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Environmental Efficiency for a Cross-Section of Spanish Port Authorities

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ABSTRACT

Shipping has well-documented environmental impacts, among which are greenhouse gas emissions that contribute to climate change and global warming. Measurement of the possibility of ports to reduce emissions by operating more efficiently provides important information for policymakers. In this study we estimate environmental efficiency for a cross section of 28 Spanish Port Authorities observed in 2016 using an output-oriented directional distance frontier with a ‘bad output’, carbon dioxide ($CO2$) emissions. We use the non-parametric mathematical programming technique of Data Envelopment Analysis (DEA) to estimate the frontier. Our novel dataset includes information on CO2 emissions obtained for these Spanish Port Authorities using the fleet activity–based emission estimation (*bottom-up*) methodology. Using ships berthing as output, if all port authorities had been environmentally efficient in providing their services, CO2 emission could have been reduced to an average of 63% of their actual observed levels with a simultaneous increase in good output. When using cargo and passenger traffic as output in order to control for ship characteristics through the output mix, we find that reductions of emissions to 82% of observed levels could be achieved with simultaneous increases in outputs, and reductions to 72 of existing levels if good outputs remain constant.

Keywords: Ports, CO2 emissions, output directional distance frontier, data envelopment analysis, environmental efficiency.

1. Introduction

The advent of climate change and global warming have led to increasing concern about the need to control the emissions of greenhouse gases (GHG) associated with economic activity, and maritime transport is no exception to this. The sector is a significant contributor to GHG emissions and the International Maritime Organization (IMO) forecasts last increases in emissions in coming decades (IMO, 2014). Awareness of these concerns is such that in April 2018 the IMO's Environment Protection Committee adopted an "initial strategy to reduce GHG emissions from ships" which includes reference to "a pathway of CO2 emissions reduction consistent with the Paris Agreement temperature goals".[1]

Concern in the European Union (EU) about GHG emissions, and particularly CO2, is reflected in the European Commission's 2011 White Paper on Transport which set quantitative targets in the EU regarding CO2 emissions. In particular, CO2 emissions from shipping should be reduced in the EU by at least 40% from 2005 levels by 2050. CO2 reduction policies were published by the EU in 2013 in its Strategy101 consisting of three steps: monitoring, reporting and verification of CO2 emissions from large ships using EU ports; greenhouse gas reduction targets for the maritime transport sector; and additional measures including Market Based Measures in the medium to long term.

To monitor ship-based emissions to and from the EU ports, the Monitoring, Reporting and Verification (MRV) system was proposed to apply to shipping activities from January 1st, 2018. From an operational perspective, the MRV focuses on CO2 as the predominant GHG emitted by ships, and proposes calculation of annual CO2 emissions based on fuel consumption and fuel type and energy efficiency.

Regarding the sources of CO2 emissions from port activity, one of the most prominent is the time spent by ships in ports (Deniz et al, 2010), with ships generating far more emissions pollution than port operations themselves (Habibi and Rehmatulla, 2009). A clear case therefore exists for reduction of ship in-port emissions. Among the benefits are reduced climate impact, the positive side effects of lower fuel use during a stay that lead to corresponding reductions in toxic gases such as nitrous oxide and sulphur dioxide in

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[1] See http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx.

the port city, as well as marketing benefits that can arise from behaviour perceived as socially responsible (Styhre et al., 2017).[2] A recent report prepared for the European Commission (COGEA, 2017) details aspects over which Port Authorities may have direct or indirect influence over shipping emissions, including, among others, on-shore power supply, green ship promotion and vessel speed reduction.

While consensus exists on the need to reduce CO2 emissions, the question arises of the capability of ports to reduce their emissions of CO2 without negatively affecting the level of service provided to clients and stakeholders. If ports are acting efficiently in the sense that they are providing a given level of port services – in this case, the loading and offloading of vessels - with the minimum possible CO2 emissions, then it would appear obvious that CO2 emission may be reduced only if there is a reduction in the number (or sizes) of vessels dealt with.[3] On the other hand, if ports are performing inefficiently in that they could provide the current level of service, or more, with lower CO2 emissions, then it would be possible to reduce emissions without negatively affecting port services. These scenarios have very different economic implications and identifying the presence of inefficiency is therefore valuable information for policy-makers.

To identify efficient and inefficient ports in a given sample, production economics offers useful tools. Production frontier techniques are especially appropriate as they facilitate comparisons across ports with regard to the environmental efficiency with which they provide port services. By estimating the appropriate production frontier (or 'technology'), efficient and inefficient ports can be identified, as can the scope for emissions reduction. Of the tools available, the output-oriented directional distance has been widely-used in environmental efficiency studies as it provides information on the scope for reducing 'bad outputs' such as CO2 emissions while simultaneously maintaining or increasing 'good outputs' such as port services.

