs is limited both by regulation and competency. Therefore, as adverse weather conditions reinforce demand variability, which hampers technical efficiency due to the overcapacity of facilities, ports located in coastal areas with greater natural constraints will find it more difficult to reduce prices, so restricting their competitive strategies. Hence, when there are exogenous circumstances conditioning port productivity in a permanent way, such as worse weather conditions, it might be desirable to reinterpret the generic profitability targets adapting them to each particular case.

5. Conclusions

Despite the fact that port activity is affected by weather conditions, no study has been found that uses standard productivity analysis techniques to assess their impact on port efficiency. The empirical analysis carried out shows that some weather variables (wave height and wind speed) influence port productivity in a statistically significant way. The simulation exercise shows that the global average of the simulated technical efficiency varies around 5.3% during the sample period (from 84.5% in 2004 to 79.2% in 2013) due exclusively to weather variability. Our results also show the relevant impact of tidal amplitude on port productivity. This illustrates the magnitude of the impact that natural constraints have on port productivity and highlights the relevance of taking these restrictions and their forecast evolution into account both when planning the facilities and assessing their productivity.

Good natural conditions are not enough to ensure port competitiveness, but competitiveness will be hampered when they are worse. Therefore, these results are of interest for the development of adaptation strategies to climate change as weather conditions influence port efficiency but are beyond the control of port managers. They also underline the importance of improving the forecasts for climatic variability as this information would help port managers improve their competitive strategies. It would help them better adjust the overcapacity of ports located where weather conditions are worse.

Additionally, geographically detailed forecasts on the evolution of weather conditions would be valuable information for policy-makers to maximise the efficiency of the port system when planning its long-term development as a whole.

Additional weather variables influencing visibility, such as fog and rain, can also be expected to affect the manoeuvrability of vessels and crane operations. Therefore, more research is needed to achieve a better understanding of the influence of weather on maritime transport and its possible impact on traffic location in a period in which the climate is changing.

References

[1] UNCTAD, Review of Maritime Transport, 2017.

[2] B.A. Blonigen, W.W. Wilson, Port efficiency and trade flows, Rev. Int. Econ. 16 (2008) 21–36. https://doi.org/10.1111/j.1467-9396.2007.00723.x.

[3] A. Becker, A.K.Y. Ng, D. McEvoy, J. Mullett, Implications of climate change for shipping: ports and supply chains, Wiley Interdiscip. Rev. Clim. Chang. (2018). https://doi.org/10.1002/wcc.508.

[4] X. Clark, D. Dollar, A. Micco, Port efficiency, maritime transport costs, and bilateral trade, J. Dev. Econ. 75 (2004) 417–450. https://doi.org/10.1016/j.jdeveco.2004.06.005.

[5] A. Suárez-Alemán, J. Morales Sarriera, T. Serebrisky, L. Trujillo, When it comes to container port efficiency, are all developing regions equal?, Transp. Res. Part A Policy Pract. 86 (2016) 56–77. https://doi.org/10.1016/j.tra.2016.01.018.

[6] J.M. Sarriera, G. Araya, T. Serebrisky, C. Briceño-Garmendía, J. Schwartz, Benchmarking Container Port Technical Efficiency in Latin America and the Caribbean: a stochastic frontier analysis, Washington D.C., 2013.

[7] T. Serebrisky, J.M. Sarriera, A. Suárez-Alemán, G. Araya, C. Briceño-Garmendía, J. Schwartz, Exploring the drivers of port efficiency in Latin America and the Caribbean, Transp. Policy. 45 (2016) 31–45. https://doi.org/10.1016/j.tranpol.2015.09.004.

[8] M.G. Karlaftis, D. Tsamboulas, Efficiency measurement in public transport: Are findings specification sensitive?, Transp. Res. Part A Policy Pract. 46 (2012) 392–402. https://doi.org/10.1016/j.tra.2011.10.005.

[9] G. Wilmsmeier, B. Tovar, R.J. Sanchez, The evolution of container terminal productivity and efficiency under changing economic environments, Res. Transp. Bus. Manag. 8 (2013) 50–66. https://doi.org/10.1016/j.rtbm.2013.07.003.

[10] B. Slack, C. Comtois, B. Wiegmans, P. Witte, Ships time in port, Int. J. Shipp. Transp. Logist. 10 (2018) 45. https://doi.org/10.1504/IJSTL.2018.088322.

[11] T.E. Notteboom, The time factor in liner shipping services, Marit. Econ. Logist. 8 (2006) 19–39. https://doi.org/10.1057/palgrave.mel.9100148.

