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Internalizing CO_2 emissions in Spanish port efficiency analysis: A stochastic frontier approach with policy insights

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ABSTRACT

Recent regulatory changes have impacted the European Union (EU) maritime sector. This study evaluates the effect of carbon dioxide (CO_2) emissions on the production frontier and Technical Efficiency (TE) of cargo handling services in Spain's 23 largest ports. Using the Material Balance Theorem, we justify the inclusion of CO_2 in a stochastic frontier model. Results show that accounting for emissions increases the weight of quasi-fixed inputs and reduces average inefficiency. These findings suggest that the new EU Maritime regulation (*FuelEU* and ETS) could help to internalize environmental externalities in port operations.

1. Introduction

Maritime transport accounts for more than 80 % of global trade by volume, according to the United Nations Conference on Trade and Development (UNCTAD, 2021). After contracting in 2022, the sector rebounded with 2.4 % growth in 2023 (UNCTAD, 2024). Although maritime shipping is considered the most environmentally efficient mode of transport per tonne of cargo, it remains a significant contributor to global Greenhouse Gas (GHG) emissions, comprising approximately 3 % of the total.

Within the European Union (EU), maritime transport accounts for around 11 % of the transport sector's carbon dioxide (CO_2) emissions and 3–4 % of the EU's overall CO_2 emissions (EU, 2022). In response, the EU introduced the "Fit for 55" legislative package, which includes the *FuelEU* Maritime Regulation (COM/2021/550 final) and the extension of the EU Emissions Trading System (ETS) to the maritime sector. These measures target a 55 % reduction in emissions by 2030 and a 90 % reduction by 2050 relative to 1990 levels, with carbon pricing mechanisms starting from January 2025.

Ports are essential nodes in maritime logistics, and emissions in these areas stem from ships at berth, cargo handling equipment, support vessels, and other activities that rely on fossil fuels. This study focuses on Scope 1 emissions, those generated directly within the port boundaries, capturing both emissions from vessels (regardless of cargo activity) and from land-based operations powered by combustion engines.

Given the growing relevance of environmental concerns, the academic literature analyzing environmental variables has expanded significantly in recent years. However, important gaps remain. Most existing studies model emissions in port areas as an undesirable output and rely on non-parametric approaches. In contrast, this study adopts a parametric approach and conceptualizes CO_2 emissions as a productive-polluting input, following the logic of the Material Balance Theorem (MBT). This methodological choice is consistent with regulatory principles aimed at internalizing environmental costs and provides a novel lens to assess the trade-offs between Technical Efficiency (TE) and environmental performance in port operations. This approach is particularly relevant in the current context, as fossil fuel combustion remains the dominant energy source in maritime logistics, despite the emergence of cleaner alternatives that are not yet widely deployed.

We analyze cargo handling services in the 23 largest Spanish ports from 2016 to 2020, applying Stochastic Frontier Analysis (SFA). The study investigates whether higher CO_2 emissions affect the production frontier and consequently the TE levels. Although higher emissions may reflect operational efficiency gains, they carry substantial environmental costs. This duality highlights the policy relevance of mechanisms like the EU's *FuelEU* Maritime Regulation, which seeks to decouple economic and environmental performance.

The rest of the paper is structured as follows: Section 2 reviews the literature on port emissions and productivity; Section 3 outlines the European maritime environmental regulations; Section 4 presents the methodological framework; Section 5 describes the data; Section 6 reports the empirical results; Section 7 concludes; and Section 8 discusses

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the study's limitations and future research directions.

2. Literature review

The literature on port emissions has expanded considerably in recent years. Several studies have addressed GHG emissions, particularly CO_2, as well as other pollutants harmful to human health and the effects of Emission Control Areas (ECAs) (Saxe and Larsen, 2004; Giuliano and O'Brien, 2007; Corbett et al., 2009; Liao et al., 2010; Tzannatos, 2010; Geerlings and Van Duin, 2011; Chang, 2013; Chang and Wang, 2014; Chang and Park, 2016; Zis and Psaraftis, 2017; Hsu and Huynh, 2023). Although less frequently analyzed, environmental regulations also play a role in firm-level location decisions, with some evidence of relocations to regions with more lenient standards (Eskeland and Harrison, 2003).

The International Maritime Organization (IMO) contributed to formalizing port emission control with the publication of the Port Emissions Toolkit (IMO, 2018a, 2018b), which offered guidance for assessing and managing emissions at both the port and vessel levels. While ports are relatively minor polluters compared to the transport sector as a whole (Acciaro and Wilmsmeier, 2015), they remain critical nodes in the maritime logistics network (Wang et al., 2022). In response, a range of mitigation strategies have been proposed to address climate and public health impacts (Du et al., 2019; Cullinane and Cullinane, 2019; Hoang et al., 2022).

The economics of port operations, especially in terms of productivity and efficiency, have long been central to port research agendas (Notteboom and Verhoeven, 2010; González and Trujillo, 2009), informing infrastructure investment and performance evaluation. However, the need to internalize environmental externalities - such as emissions in port efficiency assessments - has gained traction, especially within the EU regulatory context, which has introduced cost mechanisms for emissions (Benamara et al., 2019). These regulatory measures create a comparative disadvantage for EU ports competing with non-EU ports that are not subject to similar constraints.

In Spain, studies by Villalba and Gemechu (2011), Mateo-Mantecón et al. (2011), and Martínez-Moya et al. (2019) have highlighted the contribution of port-related emissions to environmental degradation and examined the implications of emerging environmental regulations. Despite advances in port production modeling, Rødseth and Paal (2015) note limited integration of environmental variables in efficiency assessments.

Further, Rødseth et al. (2020) applied the MBT to examine the relationship between container throughput and air pollution in Norwegian seaports. Their findings emphasize the challenge of decoupling volume growth from emissions. Additionally, Rødseth (2023) contributed by analyzing noise pollution and abatement costs, thus expanding the scope of environmental efficiency studies.

The most common methods to assess port environmental efficiency are non-parametric, particularly Data Envelopment Analysis (DEA). In East Asia, Chin and Low, (2010)examined 156 origin-destination pairs using DEA with undesirable outputs (NOx, SO_2, CO_2, and PM), finding a significant impact of emissions on efficiency scores. Chang et al. (2013) found that the majority of Chinese provinces operate at less than 50 % of their optimal environmental efficiency. Cui et al. (2023) reached similar conclusions, highlighting systemic inefficiencies in China's transport sector.

Choi et al. (2012) applied a two-step SBM-DEA model to estimate potential CO_2 reductions across China's transport infrastructure and to quantify the hidden costs of emissions. They found average abatement costs of USD 7.2 per tonne of CO_2, underscoring the economic implications of environmental inefficiency. Most recently, Hsu et al. (2024) applied an SBM model to container terminals in Kaohsiung port, finding that including CO_2 as a 'bad output' substantially affects efficiency scores. They conclude that inefficiencies can be mitigated by incorporating slack-based metrics in performance evaluations.

Focusing on container ports, Na et al. (2017) found low levels of environmental efficiency across eight Chinese terminals using a slack-based DEA model, suggesting room for improvement in emissions management. Li et al. (2020, 2023) and Quoc and Quoc (2023) further document wide variations in environmental performance, revealing a need for differentiated policy responses.

A nuanced view of the relationship between environmental and economic efficiency is provided by Chang (2013), who found high eco-efficiency levels even in economically inefficient Korean ports, and Gong et al. (2018), who reported no significant differences between environmental and economic efficiency in a sample of 26 shipping firms. Dong et al. (2019) evaluated the environmental and operational efficiency of ports along the Maritime Silk Road using an SBM-DEA model with balanced weighting of CO_2 emissions and cargo throughput. Their results suggest that their environmental efficiency is lower relative to their operational performance. Similar conclusions were drawn by Lee et al. (2014), who identified three undesirable outputs (SOx, NOx, and CO_2) and found that major ports, such as Singapore, Antwerp, and Shanghai, require further emissions reductions despite achieving operational efficiency.

In Europe, Chang et al. (2017) demonstrated that ports within ECAs recorded 15–18 % higher TE compared to those outside, indicating that stricter regulation may incentivize operational improvements. Castellano et al. (2020) assessed Italian port efficiency using DEA, treating CO_2 as an undesirable output and revealing notable disparities. In Spain, Tovar and Wall (2019) applied DEA with IMO-based CO_2 emission estimates to evaluate 28 ports. They later extended this model to include health costs as additional undesirable outputs (Tovar and Wall, 2022a), adding a public health dimension to port environmental assessments. Quintano et al. (2020) compared 24 EU ports using a two-stage SBM-DEA model and identified the main drivers of efficiency. Their results confirm that incorporating GHG emissions into performance assessments is methodologically viable and consistent.