In the present study our objective is to estimate environmental efficiency for a cross section of 28 Spanish port authorities observed in 2016 using an output-oriented directional distance frontier with a 'bad output' (CO2 emissions). Given the size of the

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[2] See also Acciaro et al (2014) for a discussion of the different motivations behind ports' desire to promote energy efficiency and relevant articles on this issue.

[3] Note also that the type of vessel visiting the port can affect emissions, as a cruise liner and, say, a container vessel will not produce the same emissions (see, for example, Tichavska and Tovar, 2015). Thus, emissions may also be affected if the traffic mix is changed.

sample, we use the non-parametric mathematical programming technique of Data Envelopment Analysis (DEA) to estimate the frontier. We avail of a novel dataset which includes information on emissions obtained for these Spanish ports authorities using the fleet activity–based emission estimation (*bottom-up*) methodology. The directional distance frontier allows us to measure the extent to which ports can reduce their emissions. Different specifications of the model are presented which permit us to identify the extent to which emission can be reduced (i) without changing port output, and (ii) while simultaneously increasing port output. The former can be considered as consistent with a purely environmental objective, while the latter takes not only environmental but also economic concerns into account. These can be thought of representing two different sets of preferences.

The paper proceeds as follows. In Section 2 the use of the directional function to measure environmental efficiency and the literature to date are discussed. In Section 3 we present the data and Section 4 provides the results. Section 5 concludes.

2. Measuring environmental efficiency: the directional distance function

Directional distance functions can be estimated using either parametric (econometric) or non-parametric (mathematical programming) techniques. We will use the non-parametric Data Envelopment Analysis (DEA) technique, which has the advantages that it does not place functional form restrictions on the technology and it can handle small samples. The existing literature on the evaluation of environmental efficiency of ports using frontier techniques has overwhelmingly used DEA. This literature is relatively recent, and is small but growing. Relevant contributions include Chin and Low (2010) for East Asian ports; Haralambides and Gujar (2012) for Indian dry ports; Shin and Jeong (2013) and Chang (2013) for Korean ports; Lee et al. (2014) for top worldwide container ports; Na et al (2014), He et al. (2015), Na et al. (2017) and Sun et al. (2017) for Chinese ports; and Cheon et al. (2017) and Liu and Lim (2017) for U.S. ports.[4]

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[4] Aside from ports, DDF estimated with DEA have been used in several other fields to calculate environmental efficiency. See, for example, Zhou et al. (2018) for air quality in cities, and Picazo-Tadeo et al. (2012) for agriculture to name but two.

In order to estimate environmental and technical efficiency for our sample of Ports Authorities, we use a directional distance function (DDF) approach with joint weak disposability and null-jointness of bad and good outputs (Chung et al., 1997). The starting point for this approach is to specify the production technology for ports that produce cargo services and a polluting by-product output (CO2). Following Fare et al (2005, page 471) this can be "represented by the output set $P(x)$, which denotes the set of good and bad outputs that can be jointly produced from the input vector x :

$$P(x) = \{(b, y) : x \text{ can produce } (b, y)\}\text{”} \tag{1}$$

By treating CO2 emissions as by-product outputs, we are assuming that they are generated in unison with the (good) cargo outputs. This assumption of null-jointness can be written as:

$$\text{If } \ (b, y) \in P(x) \quad \text{and } \ b = 0, \ \text{ then } \ y = 0 \tag{2}$$

An alternative way of thinking about this is that if the port authority produces good outputs, then some (bad) CO2 emissions must also be produced.

The assumption of joint weak disposability can be stated as follows

$$\text{If } \ (b, y) \in P(x) \ \text{ and } \ 0 \leq \theta \leq 1 \ \text{ then } \ (\theta b, \theta y) \in P(x) \tag{3}$$