[12] A. Rodriguez-Alvarez, D. Roibás, A. Wall, Reserve capacity of public and private hospitals in response to demand uncertainty, Health Econ. 21 (2012) 839–851. https://doi.org/10.1002/hec.1755.

[13] B. Tovar, A. Wall, The impact of demand uncertainty on port infrastructure costs: Useful information for regulators?, Transp. Policy. 33 (2014) 176–183. https://doi.org/10.1016/j.tranpol.2014.03.005.

[14] K. Ellot, M. Vantorre, J. Richter, Development of Decision Supporting Tools for Determining Tidal Windows for Deep-drafted Vessels, Int. J. Mar. Navig. Saf. Sea Transp. 4 (2010) 323–330.

[15] M. Szymonski, Analysis and Evaluation of Manoeuvrability Characteristics of Polish Ferries m/f "Polonia" and m/f "Gryf", Int. J. Mar. Navig. Saf. Sea Transp. 7 (2013) 515–518. https://doi.org/10.12716/1001.07.04.06.

[16] B. Vernimmen, W. Dullaert, S. Engelen, Schedule Unreliability in Liner Shipping: Origins and Consequences for the Hinterland Supply Chain, Marit. Econ. Logist. 9 (2007) 193–213. https://doi.org/10.1057/palgrave.mel.9100182.

[17] M.M. González, L. Trujillo, Efficiency measurement in the port industry: a survey of the empirical evidence, J. Transp. Econ. Policy. 43 (2009) 157–192.

[18] B. Tovar, A. Wall, Can ports increase traffic while reducing inputs? Technical efficiency of Spanish Port Authorities using a directional distance function approach, Transp. Res. Part A Policy Pract. 71 (2015) 128–140. https://doi.org/10.1016/j.tra.2014.11.003.

[19] B. Tovar, H. Rodríguez-Déniz, Classifying Ports for Efficiency Benchmarking: A Review and a Frontier-based Clustering Approach, Transp. Rev. 35 (2015) 378–400. https://doi.org/10.1080/01441647.2015.1016473.

[20] P. Coto-Millán, X.L. Fernández, S. Hidalgo, M.Á. Pesquera, Public regulation and technical efficiency in the Spanish Port Authorities: 1986-2012, Transp. Policy. 47 (2016) 139–148. https://doi.org/10.1016/j.tranpol.2016.01.006.

[21] H.O. Nguyen, H. Van Nguyen, Y.T. Chang, A.T.H. Chin, J. Tongzon, Measuring port efficiency using bootstrapped DEA: the case of Vietnamese ports, Marit. Policy Manag. 43 (2016) 644–659. https://doi.org/10.1080/03088839.2015.1107922.

[22] B. Tovar, A. Wall, Dynamic cost efficiency in port infrastructure using a directional distance function: accounting for the adjustment of quasi-fixed inputs over time, Transp. Sci. 51 (2016) 296–304. https://doi.org/10.1287/trsc.2016.0684.

[23] M.R.P. da Cruz, J.J. de Matos Ferreira, Evaluating Iberian seaport competitiveness using an alternative DEA approach, Eur. Transp. Res. Rev. 8 (2016) 1–9. https://doi.org/10.1007/s12544-015-0187-z.

[24] A. Gil-Ropero, M. Cerban, I.J. Turias, Analysis of the global and technical efficiencies of major Spanish container ports, Int. J. Transp. Econ. 42 (2015).

[25] P.F. Wanke, C. Pestana Barros, Efficiency Drivers in Brazilian Insurance: A Two-Stage DEA Meta Frontier-Data Mining Approach, Econ. Model. 53 (2016) 8–22. https://doi.org/10.1016/j.econmod.2015.11.005.

[26] P. Peng, Y. Yang, F. Lu, S. Cheng, N. Mou, R. Yang, Modelling the competitiveness of the ports along the Maritime Silk Road with big data, Transp. Res. Part A Policy Pract. 118 (2018) 852–867. https://doi.org/https://doi.org/10.1016/j.tra.2018.10.041.

[27] T.J. Coelli, D.S. Prasada Rao, C.J. O'Donnell, G.E. Battese, An introduction to efficiency and productivity analysis, 2nd ed., Springer, New York, 2005.

[28] S. Kumbhakar, C.A.K. Lovell, Stochastic frontier analysis, Cambridge University Press, 2000.

[29] L. Trujillo, B. Tovar, The European Port Industry: an analysis of its economic efficiency, 2007. https://doi.org/10.1111/etap.12031.

[30] M.M. González, L. Trujillo, Reforms and infrastructure efficiency in Spain's container ports, Transp. Res. Part A. 42 (2008) 243–257. https://doi.org/10.1016/j.tra.2007.08.006.