A smaller group of studies has employed parametric or semi-parametric methods. For example, Durán et al. (2024) applied a stochastic cost frontier to develop a method for estimating CO_2 emissions. Similarly, Yu et al. (2022) investigated port carbon emissions (using it as an unexpected output) and influencing factors in China, offering insight into sector-level mitigation strategies. Ding and Choi (2024) examined the impact of port total factor productivity on CO_2 emissions in port cities along the Yangtze River. Li et al. (2024) employed time-series modeling to study the relationship between port congestion and emissions across four major Chinese ports, finding that emissions initially decrease with congestion but rise over time, particularly in large hubs, such as Shanghai and Ningbo.

Table 1 summarizes key contributions from the literature, focusing on methodology, emissions modeling, and main empirical findings.

Beyond the port sector, studies in the broader transportation literature have applied stochastic frontier methods to evaluate environmental efficiency. Llorca et al. (2023), for instance, apply an SFA model to estimate energy demand and efficiency in the Latin American and Caribbean transport sectors, highlighting the applicability of frontier models to energy and emission assessments.

Although several studies have advanced the empirical analysis of port emissions using parametric methods, most continue to model emissions as undesirable outputs rather than as production factors. Unlike these previous approaches, this study incorporates CO_2 as a polluting input, following the MBT within a parametric frontier framework. This modeling choice provides a complementary perspective to traditional eco-efficiency metrics by capturing the direct impact of emissions on the production frontier.

Moreover, this approach is consistent with the rationale behind emerging environmental regulations, particularly in the EU, where emission pricing and decarbonization targets are reshaping how the port sector measures efficiency. By internalizing CO_2 as a cost-generating input, our model provides empirical evidence that supports the regulatory objective of decoupling operational performance from

Table 1
Overview of representative literature on port emissions and efficiency.

Study	Methodology	Emissions variable	Main findings	Region
Chin and Low (2010)	DEA	NO_X, SO_2, CO_2, PM	Environmental impacts of emissions significantly affect efficiency	East Asia
Choi et al. (2012)	SBM-DEA	CO_2	China's average abatement cost of emissions is $7.2/tonne	China
Chang et al. (2013)	DEA	CO_2	Significant eco-inefficiency in China's transportation sector	China
Lee et al. (2014)	SBM-DEA	NOx, SOx, CO_2	Major hubs like Singapore and Antwerp still need CO2 reductions	Global
Na et al. (2017)	SBM-DEA	CO_2	Low environmental efficiency in Chinese container ports	China
Gong et al. (2018)	DEA	CO_2	No significant difference between environmental and economic efficiency	East Asia
Tovar and Wall (2019)	DEA	CO_2	Environmental efficiency of Spanish ports assessed	Spain
Dong et al. (2019)	SBM-DEA	CO_2	Ports on the Maritime Silk Road show lower environmental than operational efficiency	Asia-Europe
Quintano et al. (2020)	SBM-DEA and SFA	GHG	GHG inclusion is feasible and consistent with DEA/SFA approaches	Europe
Castellano et al. (2020)	DEA	CO_2	Disparities in economic and environmental efficiency across ports	Italy
Li et al. (2020)	Meta-frontier non-radial directional distance function	CO_2	Wide variation in environmental efficiency among Chinese ports	China
Durán et al. (2024)	Stochastic Cost Frontier	CO_2	The CO_2 levels can be estimated using operational variables without the need for complete CO2 traceability throughout the logistics chain	Chilean and Mexican ports
Yu et al. (2022)	Global Malmquist Luenberger, Stochastic Regression and Multiple Linear Regression	Carbon Emission Factors	Port carbon emissions have a strong connection with port throughput, productivity, containerization, and intermodal transshipment.	China
Li et al. (2023)	DEA and Malmquist-Luenberger Model	CO_2	Mixed progress in achieving environmental efficiency	China
Cui et al. (2023)	DEA	CO_2	Significant eco-inefficiency in China's logistics and transportation sector	China
Quoc and Quoc (2023)	SBM-DEA	CO_2	Only 28.6 % of the operators achieve full efficiency; inefficient operators waste significant resources	Vietnam
Cui et al. (2023)	DEA	CO_2	Significant eco-inefficiency in China's logistics and transportation sector	China
Ding and Choi (2024)	Ship Traffic Emission Assessment Model	CO_2	Positive correlation between the improvement of port TFP and the increase in CO_2 emissions in port cities	China
Li et al. (2024)	Time Series Analysis	CO_2,	Port congestion initially decreases emissions but increases them over time, especially in large ports	China
Hsu et al. (2024)	SBM-DEA	CO_2	Slack-based metrics affect container terminal efficiency	Taiwan

Source: Own elaboration.

environmental harm, as envisioned by instruments such as the *FuelEU* Maritime Regulation and the extension of the EU ETS to maritime transport.

3. Environmental regulation and the FuelEU maritime framework

The maritime sector plays a vital role in the European economy, accounting for 60 % of exports and 85 % of imports (Puertos del Estado, 2023). However, it is also responsible for 13.5 % of EU transport-related emissions, underscoring the pressing need for effective environmental regulation. According to the Global Carbon Project (2022), global CO_2 emissions reached 40.6 billion tonnes in 2022, highlighting the need to address emissions from maritime transport as part of broader climate mitigation efforts.

In recent years, the EU has assumed a leadership role in establishing environmental standards for the maritime industry. Building on earlier frameworks, such as the MARPOL Convention (IMO, 1973), the EU first introduced the ETS and, more recently, adopted the *FuelEU* Maritime Regulation, a major step towards decarbonizing maritime transport. The regulation targets the energy used by ships, which promotes the uptake of sustainable energy sources. As said, this aligns with the EU's climate commitments under the Paris Agreement (UNCTAD, 2015) and seeks to reduce GHG emissions from ships at EU ports by 55 % by 2030, relative to 1990 levels (EU, 2022). As a cornerstone of the EU's climate policy, the regulation aims to ensure both fairness and consistency across the maritime sector.

A crucial element of the regulation is the imposition of mandatory GHG emission limits for ships calling at EU ports, including both docked and outbound vessels. Ships are required to use shore-side electricity or adopt zero-emission technologies while berthed, thereby reducing emissions during port stays and fostering the integration of renewable energy and low-carbon technologies. These provisions are aligned with the EU's overarching objective of achieving climate neutrality by 2050.

The regulation emphasizes operational efficiency while mandating emission reductions. Notably, it applies to ships with a gross tonnage of over 5,000, which account for nearly 90 % of the sector's CO_2 emissions.

Additionally, it includes safeguards to prevent port evasion and potential relocation of maritime operations to jurisdictions with less stringent regulations.

To ensure compliance, the regulation establishes a rigorous and transparent Monitoring, Reporting, and Verification (MRV) framework. Responsibility for compliance falls on shipowners or other operating entities, while verification is delegated to independent and accredited bodies. Ships that fail to comply are subject to *FuelEU* penalties, which are calculated based on electricity prices, total energy consumption, and the duration of non-compliance during port calls. Revenues collected from these penalties are earmarked for reinvestment in initiatives promoting the adoption of renewable fuels in the maritime sector.

An additional feature of the regulation is the inclusion of a reimbursement mechanism that allows purchasing bodies to compensate companies in cases where non-compliance results from circumstances beyond their control. This provision aims to ensure the proportionality and fairness of enforcement, preventing undue penalties for factors outside an operator's sphere of influence.

Beyond emissions reduction, the regulation seeks to stimulate innovation and technological development within the maritime industry. By encouraging the uptake of zero-emission technologies and the transition to clean fuels, it supports the EU's broader climate strategy to achieve net-zero emissions by mid-century.

This regulatory framework highlights the urgent need to reassess how GHG emissions are managed within the operational reality of port systems, particularly given that the industry has yet to meet its environmental performance goals. Since emissions are intrinsically linked to the combustion processes required for loading and unloading goods, they represent an operational cost that should be internalized in the production function of the terminal. Although emissions are primarily generated by ships, the recent EU regulation will enable the transfer of these costs to the shipping companies, who will bear the financial burden of the environmental fees established by the regulation.

4. Methodology

This section introduces the methodological approach adopted in the study. The objective is to examine how CO_2 emissions externalities affect the production frontier, and consequently, the levels of TE across Spanish ports. To that end, we apply a parametric SFA framework in which emissions are treated as a productive–polluting input, in line with the logic of the MBT. The following subsections present the theoretical foundations of this approach and detail the model specification used to estimate port efficiency under environmental constraints.

4.1. Modeling port emission externalities

Economic production processes often generate effects that extend beyond firms' boundaries, influencing third parties without being mediated through market prices. These effects are referred to as 'externalities', which are uncompensated costs or benefits that arise as by-products of production or consumption (Baumol and Oates, 1988). When negative, externalities impose societal costs that the producer does not bear unless they are internalized through regulatory or market-based mechanisms.