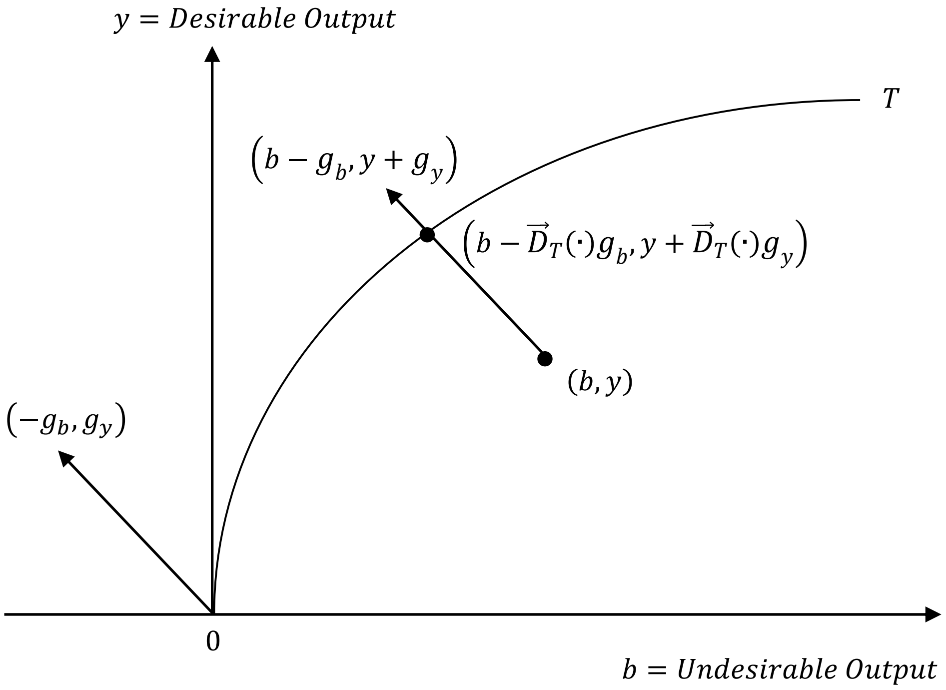
which states that any proportional reduction of both outputs (desirable and undesirable) is possible.

The output-oriented DDF, which is used to measure inefficiency, is defined as:

$$\vec{D}_O\left(x, b, y; -g_b, g_y\right) = \max\left\{\beta : \left(b - \beta g_b, y + \beta g_y\right) \in P(x)\right\} \tag{4}$$

where x is the vector of inputs, y is the vector of good outputs, b is the bad output, β is the efficiency measure, and $\left(-g_b, g_y\right) = (-b_i, y_i)$ is the direction vector defined in terms of the ports' observed outputs. The output-oriented DDF represents the maximum reduction of undesirable (bad) output and enlargement of desirable (good) output in the direction of the vector g that can be achieved while maintaining the bad output and good output combination within the production possibilities set.

Figure 1. Directional distance function with undesirable output



The negative sign on g_b and the positive sign on g_y indicate that undesirable output is being contracted and good output expanded simultaneously. In Figure 1, adding the direction vector to the bad output-good output vector we end up at $\left(b - g_b, y + g_y\right)$ outside the production possibilities set. This vector must therefore be scaled back to place it on the frontier. If the original bad output-good output combination was efficient, it would be on the frontier, and the DDF would take value zero. In Figure 1, the bad output-good output vector is technically inefficient (below the frontier) so the DDF takes a positive value.

To calculate the DDF under the assumptions above in terms of DEA, consider the general case where there are n ports, m inputs, k good outputs and s bad outputs. We can choose between constant returns to scale (CRS) or variables returns to scale (VRS) specifications. Given the differences in size among the port authorities in our sample, and the fact that we are interested in the possibilities of reducing bad outputs given their present size, we opt for VRS specifications. For VRS and direction vector $\left(-g_b, g_y\right) = (-b_i, y_i)$, the model for port i can be written as (see Hampf, 2018):

$$\vec{D}_O(x_i, b_i, y; -b_i, y_i) = \max_{\beta,\lambda} \beta$$

$s.t.$

$$
\begin{gathered}
x_i \geq X\lambda \\
(1+\beta)y_i \leq Y\lambda\theta \\
(1-\beta)b_i = B\lambda\theta \\
0 \leq \theta \leq 1 \\
1^T\lambda = 1 \\
\beta, \lambda \geq 0
\end{gathered}
\tag{5}
$$

where X is an $m \times n$ matrix, Y is an $k \times n$ matrix, B is an $s \times n$ matrix, and λ is the $n \times 1$ vector of weights. As an alternative, if we choose only to reduce bad outputs while maintaining good outputs constant so that the direction vector is $\left(-g_b, g_y\right) = (-b_i, 0)$, the model becomes:

$$\vec{D}_O(x_i, b_i, y; -b_i, y_i) = \max_{\beta,\lambda} \beta$$

$s.t.$

$$
\begin{gathered}
x_i \geq X\lambda \\
y_i \leq Y\lambda\theta \\
(1-\beta)b_i = B\lambda\theta \\
0 \leq \theta \leq 1 \\
1^T\lambda = 1 \\
\beta, \lambda \geq 0
\end{gathered}
\tag{6}
$$

3. Data

We have cross-section data on 28 ports authorities observed in 2016, with information on inputs, good outputs and a bad output. The main sources of the information on inputs and good outputs are the accounts and reports of the Spanish State Ports Authority (*Puertos del Estado*) and the individual port authorities.

The inputs used are *Labour*, which is the number of workers in each port authority; *Capital*, which refers to capital assets; and *Intermediate*, which includes expenditure on remaining productive factors.