[31] V. Chang, B. Tovar, Drivers explaining the inefficiency of Peruvian and Chilean ports terminals, Transp. Res. Part E Logist. Transp. Rev. 67 (2014) 190–203. https://doi.org/10.1016/j.tre.2014.04.011.

[32] R. Färe, D. Primont, Multi-Output Production and Duality: Theory and Applications, Kluwer Academic Publishers, 1995.

[33] R.G. Chambers, Applied production analysis: a dual approach, Cambridge University Press, New York, 1988.

[34] Z. Liu, The Comparative Performance of Public and Private Enterprises: The Case of British Ports, J. Transp. Econ. Policy. 29 (1995) 263–274.

[35] A. Estache, M. González, L. Trujillo, Efficiency gains from port reform and the potential for yardstick competition: Lessons from Mexico, World Dev. 30 (2002) 545–560. https://doi.org/10.1016/S0305-750X(01)00129-2.

[36] S. Caudill, J. Ford, D. Gropper, Frontier estimation and firm-specific inefficiency measures in the presence of heteroscedasticity, J. Bus. Econ. Stat. 13 (1995) 105–111. https://doi.org/10.2307/1392525.

[37] J.I. Castillo-Manzano, M. Castro-Nuño, F.G. Laxe, L. López-Valpuesta, M. Teresa

Arévalo-Quijada, Low-cost port competitiveness index: Implementation in the Spanish port system, Mar. Policy. 33 (2009) 591–598. https://doi.org/10.1016/J.MARPOL.2008.12.008.

[38] Ente Público Puertos del Estado, Statistical Yearbooks, (2018).

[39] Ente Público Puertos del Estado, Annual Reports, (2018).

[40] Instituto Nacional de Estadística, Contabilidad Regional de España, (2018).

[41] IPCC, Climate Change 2014: Synthesis Report, Geneva, Switzerland, 2014.

[42] European Commission, GISCO dataset, Geogr. Inf. Syst. Comm. (2016). https://doi.org/10.1007/s13398-014-0173-7.2.

[43] I.R. Young, A. Ribal, Multiplatform evaluation of global trends in wind speed and wave height., Science. 364 (2019) 548–552. https://doi.org/10.1126/science.aav9527.

[44] R. Núñez-Sánchez, P. Coto-Millán, The impact of public reforms on the productivity of Spanish ports: A parametric distance function approach, Transp. Policy. 24 (2012) 99–108. https://doi.org/10.1016/j.tranpol.2012.07.011.

[45] K. Cullinane, D.W. Song, R. Gray, A stochastic frontier model of the efficiency of major container terminals in Asia: Assessing the influence of administrative and ownership structures, Transp. Res. Part A Policy Pract. 36 (2002) 743–762. https://doi.org/10.1016/S0965-8564(01)00035-0.

[46] K.P.B. Cullinane, D.W. Song, A stochastic frontier model of the productive efficiency of Korean container terminals, Appl. Econ. 35 (2003) 251–267. https://doi.org/10.1080/00036840210139355.

[47] V. Chang, B. Tovar, Heterogeneity Unobserved and Efficiency A Latent Class Model for West Coast of South Pacific Port Terminals, J. Transp. Econ. Policy. 51 (2017) 139–156.

[48] L.-F. Lee, W.G. Tyler, The stochastic frontier production function and average efficiency: An empirical analysis, J. Econom. 7 (1978) 385–389. https://doi.org/10.1016/0304-4076(78)90061-1.

[49] E.K.-M. Chang, CMIP5 Projected Change in Northern Hemisphere Winter Cyclones with Associated Extreme Winds, J. Clim. 31 (2018) 6527–6542. https://doi.org/https://doi.org/10.1175/JCLI-D-17-0899.1.

[50] J. Morim, M. Hemer, X.L. Wang, N. Cartwright, C. Trenham, A. Semedo, I. Young, L. Bricheno, P. Camus, M. Casas-Prat, L. Erikson, L. Mentaschi, N. Mori, T. Shimura, B. Timmermans, O. Aarnes, Ø. Breivik, A. Behrens, M. Dobrynin, M.

Menendez, J. Staneva, M. Wehner, J. Wolf, B. Kamranzad, A. Webb, J. Stopa, F. Andutta, Robustness and uncertainties in global multivariate wind-wave climate projections, Nat. Clim. Chang. 9 (2019) 711–718. https://doi.org/10.1038/s41558-019-0542-5.

[51] IPCC, Climate Change 2013: The Physical Science Basis, Cambridge University Press, Cambridge, United Kingdom and New York, 2013. https://doi.org/10.1017/CBO9781107415324.