Many externalities arise during port operations, which are stochastic in nature. To date, conventional production models of port activity have not adequately captured this form of joint production. However, the use of the MBT should have the potential to capture this reality, as it allows for the employment of other models drawn from the agricultural economics literature on production risk (Färe et al., 1989).

Externalities are most commonly modeled as weakly disposable outputs in most analyses of port production, where both desirable outputs and undesirable by-products, such as pollutants, are generated. However, this method has been criticized because of its failure to adhere to the MBT. The MBT, grounded in the Law of Conservation of Mass, states that the mass of material inputs must equal that of the outputs, including both desired products and any residual by-products, such as emissions. This requirement highlights that pollutants are an inevitable consequence of the material inputs in production processes (Coelli et al., 2007).

Consequently, several physical approaches have been proposed to ensure consistency between a production model and the MBT. These include the multi-wave production method (Førsund, 2009), which focuses on the sequential nature of the production process, allowing for modeling emissions and other outputs as they evolve through different stages of production. The 'cost function' approach (Coelli et al., 2007) involves modeling the production process by incorporating the costs associated with undesirable outputs, such as pollutants. The concept of weak G-availability (Hampf and Rødseth, 2015) refers to the flexibility in resource availability when accounting for undesirable outputs. It extends traditional notions of resource availability to include considerations of emissions and other by-products.

There are two distinct approaches to modeling emissions. The first specifies an explicit emission function, where emissions are treated as a by-product of the production process. These models illustrate the number of emissions based on the intended output level, focusing on how emissions arise from production activities.

The second defines a production function where emissions are considered as inputs for producing a desired output (Lauwers, 2009). This approach highlights that efforts to reduce pollution often involve reallocating inputs towards abatement activities, which can lead to decreased production (Cropper and Oates, 1992).

The physical approaches (multi-wave production, cost function, and weak G-availability) and the emission modeling approaches (explicit emission function and emissions as inputs) are complementary. The former integrates MBT principles into production models, while the latter considers how emissions are treated within the production process. Both approaches contribute to a comprehensive understanding of emissions management in the context of MBT.

In this study, we employ the second approach, in which emissions are incorporated into the production function. We rely on an adaptation of MBT's microeconomic approach, which allows us to account for the impact of emissions on production efficiency and output levels.

Exploring the framework in greater depth, the use of natural resources is inherent in every industrial process, whose outputs can be divided into two categories: desired (which are the primary goal) and undesired (such as by-products or waste). According to the law of conservation of mass, the mass of the materials entering the process must equal the mass of the outputs, whether desired or not:

$$M = Y + E \tag{1}$$

Here, M represents the material inputs, Y represents the desired outputs, and E represents the undesirable outputs.

Baumgärtner et al. (2001) assert that an incremental unit of material input cannot possibly be entirely transformed into the intended output: a certain residual will inevitably persist. Consequently, the derivative of E with respect to M will always be positive. Thus, for a port, an increase in productive activity always implies an increase in emissions (in our case, CO_2).

Production processes include not only material inputs but also a nonmaterial input, X, such as labour, capital, or energy. It can be posited that additional nonmaterial inputs may lead to improved utilization of a given quantity of material inputs; that is, when a specific quantity of material inputs is used, a more desired output can be achieved.

We can describe the technology by a production function

$$Y = F(M, X), \tag{2}$$

where $F(.)$ is supposed to have the standard properties of a production function:

$F(M, X)$ is twice continuously differentiable on R_+^2 (3a)

$F(0, X) = 0$ (3b)

For every $Y > 0$ there is (M, X) such that $Y = F(M, X)$ (3c)

$0 < F_M(.) < 1$ and $0 < F_E(.)$ For $(M, X) \gg 0$ (3d)

$F(.)$ is strictly concave in (M, X) (3e)

According to the MBT, the undesirable output is determined by $E = M - Y = M - F(M,X)$. To introduce E modeled as an input, the following expression is proposed: $Y = F(Y + E, X)$, by replacing M (normally unobserved). Now the output function can be interpreted as an implicit function of E and N, called G:

$$Y = G(E, X) \tag{4}$$

Following Ebert and Welsch (2007), we can prove that $G(E, X)$ is defined on R_+^2 and has the usual properties of a production function, analogous to (3a) - (3e). Furthermore, it has positive and decreasing marginal products and is strictly concave.

We will apply this framework to our specific case, the analysis of the port industry, considering that one desirable output is proxied by the cargo movement (Y). The nonmaterial inputs are the terminal workers and infrastructure (expressed in a vector X). Finally, the tonnes of CO_2 emitted in the port area serve as a proxy for port emissions (E).

4.2. Stochastic production frontier

Our method is based on a parametric approach, with an estimation of the stochastic frontier advanced by Aigner et al. (1977) and Meeusen and Van Den Broeck (1977). The production function of the Random Effect Panel Data Model is that proposed by Battese and Coelli (1995).

$$Y_{it} = exp(X_{it}\beta + V_{it} - U_{it}) \tag{5}$$

where Y_{it} is the output at the time of the t-th observation for the i-th port, X_{it} is a $(1 \times k)$ vector of inputs and port emissions associated with the i-th port and t-th observation, β is a $(1 \times k)$ vector of parameters to be estimated, and V_{it} are assumed to be iid $N(0, \vartheta^2)$ random errors. The U_{it} are non-negative random variables associated with the technical inefficiency of production, which are assumed to be independently distributed following the same structure:

$$U_{it} = z_{it}\delta + W_{it} \tag{6}$$

$$W_{it} \sim N^+(0, \vartheta^2) \tag{7}$$

To identify and explain the inefficiency term (U_{it}), we allow it to be a function of a $(1 \times m)$ vector of explanatory z_{it} and a δ $(m \times 1)$ vector of unknown coefficients. The term W_{it} follows a truncation of the normal distribution, with zero mean and variance ϑ^2, of which the cut-off point is $-z_{it}\delta$.

The TE for the i-th port at the t-th observation is defined as $exp(-U_{it}) = exp(-z_{it}\delta - W_{it})$.

The empirical models estimated are output-oriented. This orientation has been chosen since it is assumed that ports can influence the level of merchandise using supply and demand policies. However, the decision on the expansion or reduction of an input is usually more limited, as in this industry, even labour input is quasi-fixed. Thus, it is assumed that a port operator starts from a given level of input and seeks to produce more output (González and Trujillo, 2009).

To make a proper assessment of the emission variable in the production and efficiency analysis, two productions will be estimated. The first, Eq. (8), is what we refer to as the traditional model, which does not consider CO_2 emissions. The second, Eq. (9), includes the CO_2 emissions as a regressor of the production function, justified by MBT.

The present study adopts a translog specification to represent the technology of cargo-handling services in ports. The parameters of the stochastic frontier and the associated inefficiency effects are estimated simultaneously using Maximum Likelihood Estimation. This flexible functional form allows for variable substitution and scale effects, providing a robust and normatively consistent framework for evaluating port performance.

Production Functions

$$ln\ Y_{it} = \beta_0 + \sum_{m=1}^{M} \beta_m lnX_{mit} + \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M} \beta_{mn} lnX_{mit} lnX_{nit} + \sum_{t=1}^{T} \varphi_t f_t + \delta_c C_{it} + v_{it} - U_{it} \tag{8}$$

$$ln\ Y_{it} = \beta_0 + \sum_{m=1}^{M} \beta_m lnX_{mit} + \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M} \beta_{mn} lnX_{mit} lnX_{nit} + \gamma_0\ ln\ E_{it} + \gamma_1\ ln\ E_{it}^2 + \sum_{m=1}^{M} \gamma_m lnE_{it} lnX_{mit} + \sum_{t=1}^{T} \varphi_t f_t + \delta_c C_{it} + v_{it} - U_{it} \tag{9}$$

Inefficiency Function

$$U_{it} = \delta_0 + \delta_1 lnH_{it} + \delta_3 T_t + W_{it} \tag{10}$$

- Y_{it} is the output of port i at time t (total cargo, in tonnes)
- X_{mit} m-th is the input variable of port i at time t (e.g., area, cranes, draught, labour)
- E_{it} is the CO_2 emissions of port i at time t (in tonnes)
- C_{it} is the control variable – intensity of crane usage in port i at time t (Bird index)
- H_{it} is the inefficiency variable – Port Liner Shipping Connectivity Index (PLSCI)
- f_t is the year-specific fixed effects (temporal dummies)
- T_t is the time trend variable
- v_{it} is the statistical noise
- U_{it} is the one-sided inefficiency component
- W_{it} is the random component of the inefficiency model

The double summation in both models captures interaction effects between inputs, allowing us to estimate cross-partial elasticities and test for variable complementarity or substitution, which is standard in translog specifications.