The bad output is *CO2*, which represents carbon dioxide emissions from vessels at berth. When it comes to estimate ship emission, Tichavska and Tovar (2017, page 391) identify two approach: “the bottom-up approach which is based on fleet activity (vessel tracks or port calls), and the top-down approach which is based on fuel sales statistics”. In the dataset we have available, the fleet activity–based on vessels tracks (bottom-up) methodology was used as it is believed to more accurate if good information is available because as asserted by Tichavska and Tovar (2015a, page 127) “integrating high-definition traffic information avoids operative assumptions of vessels and estimations are enabled with a greater precision based on the most reliable information presently available”.

Although sea-based emissions in ports are released during different operational modes of vessels, vessel emission calculation in this study is exclusive to the hotelling or berthing mode, which is the mode generating most emissions. (Deniz et al., 2010; Styhre et al., 2017). Moreover, in this way we also avoid obtaining results that may reflect differences among ports due to their physical characteristics such as, for example, fairway differences.

Therefore, the bad output consider in this paper is the estimated tons of CO2 released by vessels while at berth at the Spanish ports authorities under study during 2016.[5] Figure 2 below shows the potential reduction in CO2 emissions that could be achieved if vessels were connected to the on-shore power supply while at berth. [6]

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[5] This has been calculated as part of the EU-funded research project Master Plan for OPS in Spanish Ports. These CO2 emissions are calculated from vessels while at berth.

[6] It should be noted, however, that the potential reduction for each Port Authority depends on how their corresponding on-shore electricity supply is generated (e.g., oil, coal, nuclear…).

Figure 2. Potential reductions in CO2 emissions by Port Authority if on-shore power supply were used

Source: OPS Master Plan for Spanish Ports Project (http://poweratberth.eu/?page_id=40&lang=es)

The methodology used to calculate these emissions is the fleet activity–based emission estimation (bottom-up) proposed by the IMO (*Third IMO Greenhouse Gas Study 2014*). Thus, CO2 emissions at berth are calculated as:

$$CO2 = IEAP * t * EF \tag{7}$$

where $CO2$ is the estimated tons of CO2, $IEAP$ is installed auxiliary engine power (Kw), t is time at berth (measured in hours), and EF is an emission factor (t/kWh). The emission factor used for CO2 was 707 gr/kWh.

With regard to good outputs, port authorities are fundamentally in the business of catering for vessels, for which they charge fees which vary according to the type and size of the ship. We have information on the type, numbers and sizes of the vessels visiting the ports in our sample. As our sample of 28 observations is relatively small, we need to aggregate the outputs in order to be able to calculate meaningful efficiency scores. In particular, care must be taken to avoid the so-called "curse of dimensionality" so as to be able to discriminate between decision-making-units (Paradi and Zhu, 2013). Some simple rules of thumb have been proposed in the literature. In the case that we have K observations on N inputs and M outputs, a simple constraint proposed by Jenkins and Anderson (2003) for DEA to work well is that $K \geq 3(N+M)$. An alternative widely-used constraint proposed by Cooper et al. (2007) is $K \geq max\{NM, 3(N+M)\}$. Given that we already have three inputs and one (bad) output, we need to aggregate the information on ships.

There are two basic ways of doing this: aggregating the number of ships, or aggregating ships by their weight. Ship size (weight) is crucial for fuel consumption and therefore emission. Tichavska and Tovar (2015b, page 352) provide an illustrative example by noting that "large cruise vessels with possibly more than a thousand air-conditioned cabins will probably demand more energy and generate more emission than a cargo carrier when berthed at a port." We therefore opt to aggregate ships by weight (gross tons). With $N=3$ and $M=2$, the aforementioned constraints are comfortable complied with for $K=28$ and should ensure discriminatory power to identify inefficient ports.

In our empirical section we will estimate alternative models using cargo and passenger traffic as good outputs. We have information on four different types of cargo, namely liquid bulk, solid bulk, general non-containerized merchandise and general containerized merchandise, but given the dimensionality issues mentioned we aggregate these four categories by weight (*Cargo Traffic*). Data on passengers includes ferry and cruise passengers, which we also aggregate (*Passenger Traffic*).[7]

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[7] In this case, $N=3$ and $M=3$, so the dimensionality rules of thumb are still complied with.

Some descriptive statistics of the data are presented in Table 1.