[52] N. Demir, S.F. Mahmud, Agro-Climatic Conditions and Regional Technical Inefficiencies in Agriculture, Can. J. Agric. Econ. 50 (2002) 269–280. https://doi.org/10.1111/j.1744-7976.2002.tb00337.x.

[53] S. Barrios, B. Ouattara, E. Strobl, The impact of climatic change on agricultural production: Is it different for Africa?, Food Policy. 33 (2008) 287–298. https://doi.org/10.1016/j.foodpol.2008.01.003.

[54] J.A. Perez-Mendez, D. Roibas, A. Wall, The influence of weather conditions on dairy production, Agric. Econ. 50 (2019) 165–175. https://doi.org/https://doi.org/10.1111/agec.12474.

[55] L. Orea, C. Growitsch, T. Jamasb, Using Supervised Environmental Composites in Production and Efficiency Analyses, Compet. Regul. Netw. Ind. 16 (2015) 260–287. https://doi.org/10.1177/178359171501600303.

[56] M. Llorca, L. Orea, M.G. Pollitt, Efficiency and environmental factors in the US electricity transmission industry, Energy Econ. 55 (2016) 234–246. https://doi.org/10.1016/J.ENECO.2016.02.004.

[57] K.L. Anaya, M.G. Pollitt, Using stochastic frontier analysis to measure the impact of weather on the efficiency of electricity distribution businesses in developing economies, Eur. J. Oper. Res. 263 (2017) 1078–1094. https://doi.org/10.1016/j.ejor.2017.05.054.

[58] M.J. Koetse, P. Rietveld, The impact of climate change and weather on transport: An overview of empirical findings, Transp. Res. Part D Transp. Environ. 14 (2009) 205–221. https://doi.org/10.1016/J.TRD.2008.12.004.

[59] A. Vajda, H. Tuomenvirta, I. Juga, P. Nurmi, P. Jokinen, J. Rauhala, Severe weather affecting European transport systems: the identification, classification and frequencies of events, Nat. Hazards. 72 (2014) 169–188. https://doi.org/10.1007/s11069-013-0895-4.

[60] J.M. O'Keeffe, V. Cummins, R.J.N. Devoy, D. Lyons, J. Gault, Stakeholder

awareness of climate adaptation in the commercial seaport sector: A case study from Ireland, Mar. Policy. (2016). https://doi.org/10.1016/J.MARPOL.2016.04.044.

[61] R. Asariotis, H. Benamara, V.M.- Naray, Port Industry Survey on Climate Change Impacts and Adaptation - UNCTAD/SER.RP/2017/18, 2017.

[62] A. Becker, S. Inoue, M. Fischer, B. Schwegler, Climate change impacts on international seaports: Knowledge, perceptions, and planning efforts among port administrators, Clim. Change. 110 (2012) 5–29. https://doi.org/10.1007/s10584-011-0043-7.

[63] A.K.Y. Ng, H. Zhang, M. Afenyo, A. Becker, S. Cahoon, S.L. Chen, M. Esteben, C. Ferrari, Y.Y. Lau, P.T.W. Lee, J. Monios, A. Tei, Z. Yang, M. Acciaro, Port decision-maker perceptions on the effectiveness of climate adaptation actions, Coast. Manag. (2018). https://doi.org/10.1080/08920753.2018.1451731.

[64] S.C. Drewry, The Drewry container shipper insight – fourth quarter 2006, London, 2006.

[65] G.F. de Oliveira, P. Cariou, The impact of competition on container port (in)efficiency, Transp. Res. Part A Policy Pract. 78 (2015) 124–133. https://doi.org/10.1016/j.tra.2015.04.034.

[66] C.-S. Lu, K.-C. Shang, C.-C. Lin, Identifying crucial sustainability assessment criteria for container seaports, Marit. Bus. Rev. 1 (2016) 90–106. https://doi.org/10.1108/MABR-05-2016-0009.

[67] REDMAR, Resumen de parámetros relacionados con el nivel del mar y la marea que afectan a las condiciones de diseño y explotación portuaria, 2014. http://calipso.puertos.es/BD/informes/globales/GLOB_2_3_3108.pdf.

[68] S.B. Goldenberg, C.W. Landsea, A.M. Mestas-Nuñez, W.M. Gray, The recent increase in Atlantic hurricane activity: causes and implications, Science (80-.). 293 (2001) 474–479. https://doi.org/10.1126/science.1060040.

[69] M. Dobrynin, J. Murawski, J. Baehr, T. Ilyina, Detection and attribution of climate change signal in ocean wind waves, J. Clim. 28 (2015) 1578–1591. https://doi.org/10.1175/JCLI-D-13-00664.1.