5. Data

Spain has the longest coastline in the EU, so the port industry is highly developed. The country has a total of 46 ports managed by 28 Port Authorities (PAs), which report to the Ministry of Transport, Communications and Urban Environment Program through the central entity: *Puertos del Estado* (Puertos del Estado, 2023).

The National Port System (NPS) handles 60 % of Spain's exports and 85 % of its imports. Moreover, 53 % of Spain's trade is with other EU countries. Within the transportation sector, the NPS accounts for 20 % of GDP (Puertos del Estado, 2023). A number of Spanish ports consistently rank among the top 10 in Europe in terms of cargo volume, including those of Barcelona, Bahía de Algeciras, and Valencia (Eurostat, 2024).

To assess the port TE of its cargo handling service, a data panel is available, including 23 PAs, covering the largest ports in terms of cargo movement between 2016 and 2020. Ports were excluded from the sample if they were deemed too small or lacked sufficient available data.

The data set includes the ports of A Coruña, Alicante, Almería, Bahía de Algeciras, Bahía de Cádiz, Barcelona, Bilbao, Cartagena, Castellón, Ferrol, Gijón, Huelva, Las Palmas, Marín, Málaga, Palma, Santa Cruz de Tenerife, Santander, Sevilla, Tarragona, Valencia, Vigo, and Villagarcía de Arousa.

Before outlining the variables included in the analysis, it is important to emphasize that their selection is neither subjective nor arbitrary but rather follows a systematic framework grounded in the theoretical and empirical literature on port efficiency. Numerous studies, both parametric and non-parametric, have analyzed the productivity and performance of ports using a variety of input-output configurations, depending on the service under study (see González and Trujillo, 2009). In the Spanish context, a large body of research has developed precise criteria for variable selection, distinguishing between studies focused on cargo handling services (Coto-Millán et al., 2000; Núñez-Sánchez and Coto-Millán, 2012; Pérez et al., 2020, among others) and those centred on infrastructure provision and overall port performance (Baños-Pino et al., 1999; González and Trujillo, 2008; Rodríguez-Álvarez et al., 2011; Rodríguez-Álvarez and Tovar, 2012, among others). These national contributions are consistent with the international benchmark frameworks proposed by Cullinane et al. (2004, 2006), which have become standard references for variable selection in port efficiency studies. Based on this combined literature, the present study adopts an established and replicable set of variables, including cargo throughput as the primary output and capital, labour, and emissions as key inputs, aligning with best practices in the field.

The data panel was primarily constructed using the PAs' Annual Reports, which are published on the official website of *Puertos del Estado*. In certain specific cases, data were obtained directly from the statistical departments of the respective PAs. Additionally, information from IHS Markit, UNCTAD, the OPS Master Plan of Spanish Ports,[1] and Activity Reports on State Stevedoring Companies was also employed.

5.1. Output variable

The output variable (Y) represents the total quantity of solid bulk, general containerized cargo, and general non-containerized cargo, measured in tonnes. Liquid bulk is excluded from this specification due to its distinct handling requirements. For example, the management of liquid bulk does not require cranes, stevedores, or similar resources typically needed for handling other cargo at terminals.

The average cargo throughput from 2016 to 2020 varies greatly from port to port. Bahía de Algeciras leads with an average total cargo of approximately 101 million tonnes. Valencia and Barcelona follow with averages of 69.9 million tonnes and 59.6 million tonnes, respectively.

Some ports, such as Santa Cruz de Tenerife and Villagarcía de Arousa, handle considerably smaller volumes, at 10.6 million tonnes and 1.2 million tonnes, respectively. This variation reflects the diverse capacities and specializations of Spanish ports, with major ports focusing on substantial cargo handling, while others cater to more specialized or regional needs.

5.2. Port emission variable

To better explain the different types of emissions generated in the port maritime sector, Figure A.1 shows that the emissions fall into two distinct categories (Cortez-Huerta et al., 2024; Shu et al., 2023; Mocerino et al., 2023; Fan et al., 2023; Barberi et al., 2021).

- On the one hand, emissions generate Air Pollution (AP) and can have a direct impact on health. This group includes Sulphur Oxides (SOx), Nitrogen, Carbon Oxide (CO), volatile organic compounds other than methane (NMVOCs), and particles with a diameter of less than 10 μm, denoted as PM10. Within the PM10 fraction, the smallest particles are <2.5 μm (PM2.5).
- On the other hand, GHG emissions include Carbon Dioxide (CO_2), Methane (CH4), Nitrous oxide (N2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulphur hexafluoride (SF6), with CO_2 being the most significant contributor. Furthermore, in most cases, GHG emissions are expressed in units of CO_2 (known as 'CO_2 equivalent').

For this analysis, pure (not equivalent) CO_2 emissions (E) generated within the port area, measured in tonnes, have been considered (Scope 1 emissions).[2] The data for this variable were calculated and published as part of the Onshore Power Supply (OPS) Master Plan (2021) and have been used without further modification. These emissions primarily come from all types of vessels berthed at the port, accounting for over 95 % of total port emissions. However, the emission variable also includes residual CO_2 emissions from various port operations, such as transport movements and the use of machinery.

The methodology for estimating CO_2 emissions is based on the IMO's guidelines, as outlined in the Third IMO GHG Study 2014 (IMO, 2015). The CO_2 emissions are calculated using vessel-specific data such as the time each vessel remains moored in the port (measured in annual hours), vessel size (which varies based on fleet type), and the type of vessel (to estimate the power of the auxiliary engines). These inputs enable a tailored calculation that reflects the unique characteristics of each vessel.

To measure emissions, the following equation is used:

$$E_i = AE \times t \times FE_i \tag{11}$$

The term E_i represents the emission of contaminant i (in this case, CO_2) expressed in tonnes. AE refers to the power of auxiliary engines (in kilowatts), which varies by vessel type, and t is the time in hours that the vessel remains moored. FE_i denotes the emission factor, indicating the amount of contaminant i emitted per kilowatt-hour (t/kWh). The emission factor (FE_i) is derived from established datasets, such as those provided by the IMO and other relevant environmental agencies, ensuring that the calculated values accurately reflect actual emissions.

Table 2 presents the average CO_2 emissions for the top 10 most polluted ports in the sample from 2016 to 2020, both in total emissions (in tonnes) and in emissions per tonne of cargo handled. These data facilitate a comparison not only in terms of overall emissions but also relative to the amount of cargo processed. For example, Barcelona shows the highest average CO_2 emissions (92,945.04 tonnes), followed by the port of Valencia (60,294.29 tonnes). However, when considering CO_2 emissions relative to the amount of cargo handled, Barcelona ranks sixth (0.001563 tonnes of CO_2 per tonne of cargo), showing that despite its

Table 2
Average CO_2 emissions in the 10 most polluted ports (2016–2020).

Port	Average CO_2 emissions in tonnes	Average intensity of CO_2 emissions per cargo
Barcelona	92,945.04	0.001563 (6th)
Valencia	60,294.29	0.000864 (8th)
Las Palmas	55,483.61	0.002808 (4th)
Bahía de Algeciras	51,243.32	0.000508 (10th)
Palma	38,226.79	0.004018 (3rd)
Bilbao	28,943.94	0.000868 (7th)
Santa Cruz de Tenerife	26,122.89	0.002552 (5th)
Tarragona	24,036.57	0.000773 (9th)
Bahía de Cádiz	20,909.51	0.005219 (2nd)
Málaga	16,782.69	0.005584 (1st)

Source: Own elaboration.

[1] Official OPS Master Plan Project website: http://poweratberth.eu/?lang=es.

[2] Scope 1 emissions are defined by the GHG Protocol (WRI and WBCSD, 2004) as direct emissions from sources that are owned or controlled by an organization, such as fuel combustion in vehicles, vessels or equipment operated within the port area.

high absolute emissions, its emissions intensity is lower than that of other ports. In contrast, smaller ports like Málaga (16,782.69 tonnes) and Bahía de Cádiz (20,909.51 tonnes) rank first and second, respectively, in CO_2 emissions per tonne of cargo, with intensities of 0.005584 and 0.005219 tonnes, significantly higher than those of larger ports.

In this context, Spain ranked second among European countries for port-related CO_2 emissions in 2018, contributing 16.3 million tonnes, according to Transport & Environment (2022). Furthermore, three Spanish ports—Algeciras, Valencia, and Barcelona—were among the top 10 European ports with the highest CO_2 emissions that year, recording 3.3, 2.7, and 2.8 million tonnes, respectively.

5.3. Input variables

5.3.1. Infrastructure variables (fixed variables)

The terminal's infrastructure is represented by the total area of the port in square metres (X_1), which includes the length of the quay and the storage area. Alongside this, other key infrastructure variables considered are the maximum draught (X_3) measured in metres. All these variables are treated as fixed, as no infrastructural expansions occurred during the period analyzed.