Table 1. Descriptive statistics

Variable	**Description**	**Mean**	**Min.**	**Max.**	**Std. Dev.**
Output (Good)					
Ships	Weight (Gross tons)	78,021,038	1,720,024	452,407,013	113,212,413
Cargo Traffic	Weight (tons)	17,700,285	1,105,782	96,861,660	22,583,836
Passenger Traffic	Number	1,160,495	0	7,782,400	2,031,260
Output (Bad)					
CO2	CO2 emissions (tons)	29,845	2,349	114,673	32,346
Inputs					
Labour	Workers (number)	191	69	552	114
Capital	Capital assets (€m.)	456.96	75.23	1833.98	415.54
Intermediate	Inter. consumption (€m.)	3,546,198	274,646	17,514,885	3,833,958

4. Results

The results from the output-oriented directional distance frontiers under VRS are presented in Table 2 and summarised in Table 3. The first two models (Models 1-2) uses *Ships* as the good output. We begin by choosing the direction vector $(-g_b, g_y) = (-b_i, y_i)$, namely the direction of the ports' observed outputs and inputs. From the summary in Table 3, the average value of the directional distance function (β) was 0.367. Values greater than 0 represent inefficiency, and the specific value of the coefficient represent the proportional increase (decrease) in the good (bad) output than could be achieved if ports were operating efficiently. Thus, good outputs (*Ships*) could be increased by an average of 37% of their existing level with a simultaneous reduction of bad outputs (*CO2*) to $(1-\beta)$ =0.63 or 63% of their existing level. Of the 28 ports in the sample, only eight were found to be efficient. These efficient ports represent benchmarks or the 'good practice frontier' for the remaining ports. We note that this group comprises small and medium-sized port authorities, as well as large and complex port authorities.[8] Maximum values of the distance function of over 0.8 show that substantial efficiency gains are possible.

In the next model (Model 2) we change the specification of the direction to $\left(-g_b, g_y\right) = (-b_i, 0)$ so that instead of identifying the possibilities of simultaneously increasing good output and reducing emissions we investigate the extent to which ports could reduce emissions given the existing levels of good output and inputs (i.e., maintaining the latter constant). From Table 3 it can be seen that emissions could be reduced to $(1-\beta)$ = 0.56 or 56% of their existing level.

Emissions depend, among other things on the number and characteristics (weight, size, age, etc.) of the ships berthing in the port. Hence, measured efficiency will be affected by the type of traffic (passengers and cargo) that the port handles. If, for example, large cruise liners emit more CO2 than cargo vessels while berthing, then ports with a greater relative presence of passenger traffic will register higher measured inefficiencies. Thus, at least part of these ports' measured inefficiency will be a consequence of their output mix rather than what we may term 'pure' inefficiency. With our relatively small sample, we cannot hope to completely control for ship characteristics. However, to partly control for these, we incorporate the output mix into our model by replacing the good output *Ships* with two traffic outputs: passenger traffic and cargo traffic. We replicate the models estimated with *Ships* by using the two different direction vectors, $(-b_i, y_i)$ and $(-b_i, 0)$. The results are presented in the final two columns of Table 2 and summarized in the bottom half of Table 3 (models 3 and 4).

As we would expect, taking into account the characteristics of the ships by using output mix as a proxy increases the number of ports found to be efficient. Whereas in the previous models using *Ships* we found that only eight ports were efficient when investigating simultaneous reduction of emissions and increase in good output (Model 1), when output mix is controlled for we find that the number of efficient ports increases to 14 (Model 3). Thus, when controlling for the output mix in Model 3, six port authorities that were found to be inefficient under Model 1 are now found to be efficient: Almería,

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[8] See Tovar and Wall (2017, 2019) for recent analyses of the effect of specialization/diversification, size and complexity (large volume of multiple types of cargo) on efficiency and also productivity of Spanish port authorities.

Baleares, Cartagena, Castellón, Ferrol-San Cibrao and Huelva. Overall, when controlling for output mix, average inefficiency scores fall substantially from 0.367 to 0.177.

Table 2. Directional distance function results

Port Authority	$\boldsymbol{y = (ships)}$		$\boldsymbol{y = (cargo, passengers)}$	
	Model 1	*Model 2*	*Model 3*	*Model 4*
	$g = (-b_i, y_i)$	$g = (-b_i, 0)$	$g = (-b_i, y_i)$	$g = (-b_i, 0)$
A Coruña	0.715	0.820	0.253	0.801
Alicante	0.346	0.394	0.202	0.313
Almería	0.291	0.394	0.000	0.000
Avilés	0.464	0.491	0.145	0.235
Bahía de Algeciras	0.000	0.000	0.000	0.000
Bahía de Cádiz	0.614	0.730	0.667	0.757
Baleares	0.146	0.288	0.000	0.000
Barcelona	0.112	0.226	0.223	0.396
Bilbao	0.767	0.870	0.337	0.597
Cartagena	0.676	0.799	0.000	0.000
Castellón	0.702	0.792	0.000	0.000
Ceuta	0.000	0.000	0.000	0.000
Ferrol-San Cibrao	0.830	0.868	0.000	0.000
Gijón	0.000	0.000	0.000	0.000
Huelva	0.618	0.758	0.000	0.000
Las Palmas	0.367	0.589	0.644	0.822
Málaga	0.331	0.481	0.378	0.548
Marín-Ría de Pontevedra	0.595	0.625	0.016	0.505
Melilla	0.000	0.000	0.000	0.000
Motril	0.000	0.000	0.000	0.000
Pasaia	0.567	0.597	0.391	0.513
Santander	0.503	0.635	0.545	0.708
Sevilla	0.000	0.000	0.000	0.000
Sta. C. de Tenerife	0.000	0.000	0.000	0.000
Tarragona	0.745	0.851	0.278	0.518
Valencia	0.373	0.590	0.239	0.419
Vigo	0.482	0.636	0.646	0.761
Vilagarcía	0.000	0.000	0.000	0.000

Table 3. Summary of efficiency scores from the models

Model	**Mean**	**Min.**	**Max**	**Std. Dev.**	**Efficient Ports**
$y = (ships)$					
Model 1. $g = (-b_i, y_i)$	0.367	0.000	0.838	0.293	8
Model 2. $g = (-b_i, 0)$	0.444	0.000	0.870	0.329	8
$y = (cargo, passengers)$					
Model 3. $g = (-b_i, y_i)$	0.177	0.000	0.667	0.229	14
Model 4. $g = (-b_i, 0)$	0.282	0.000	0.822	0.315	14

When using the direction vector $(-b_i, 0)$, inefficiencies are lower on average than they were when using *Ships* as output as can be seen by comparing the scores from Model 4 with those from Model 2 in Table 3, which shows that average inefficiency fell from 0.444 to 0.282.

While our DEA models cannot explain the determinants of inefficiency, they can identify the relevant peers or benchmarks for inefficient port authorities. In particular, the λ parameters in (5) and (6) identify the port authorities that determine the efficient frontier for inefficient port authorities, with the size of the parameters indicating the weight (relevance) of the efficient port authorities that comprise the efficient frontier. This is useful information for inefficient port authorities as it permits them to identify relevant best-practice peers from which they can learn. Table 4 shows the number of times that efficient port authorities serve as benchmarks for each of the four models we have estimated.

Table 4. Number of times efficient ports serve as benchmarks

Port Authority	Model 1	Model 2	Model 3	Model 4.
Bahía de Algeciras	4	4	8	7
Cartegena			3	1
Ceuta	1	1	2	1
Gijón	13	12	12	12
Huelva			8	4
Melilla	14	16	3	6
Motril			5	2
Sevilla	5	9		4
S.C. de Tenerife	15	10	2	2
Vilagarcía	5	8	6	9

From the table it can be seen that Bahía de Algeciras, Gijón, Melilla, Santa Cruz de Tenerife and Vilagarcía appear as the most frequent benchmarks. However, it should be noted that each of these serve as benchmarks for only a subset of inefficient port authorities. Also, port authorities that are benchmarks for certain inefficient port authorities when output is defined as Ships (Models 1 and 2) may no longer appear as benchmarks when output is defined as Cargo and Passengers, and vice versa. To get a better idea of the relevance of the efficient port authorities as benchmarks for their inefficient counterparts, we focus on those port authorities that are inefficient in all four models and check which efficient port authorities appear as benchmarks in all four models. These are summarized in Table 5.

Table 5. Inefficient port authorities in all models and the port authorities that are their benchmarks in all models

Port Authority	Port authorities that are benchmarks in all models
A Coruña	Gijón
Alicante	Gijón
Avilés	Vilagarcía
Bahía de Cádiz	Gijón, Melilla
Barcelona	Bahía de Algeciras, Santa Cruz de Tenerife
Bilbao	Gijón
Las Palmas	Bahía de Algeciras, Santa Cruz de Tenerife
Málaga	Gijón
Marín-Ría de Pontevedra	Vilagarcía
Pasaia	Vilagarcía
Santander	Gijón, Melilla
Tarragona	Gijón, Melilla, Santa Cruz de Tenerife
Valencia	Bahía de Algeciras
Vigo	Gijón

From Table 5 we see that Gijón always appears as a benchmark for eight inefficient port authorities, including it neighboring north Atlantic coast ports of A Coruña, Avilés, Bilbao, Santander and Vigo, as well as the port of Bahía de Cádiz, Málaga and Tarragona. All of these can be considered small- or medium-sized port authorities in Spain. The large and complex port authorities of Barcelona, Las Palmas and Valencia, on the other hand, all have Bahía de Algeciras, also a large and complex port, as their benchmark. In the same vein, the large and complex port authority of Santa Cruz de Tenerife also serves as a constant benchmark for Barcelona and Las Palmas, as well as for the large port of Tarragona. The small north Atlantic port authority of Vilagarcía serves as benchmark for Avilés, Marín-Ría de Pontevedra and Pasaia, all of which are also small north Atlantic ports. Finally, Melilla serves as a benchmark for Bahía de Cádiz, Santander and Tarragona. As a broad summary, it would appear that the environmentally-inefficient north Atlantic port authorities that wish to improve their performance would do well to look closely at Gijón and Vilagarcía, whereas the large and complex but environmentally-inefficient ports of Barcelona, Las Palmas and Valencia should look at Bahía de Algeciras and Santa Cruz de Tenerife.