5.3.2. Capital and labour variables (quasi-fixed variables)

Cranes (X_2) are one of the most controversial variables that measure port terminal capital. These variables require special consideration, as all cranes are not equal (Cullinane et al., 2005; Cheon et al., 2010; Yip et al., 2011; Bichou, 2013; Yuen et al., 2013; Pérez et al., 2020). This study has distinguished between two types of cranes: gantry cranes, measured by an index of total capacity in tonnes, and container cranes.[3]

The labour variable (X_4) is measured as the number of 'stevedore person-days', i.e., the total number of individual working days performed by stevedores at each port over the reference year. This approach is consistent with Pérez et al. (2020), who use the number of port stevedores as a direct labour input in their SFA of Spanish cargo-handling efficiency, highlighting the relevance and scarcity of such data in port studies.

In Spain, cargo can only be moved by stevedores, who work under the Port Workers' Organization, which is independent of the Ministry of Labour. Over the years, the labour market has seen an increase in the number of stevedores, and their wage demands are often met, regardless of productivity. The combination of these factors explains the reality in which the Spanish stevedoring industry operates, characterized by significant barriers to market entry, lack of transparency, and, consequently, a significant reduction in the competitiveness of Spanish ports (Díaz-Hernández et al., 2012).

In 2010, Law 33/2010 was enacted, which introduced a new management model for private company workers in ports. The role of PAs was limited to supervising the work (Gobierno de España, 2010). As a result, private companies, now responsible for stevedoring, do not provide transparent and straightforward data on their stevedores, due to data protection principles and internal regulations.

The data on stevedores is highly debated in Spain's port industry, not only due to this activity's regulatory context but also because of the complexity of obtaining reliable data (Arrillaga Canedo, 2022). This difficulty arises because no single administrative body manages and consolidates these data or makes them publicly available, particularly over extended periods of time. The literature notes that this issue is also prevalent in other countries with similar regulatory frameworks. For example, Rødseth and Wangsness (2015) report that obtaining consistent and updated data on labour, capital, and energy consumption in Norwegian ports is particularly difficult due to fragmentation across institutions and the high resource demands of data collection efforts.

Traditionally, the study of cargo handling services often assumes a fixed relationship between the actual number of stevedores at a terminal and the number of cranes, sometimes specifying their features (Cullinane et al., 2004). In our study, we prioritized selecting the most appropriate variables for assessing port efficiency and successfully acquired the necessary data on the stevedores, further enhancing the robustness of our analysis.

5.4. Control variable

Furthermore, a control variable (C)[4] is introduced to account for crane deployment intensity at the port level, using the Bird Index proposed by Frémont and Soppé (2007). This index quantifies the extent to which a port is specialized in certain types of cranes, both internally (relative to other crane types within the same port) and externally (relative to the crane configuration in the entire sample of ports in the NPS).

The decision to incorporate this into the model stems from the inherently complex nature of cranes. As a quasi-fixed variable, crane-related returns to scale can become negative in some segments of the production frontier. However, due to the high specialization observed in Spanish ports, this effect may not be uniformly negative,[5] which necessitates the inclusion of control variables that position each port relative to the entire sample in terms of crane usage. Thus, while an overall increase in cranes might have a marginally negative impact, the addition of specific cranes tailored to the port's specialized cargo could be positive.

The numerator of the Bird Index measures the relative share of a specific type of crane in the total operations of a particular port, and the denominator assesses the relative importance of that type of crane within the entire port system. Index values greater than 100 indicate a higher specialization than the overall system. The higher the value, the greater the specialization.

5.5. Inefficiency variable

As several studies have emphasized, it is essential to consider port connectivity when evaluating port efficiency. The most well-known and widely used connectivity indicators are those developed by UNCTAD. The first of these was the Liner Shipping Connectivity Index (LSCI), introduced in 2004, which measures a country's integration into global liner shipping networks and monitors its evolution over time through a gravity-model-based approach (Fugazza and Hoffmann, 2017).

Connectivity indices can help assess the efficacy of investments made to improve ports in accomplishing their desired goals (Martínez-Moya and Feo-Valero, 2020). The primary aim of connectivity indices is to identify the relevant characteristics of ports that are crucial for evaluating the level of their connectivity. Martinez-Moya et al. (2024) provide a comprehensive collection of connection indices, outlining their key features. Beyond capacity, these factors encompass a wide range of additional variables, such as the frequency and number of shipping lines.

The significance of using connectivity as a variable in productivity and efficiency research arises from the recognition of ports as pivotal junctions between sea and land, with intermodal and supply chain issues

[3] Applying a coefficient of each kind of crane provided by sector experts produces a final unique variable that has been developed to capture the complex reality of cranes.

[4] Control variables are used to isolate the effect of the key explanatory variables by holding constant other factors that could confound the results. By incorporating these variables, the model aims to provide a more accurate estimation of the relationship between the input and output variables, ensuring that the observed effects are not biased by omitted variable influences.

[5] Without this control, the production function could reflect negative marginal effects, not due to inefficiency, but to the presence of diseconomies of scale at certain levels of crane usage.

gaining greater prominence (Ducruet, 2020). For this purpose, we utilize the Port Liner Shipping Connectivity Index (PLSCI) as a determinant of inefficiency in our model. The PLSCI, published by UNCTAD in 2019, captures port-level connectivity within global liner shipping networks. Its relevance for efficiency analysis was demonstrated by Tovar and Wall (2022b), who found a positive relationship between PLSCI and TE in Spanish ports. This finding is consistent with previous research that has employed connectivity indicators across a broader range of contexts (Figueiredo De Oliveira and Cariou, 2015; Serebrisky et al., 2016; Suárez-Alemán et al., 2016; Rodríguez et al., 2025a).

Table 3 summarizes all the basic information of the panel database.

6. Results

The estimated production functions meet the expected theoretical requirements. On average, all input variables satisfied the traditional production conditions at the sample mean. The estimation, conducted using Stata17, presents the parameters for both the stochastic frontier model and the technical inefficiency model, as shown in Table 4.

As part of the robustness checks applied during the estimation process and the selection of the final model specification, we estimated alternative stochastic frontier models using different functional forms, including Cobb-Douglas and translog specifications. This approach enables the assessment of the sensitivity of efficiency scores and coefficient estimates to the functional form assumption, as recommended by Kumbhakar and Lovell (2003). Additionally, we assessed the statistical significance and explanatory power of all included variables to ensure the validity and internal consistency of the model.

6.1. Crane variables

For cranes, a negative marginal effect may arise if we consider only the cargo capacity that can be moved. This negative impact of the crane variable indicates that some ports are operating under conditions of excess capacity. This overcapacity situation is further complicated by the high costs associated with adjusting crane capacity, making it significantly more challenging than for other input variables. Consequently, the high adjustment cost suggests that crane capacity may reach a threshold at which a neoclassical production function with a negative slope becomes evident.

Therefore, it is essential to treat crane capacity as a distinct variable due to its unique characteristics and high adjustment costs. By incorporating the intensity variable (Control variable), we can assess how efficiently cranes, as key inputs, are utilized relative to the total port capacity (level of specialization). This approach not only allows us to monitor operational efficiency in relative terms but also evaluates how close the port is to achieving economies of scale.

While a single crane's increase in capacity has a negative direct effect when considered in isolation, the overall marginal effect on crane intensity is positive. This finding relates to the port superstructure; having a specific number of cranes implies that they are being fully utilized (Squires and Segerson, 2020).

6.2. Time effect variables

Regarding the year dummy variables, all are statistically significant in the first model (Eq. (8)). These variables capture time-specific effects that influenced all ports in the sample uniformly during the period 2016–2020, with 2020 serving as the reference category. The coefficients for all previous years are positive, although their magnitudes vary, indicating higher output levels relative to 2020. While the panel structure limits a detailed analysis of the pandemic's progression, the results suggest that the adverse effects associated with the COVID-19 shock had already begun to manifest by 2020 (Liu et al., 2023). The decline in production, therefore, appears to have started in the transition between 2019 and 2020.

6.3. CO_2 emission variable

The CO_2 emission variable included in Eq. (9) aims to identify how port area emissions can be modeled within the context of port production. The first order parameter of CO_2 is positive and statistically significant. Then, we find a positive marginal productivity of CO_2 relative to total cargo at the sample mean, as expected. Moreover, only two of the second-order parameters are statistically non-significant.

On the one hand, the coefficient related to the interaction between CO_2 and port area is −0.34. Then, we find a statistically significant negative relationship between the port area and the marginal productivity of CO_2 relative to total cargo. We observe a similar effect analysing CO_2 and cranes, but in a lower magnitude. On the other hand, there is a positive relationship between port draught and the marginal productivity of CO_2 relative to total cargo. Thus, it can be inferred that a greater port draught is associated with higher marginal productivity of CO_2 relative to total cargo (this may be because larger draughts enable larger vessels to dock). We use an F-test to check the overall significance of the CO_2 parameters. The results show the rejection of the null hypothesis (chi2(6) = 127.82; p = 0.00). Then, test results support the inclusion of CO_2 emission variables in the empirical specification of the port production frontier.

Concern about climate change is currently growing. However, it is a reality that without the emission of CO_2, this industry would not be able to carry out any kind of activity.[6] As explained, CO_2 is an undesirable output of the industry that acts as a polluting input in the production function. In this sense, and as has been empirically tested, it is necessary to think about CO_2 emissions in terms of production, since emission levels are related to the possibility of more ships arriving, more cargo movements in the port, and, in short, more industrial activity.

The elasticity of CO_2 relative to output indicates that if CO_2 increases by 1 %, total cargo will increase by 0.33 %. The challenges for the maritime transport industry come because the new regulation aims to reduce emissions, which puts the port industry at a disadvantage, as it will have to face a new "cost" that it has not borne to date.

6.4. Comparison of the two frontier production function models

The comparison of both models presented in Table 4 demonstrates that the inclusion of CO_2 variables in the empirical specification of the port production frontier alters the magnitude of the relationships between port inputs and port cargo. This effect is apparent for coefficients related to the port area, port draught, or labour. The effect of both the port area and draught on total cargo increases when we consider the CO_2 variables. The opposite result occurs in the case of labour and the intensity of cranes.

We conclude, then, that the inclusion of CO_2 variables tends to give more weight to the port quasi-fixed inputs or port infrastructure to the detriment of the port superstructure and variable inputs.

6.5. Technical efficiency

Turning to technical inefficiency, to make the two models as comparable as possible, the technical inefficiency estimation of both models (with and without CO_2 variables) has been carried out using the variables.

According to Table 4, the variables PLSCI and Trend, which describe inefficiency, were both negative and substantially different from zero. These results indicate that both variables contribute to the explanation of technical inefficiency. A decrease in technical inefficiency is indicated by the negative sign of the parameters as the values of the variables

[6] Note that the CO_2 emission variable is not a linear function of the cargo output variable, as it includes emissions from all types of vessels arriving at a port for various activities, such as repairs or bunkering.

Table 3
Summary statistics of the data.

Variable	Description	Mean	Std. Dev.	Min	P25	Median	P75	Max
Output Variable								
Y [1]	Annual cargo throughput (tonnes)	13,900,000	19,600,000	921,622	3,399,245	6,245,167	12,200,000	75,300,000
Input Variable								
X1 [1]	Port area (m^2)	3,692,954	3,786,686	573,419	1,098,142	2,777,493	4,028,435	17,500,000
X2 [1]	Total crane capacity (tonnes)	1221.43	1734.30	40.00	300.00	803.30	1269.00	8646.00
X3 [2]	Maximum water depth (m)	15.51	4.48	7.20	12.50	15.00	18.00	30.00
X4 [5]	Total working person-days	83,603.32	152,634.50	1473.28	11,213.22	23,132.84	48,382.71	576,710.90
E [3]	Port-level CO_2 emissions (tonnes)	21,665.60	23,572.33	452.50	5385.73	13,302.75	27,143.10	107,050.50
Control Variable								
C [1]	Index of specialized internal cranes	1.00	0.33	0.13	0.82	1.10	1.23	1.44
Inefficiency Variable								
H [4]	Port Liner Shipping Connectivity Index	15.27	18.78	0.70	2.98	6.67	15.66	67.24

Source: Own elaboration based on data from [1] Annual Reports of Spanish Port Authorities (PAs), [2] IHS Markit, [3] OPS Master Plan of Spanish Ports, [4] UNCTAD Database Base, and [5] Activity Reports on State Stevedoring Companies.

Table 4
Estimations of the production functions.

Model (1): Equation 8			Model (2): Equation 9		
Variable	Coeff.	St. Err	Variable	Coeff.	S. Err
Constant	−1.276***	0.28090	Constant	−0.154	0.26084
L(Area)	0.334***	0.05968	L(Area)	0.673***	0.078176
L(Cranes)	−0.316***	0.04318	L(Cranes)	−0.316***	0.05527
L(Draught)	0.211	0.16543	L(Draught)	0.807***	0.10459
L(Labour)	0.377***	0.03209	L(Labour)	0.083*	0.04836
L(Area)*L(Area)	−0.973***	0.15745	L(Area)*L(Area)	−0.131	0.09480
L(Cranes)*L(Cranes)	−0.041	0.04609	L(Cranes)*L(Cranes)	−0.102*	0.06142
L(Draught)*L(Draught)	−4.301***	1.33442	L(Draught)*L(Draught)	−6.613***	0.76733
L(Labour)*L(Labour)	0.580***	0.05922	L(Labour)*L(Labour)	0.038	0.11138
L(Area)*L(Cranes)	−0.355**	0.11450	L(Area)*L(Cranes)	−0.860***	0.07418
L(Area)*L(Draught)	−0.243	0.31839	L(Area)*L(Draught)	−0.495	0.2816
L(Area)*L(Labour)	−0.520***	0.05793	L(Area)*L(Labour)	−0.042***	0.07911
L(Cranes)*L(Draught)	0.256	0.26358	L(Cranes)*L(Draught)	0.071	0.21198
L(Cranes)*L(Labour)	0.111***	0.03084	L(Cranes)*L(Labour)	0.214***	0.05374
L(Draught)*L(Labour)	1.526***	0.34553	L(Draught)*L(Labour)	1.261***	0.34263
Intensity of Cranes	1.638***	0.23548	Intensity of Cranes	0.587***	0.16789
Dummy Year 2016	0.172**	0.05091	Dummy Year 2016	0.124	0.09046
Dummy Year 2017	0.229***	0.05963	Dummy Year 2017	0.097	0.07356
Dummy Year 2018	0.177*	0.07058	Dummy Year 2018	0.131*	0.05798
Dummy Year 2019	0.203**	0.07393	Dummy Year 2019	0.087	0.05216
			L(CO_2)	0.330***	0.04309
			L(CO_2)*L(CO_2)	−0.632	0.10202
			L(CO_2)*L(Area)	−0.339***	0.09715
			L(CO_2)*L(Cranes)	−0.157*	0.06333
			L(CO_2)*L(Draught)	0.712*	0.27779
			L(CO_2)*L(Labour)	0.145	0.08724
Inefficiency model (U)			**Inefficiency model (U)**		
Constant	0.285**	0.15110	Constant	−1.107	2.57464
L(PLCI)	−0.403***	0.07163	L(PLCI)	−0.862	1.04022
Trend	−0.013	0.03682	Trend	−0.289	0.39076
Log likelihood	11.8522		Log likelihood	14.9096	
Obs	115		Obs	115	

*Significant at 1 %.
**Significant at 5 %.
***Significant at 10 %.
Source: Own Elaboration.

increase. The ports' PLSC, as thought, has a beneficial impact by enhancing efficiency. Indeed, when the average port connectivity increases, technical inefficiency decreases.

To clarify the discussion about the models' second stage, efficiency estimates from the model that includes CO_2 in the specification are represented by the notation Environmentally Adjusted Technical Efficiency (EATE), while the term TE is used to refer to efficiency scores estimates derived from the model not considering CO_2 emissions, as in Le et al. (2020). Overall, the estimated levels of efficiency of the two models show significant differences on average. The EATE is 81 % whereas the TE is 67 %. Then, the inclusion of CO_2 emissions in the frontier production function for the Spanish port generates lower levels of technical inefficiency at the mean sample; we found a reduction of 14 %.

There is a positive correlation between EATE and TE, as indicated by a Pearson's correlation coefficient of 0.692 and a Spearman's rank correlation value of 0.668. This finding implies that the port objective of maximizing total cargo (for a given amount of inputs) may not be contradicted by minimizing CO_2 emissions (see Fig. 1).