5. Conclusions

We have estimated technical and environmental efficiency for a cross section of Spanish ports authorities using a directional distance frontier with a bad output, namely CO2 emissions while at berth calculated using fleet-based 'bottom-up' methodology. We find evidence of substantial inefficient behaviour, with large differences across port authorities. Using ships berthing as output, if all port authorities had been environmentally efficient in providing their services, CO2 emission could have been reduced to an average of 63% of their actual observed levels with a simultaneous increase in good output (or 56% given the existing levels of good output and inputs). When using cargo and passenger traffic as output in order to control for ship characteristics through the output mix, we find that reductions of emissions to an average of 82% of their existing levels could be achieved with simultaneous increases in outputs, and reductions to 72% of existing levels if good output remains constant.

While our analysis suggests that substantial increases in environmental efficiency in the form of CO2 emissions reductions emissions are possible, the question remains as to how these reductions could be achieved in practice. As noted by Acciaro et al. (2014), port authorities can influence GHG emissions from ships through support for technologies and incentive programs. These include the supply of alternative fuels and on-shore power supply (OPS), as well as environmentally-differentiated port dues for ships. Some of these measures are already being contemplated in Spain. Spanish law already formalises environmental sustainability as an objective of port authority management. Thus, Law 33/2010 obliges the Port Authorities to publish an annual Environmental Sustainability Report containing a series of environmental indicators and contemplates reductions in port dues for agents engaging in environmentally-friendly practices (Art. 245). As an example, in 2018 Congress approved a reduction of 50% in port dues for ships at berth that either use LNG or on-shore electricity while at berth. Further incentives to use on-shore power supply were provided in 2018 by European Council authorisation of a plan promoted by the State Ports Authority to reduce taxes on electricity supply from €0.05/kWh to a 'symbolic' €0.0005/kWh for vessels that shut down their auxiliary engines and connect to the general network while at berth. Cullinane and Cullinane (2019, page 57), while recognising the need for waste reception facilities, OPS and alternative fuels for ships, underline "the need for ports to maximize efficiency by minimizing the time ships spend in ports and facilitating the servicing of larger ships given that there are economies of scale in ship emissions". This is in line with the philosophy of our analysis, where we quantify the gains that could be made if ports were efficient. Cullinane and Cullinane (2019) also recognise that the environmental problems generated by the shipping industry will not be solved by market forces alone, implying that not only regulatory intervention but also cooperation and coordination between the IMO and regional powers are needed.

Our work has identified where inefficiencies exist and the port authorities that serve as benchmarks or models of good practice for their environmentally-inefficient counterparts. The port authorities of Bahía de Algeciras, Gijón, Santa Cruz de Tenerife and Vilagarcía appear as particularly relevant benchmarks of best practice. This is a crucial first step for the implementation of any policy to reduce CO2 emissions, providing useful information for policymakers. The flexibility of the models presented allow analysis of the possibilities of reducing emissions both maintaining overall traffic constant as well as expanding traffic, which may reflect different political preferences.

On a final note, the dataset available has the drawback that we are limited to cross-section analysis. It would be desirable that port authorities world-wide promote in-port shipping emissions measurement in the future on a continual basis, which wold permit a richer panel data analysis. This would in turn permit more information on fleet composition and berthing hours by type of vessel and size to be incorporated into the efficiency models and open the possibility of estimating econometric models to better identify drivers of environmental inefficiency.

References

Acciaro M, Ghiara H, Cusano, MI (2014). Energy management in seaports: a new role for port authorities. *Energy Policy* 71, 4–12.

Chang Y-T (2013). Environmental efficiency of ports: a Data Envelopment Analysis approach. *Maritime Policy & Management* 40(5), 467–478.

Cheon S, Maltz A, Dooley K (2017). The link between economic and environmental performance of the top 10 U.S. ports. *Maritime Policy & Management*, 44 (2), 227-247.

Chin ATH, Low JMW (2010). Port performance in Asia: Does production efficiency imply environmental efficiency? *Transportation Research Part D* 15, 483-488.

Chung Y, Färe R, Grosskopf S (1997). Productivity and undesirable outputs: a directional distance function approach. *Journal of Environmental Management* 51(3), 229–240.

COGEA (2017). Study on differentiated port infrastructure charges to promote environmentally friendly maritime transport activities and sustainable transportation. Retrieved from https://ec.europa.eu/transport/modes/maritime/news/2017-06-27-study-differentiated-port-infrastructure-charges-promote_en.