As shown in Fig. 2, the distribution of TEs across ports reveals significant differences. In some cases, the EATE has a positive impact on port efficiency, while in others it does not. The inclusion of the CO_2

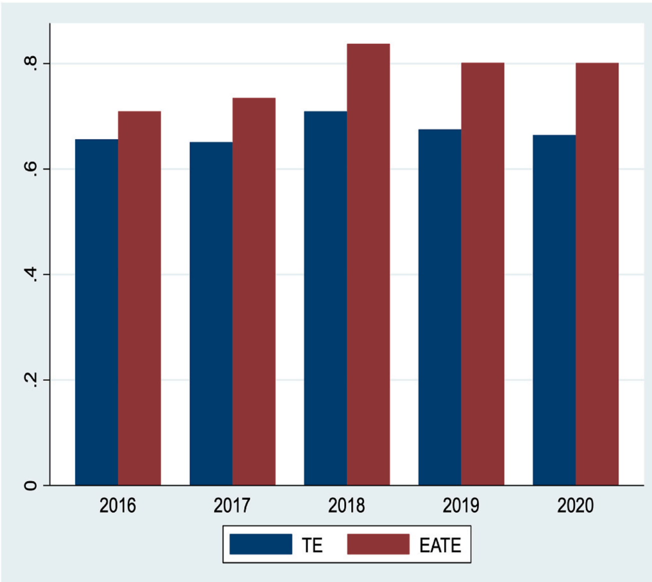

Fig. 1. Mean TE and EATE (2016–2020).
Source: Own Elaboration.

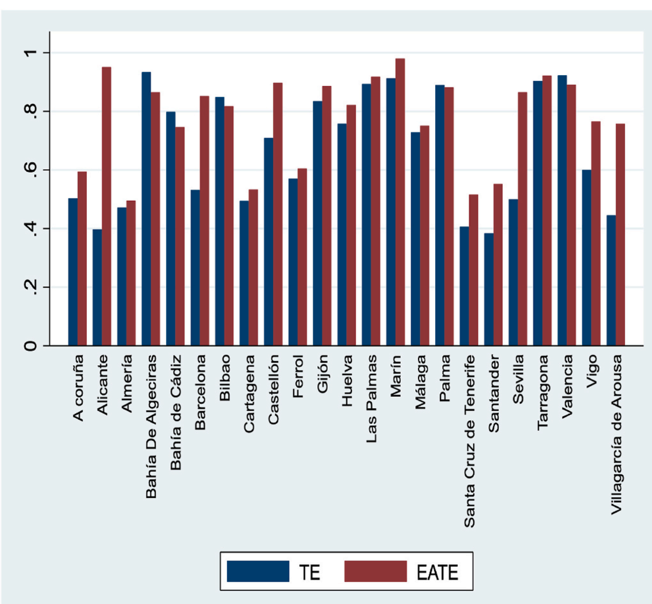

Fig. 2. TE and EATE by port.
Source: Own Elaboration.

variable alters the traditional efficiency ranking of ports without a clear pattern. Generally, larger ports in terms of cargo volume rank higher, which may be explained by the fact that CO_2 emissions in the port area originate not only from cargo-related vessels but also from vessels engaged in complementary activities. These activities are more closely linked to the port's specialization and infrastructure. As a result, a new ranking emerges in which some ports are negatively affected, regardless of their cargo volumes.

While the reason for the negative impact of emissions on some ports remains unclear, these ports can be grouped into two categories. Valencia and the Port of Algeciras, which handle the largest cargo volumes, contrast with Bilbao, Palma, and Bahía de Cádiz, which have smaller volumes and are also affected by CO_2 emissions in their efficiency assessments. These two groups are distinguished by infrastructure size: large ports (in orange) with extensive infrastructure, and smaller ports (in green) with more limited facilities (see Fig. 3).

The analysis supports the considerable concern about emission restrictions in port areas from a classical production perspective. Thus, the treatment of this variable, now more than ever, should be considered in the efficiency analysis, to evaluate not only the TE but also EATE.

7. Conclusions and policy discussion

Although policy interventions in the transport sector often focus on external costs, the economic impact of externalities from port operations has received limited attention. In contrast, the EU's latest environmental policies (EU, 2022) acknowledge the urgent need to internalize the externalities associated with the maritime sector's activities. We examine the trade-offs associated with recognizing CO_2 as a vital energy input within port production frameworks prior to a full transition to clean (or "green") energy. The findings suggest that meaningful policy outcomes are possible.

CO_2 emissions at ports should be understood not only as an environmental concern but also as a functional component of industrial activity. However, in the current regulatory landscape, the effective management of such emissions has become a central policy challenge. The absence of global regulatory harmonization raises concerns about the competitive disadvantage faced by EU ports, potentially prompting relocations to jurisdictions with more lenient environmental standards (Rodríguez et al., 2025b).

To address this, two models have been developed. These demonstrate that emissions are a process-polluting input variable according to the MBT, satisfying the conditions of a positive relation between CO_2 emissions and production output. The analysis reveals a significant difference between EATE (which takes CO_2 into account) and TE (which does not), with empirical evidence indicating that a 1 % increase in CO_2 emissions is associated with a 0.33 % increase in total cargo moved at the port, *ceteris paribus*.

In sum, "the more I pollute, the more I can produce." However, this trade-off between production and environmental cost does not align with society's best interests. Once externalities are internalized, reducing production at a higher cost may prove to be the optimal solution.

We suggest that the objective of efficiency improvements within an industry is to transfer those savings to consumers. However, while the industry may experience efficiency gains, it is not accurate to say that these gains are fully passed on to society, as they come at the expense of producing adverse societal externalities. In other words, ports operate more efficiently under current productive conditions, but at what cost in terms of damage to public health and the climate? (see Fig. 4).

This understanding underscores the significance of the new EU regulation as a mechanism to internalize these externalities. It can be inferred that gains in efficiency obscure their true nature, in that they ought to be considered as including their attendant emissions, a reality that is now revealed by the new regulation and demonstrated in this research. The transmission of efficiency gains to users, in this case, also entails a transfer of emissions, meaning these gains may not be as positive as they initially appear. Ports currently depend on carbon-intensive processes, and any policy aimed at reducing emissions will inevitably alter the cost structures and productivity levels of terminal operators.

Notably, this study contributes to the ongoing policy and academic debate by providing a replicable methodological framework for quantifying the environmental cost embedded in port productive processes. The practical implications not only apply to the implementation of the *FuelEU* Maritime Regulation but also to other initiatives under the EU Green Deal, the ETS, and the emerging green corridors led by frontrunner regions such as the Nordic countries, the Netherlands, and Singapore. These initiatives demonstrate how targeted environmental strategies in maritime transport can be both ambitious and feasible, provided there is policy coordination, public support, and shared

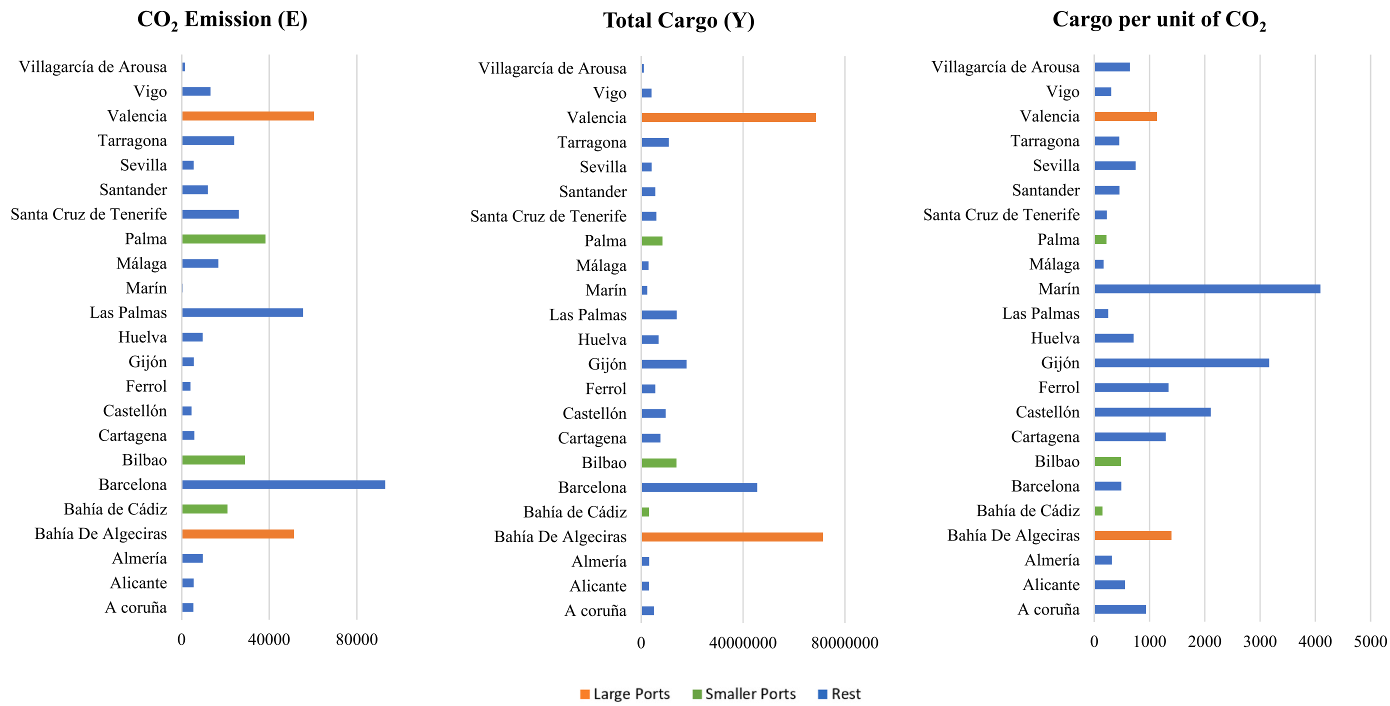

Fig. 3. CO_2 Emissions, Total Cargo, and Cargo per unit of CO_2.
Source: Own Elaboration.