Cooper WW, Seiford LM, Tone K (2007) *Data envelopment analysis: a comprehensive text with models, applications, references and DEA-solver software*. Springer, New York

Cullinane K, Cullinane S (2019). Policy on Reducing Shipping Emissions: Implications for "Green Ports". In *Green Ports Inland and Seaside Sustainable Transportation Strategies*, Bergqvist R, Monios J (eds). Elsevier.

Deniz C, Kilic A, Civkaroglu G (2010). Estimation of shipping emissions in Candarli gulf, Turkey. *Environmental Monitoring and Assessment* 271, 219-228.

Färe R, Grosskopf S, Noh D-W, Weber W (2005) Characteristics of a polluting technology: theory and practice. *Journal of Econometrics*, 126(2), 469-492.

Habibi M, Rehmatulla N (2009). *Carbon emission policies in the context of the shipping industry*. CASS Business School, City University, London.

Hampf B (2018). Measuring inefficiency in the presence of bad outputs: Does the disposability assumption matter? *Empirical Economics* 54, 101–127.

Haralambides H., Gujar G. (2012). On balancing supply chain efficiency and environmental impacts: An eco-DEA model applied to the dry port sector of India. *Maritime Economics & Logistics* 14(1), 122–137.

He, Y, Liao Z, Huang L (2015). Comprehensive benefit evaluation for port container transportation based on Malmquist index and cluster analysis. 6th International Conference on Electronics, Mechanics, Culture and Medicine (EMCM 2015).

IMO GHG Study, (2014). Smith, T.W.P., Jalkanen, J.-P., Anderson, B.A., Corbett, J.J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D.S., Ng, S., Agrawal, A., Winebrake, J.J., Hoen, M., Chesworth, S., Pandey, A. International Maritime Organization (IMO), London, UK.

Jenkins L, Anderson M (2003) A multivariate statistical approach to reducing the number of variables in data envelopment analysis. *European Journal of Operational Research* 147(1), 51–61.

Lee T, Yeo G-T, Thai V (2014). Environmental efficiency analysis of port cities: Slacks-based measure data envelopment analysis approach. *Transport Policy* 33, 82–88.

Liu Q, Lim S-H (2017). Toxic air pollution and container port efficiency in the USA. *Maritime Economics & Logistics* 19, 94–105.

Na J-H, Ji J-H, Choi A-Y (2014). An analysis of the environmental efficiency of Chinese container ports based on CO2 emissions. IFSPA 2014 Conference Proceedings.

Na J-H, Choi A-Y, Ji J, Zhang D (2017). Environmental efficiency analysis of Chinese container ports with CO2 emissions: An inseparable input-output SBM model. *Journal of Transport Geography* 65, 13–24.

Paradi JC, Zhu H (2013). A survey on bank branch efficiency and performance research with data envelopment analysis. *Omega* 41:61–79

Picazo-Tadeo AJ, Beltrán-Esteve M, Gómez-Limón JA (2012). Assessing eco-efficiency with directional distance functions. *European Journal of Operational Research* 220 798–809.

Shin C-H, Jeong D-H (2013). Data envelopment analysis for container terminals considering an undesirable output - focus on Busan port and Kwangyang port. *Journal of Navigation and Port Research*, 37(2), 195-201

Styhre L, Winnes H, Black J, Lee J, Le-Griffin H (2017). Greenhouse gas emissions from ships in ports – Case studies in four continents. *Transportation Research Part D*, 54, 212–224

Sun J, Yuan Y, Yang R, Ji X, Wu J (2017). Performance evaluation of Chinese port enterprises under significant environmental concerns: An extended DEA-based analysis. *Transport Policy* 60, 75–86.

Tichavska, M., & Tovar, B. (2015a). Environmental cost and eco-efficiency from vessel emissions in Las Palmas Port. Transportation Research Part E, 83, 126–140.

Tichavska M, Tovar B (2015b). Port-city exhaust emission model: an application to cruise and ferry operations in Las Palmas port. *Transportation Research Part A: Policy and Practice,* 78, pp. 347-360.

Tichavska M, Tovar B (2017). External costs of vessel emissions at port: A review of the methodological and empirical state of the art. *Transport Reviews*. 37, 3, 383-402.

Tovar B, Wall A (2017). Specialisation, diversification, size and technical efficiency in ports: an empirical analysis using frontier techniques. EJTIR 17(2), 2017, pp.279-303 303.

Tovar B, Wall A (2019). Are larger and more complex port more productive? An analysis of Spanish port authorities. *Transportation Research Part A: Policy and Practice* 121, 265-276.

Zhou Z, Guo X, Wu H, Yu J (2018). Evaluating air quality in China based on daily data: Application of integer data envelopment analysis. *Journal of Cleaner Production* 198, 304-311.