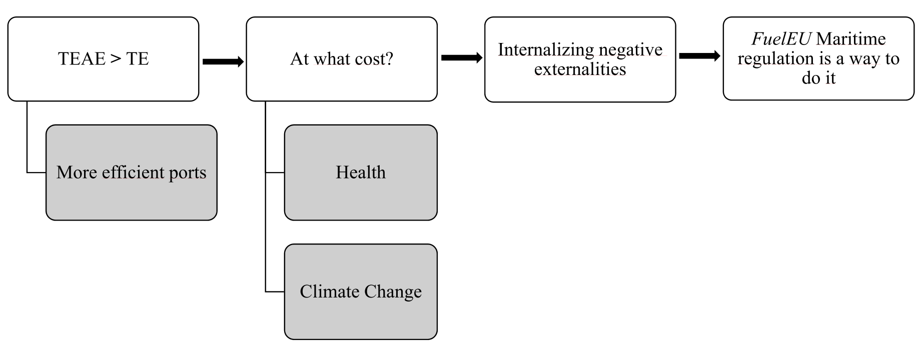

Fig. 4. Key ideas of findings and conclusions.
Source: Own Elaboration.

technological innovation.

From a policy standpoint, our study offers three key insights.

1. **Internalizing externalities through regulation is necessary and should be feasible.** The *FuelEU* Maritime Regulation emerges as a critical policy tool for incorporating the environmental costs of CO_2 emissions into port operations. Our model supports the rationale behind emission-based penalties, as it makes the relationship between emissions and productive capacity explicit. However, this internalization must be accompanied by targeted public support to help ports and port-operating companies adapt to the clean-energy transition. Without this support, there is a risk that the associated costs will be disproportionately transferred to final users, potentially undermining both the social acceptability and economic competitiveness of the regulatory effort.
2. **Efficiency gains must be reassessed in light of environmental costs.** Traditional models that overlook emissions may overstate port efficiency. By introducing the EATE, we demonstrate that "efficient" ports may be those that pollute more, raising serious questions about the actual societal benefits of such gains.
3. **There is an urgent need for international regulatory alignment.** It is important to note that the European Commission has been granted executive powers to ensure consistency in the implementation and ongoing monitoring of this legislation. Given the global nature of the maritime transport industry, we recommend establishing an active partnership among the EU, IMO, and other international organizations. Such collaboration would involve the exchange of key information on the implementation of regulations and working jointly to develop international standards for maritime transport, thereby addressing the global environmental challenge and creating a fair and competitive environment for the port and maritime industries.

Based on the evidence, it could be said that while decarbonizing port operations presents a complex challenge, this study offers an empirical foundation and a clear direction: a transition to greener ports must account for both efficiency and environmental responsibility. Only by integrating emissions into the assessment of port performance and aligning policies at multiple governance levels can the maritime sector become a driver of sustainable economic growth rather than a source of unchecked external costs.

8. Challenges and limitations

Our research is based on a microeconomic model, which considers the Material Balance Theorem (MBT) framework to justify the inclusion of CO_2 emissions as an input. Next, we propose an empirical specification based on a frontier production function that only considers an aggregate output. In our opinion, this proposal might be beneficial in those cases where the units of observation are not detailed or long enough to support a multi-output approach.

This study has several specific limitations, primarily due to the limited availability of CO_2 data for Spanish ports, which restricted the temporal scope of the analysis. Having access to a longer time series would enhance the ability to examine long-run trends, test robustness, and better capture the dynamic effects of regulatory or technological changes over time. Moreover, although the CO_2 emissions data used in this study go beyond main engine propulsion and include all ships calling at the port, whether engaged in cargo operations or not, they also account for auxiliary activities directly related to cargo throughput, such as manoeuvring, berthing, and cargo handling. This approach enhances the relevance of our emissions measure as a port-related input.

However, our analysis still lacks information on other types of port-related environmental pressures, which would be essential for a more holistic assessment of sustainability and environmental efficiency. In particular, it would be valuable to have access to data on.

- Energy consumption (electricity and fossil fuels) from port infrastructure and operations (e.g., lighting systems, reefer plugs, administrative buildings).
- Water consumption and wastewater generation, both from vessels and onshore facilities.
- Solid waste production, including residues from cargo, vessels, and terminal operations.
- Other pollutants such as NO_x, SO_x, and particulate matter (PM), which have important local externalities.
- Emissions from hinterland transportation (road and rail) and port worker commuting.

Broader access to such comprehensive and disaggregated environmental data, ideally with high spatial and temporal resolution, would enable a deeper exploration of sustainability trends and facilitate the estimation of the full environmental footprint of port activity.

Additionally, the rapid evolution of environmental issues presents another challenge: ongoing changes in regulatory frameworks and technological advances complicate efforts to conduct a fully predictive analysis of a CO_2-free production landscape.

A notable statistical challenge concerns the potential endogeneity of the CO_2 variable with cargo output. While the analysis in this paper did not identify significant correlation issues between these variables, indicating no immediate econometric problems, endogeneity might still be a concern. However, as explained above, the CO_2 emissions variable accounts for all ships arriving at the port, regardless of whether they are engaged in cargo unloading or not. Thus, there is no straightforward linear relation between cargo volumes and emissions, as the emissions reflect more than just the ships involved in loading and unloading operations. Nonetheless, it would be valuable for future studies to explore the interdependent patterns and potential causality between emissions and output. The use of advanced econometric techniques, such as instrumental variable models (e.g., Karakaplan, 2022), might offer valuable tools to address this issue.

Consequently, this study focuses on the current role of CO_2, acknowledging that the energy transition is not yet a reality and that CO_2 remains an energy input in production processes. Using the MBT as explained in the methodology section, CO_2 is treated as a polluting input rather than an undesirable output, given its necessity for the production process in the current industrial context. As such, it remains an inherent part of the productive process, and when CO_2 increases, production tends to rise as well. However, as industries transition toward cleaner energy sources, CO_2 may become less relevant as an input. Future research might produce valuable insights through a comparative analysis of scenarios with and without CO_2, addressing questions not fully covered in this study.

CRediT authorship contribution statement

Andrea Rodríguez: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Lourdes Trujillo:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Submission declaration and verification

The work described has not been published previously.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this paper, the author(s) used AI to search for synonyms, find proposed alternative wording for some sentences, and identify possible errors caused by one of the author's dyslexia. After using this tool/service, the authors reviewed and edited the content as necessary and take full responsibility for any errors.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Lourdes Trujillo Castellano reports financial support and administrative support were provided by Canarian Agency for Research Innovation and Information Society. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

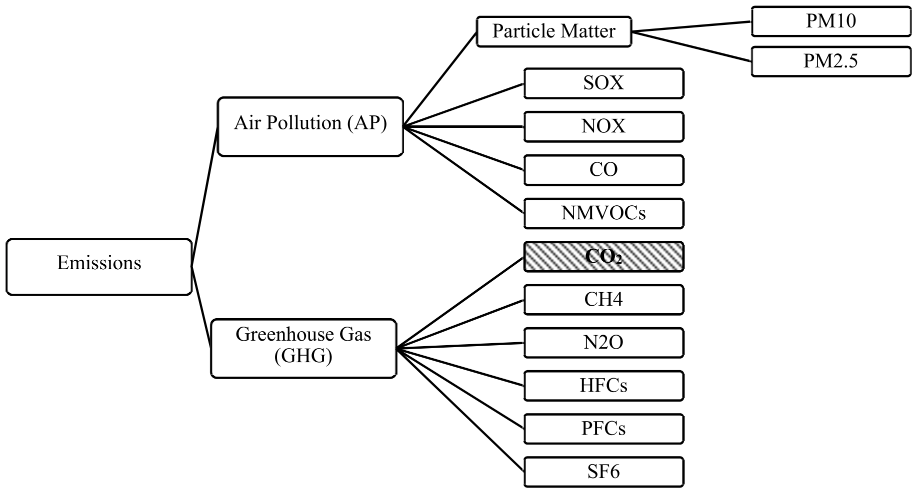

Fig. A.1. Different types of Port Emissions
Note: CO_2 is highlighted because it is the variable used in this study.
Source: Own elaboration.

Data availability

Data will be made available on request.

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