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Economic Analysis of the Maritime-Port Sector in an International Context

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Programa de Doctorado en Turismo, Economía y Gestión - Línea de Investigación en Economía y Métodos Cuantitativos

Economic Analysis of the Maritime-Port Sector in an International Context

Tesis doctoral presentada por Dª Andrea Rodríguez Ramos
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Cuando lo escuchas en boca de otros, parece una utopía, pero es completamente cierto: los momentos de agradecimiento, a pesar de ser la parte más íntima de cada etapa de la vida, son también los más difíciles de poner en palabras. Aun así, siempre he creído firmemente que somos en parte los que nos rodean; por eso, para mí, agradecer es una forma indispensable de cerrar un ciclo y, de algún modo, honrar que las victorias nunca son solo propias: quienes comparten tu día a día también se llevan un pequeño trozo de ellas.

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RESUMEN EN ESPAÑOL

Esta tesis doctoral tiene como objetivo analizar el sector marítimo-portuario en un marco internacional, con especial atención a los puertos de Europa y África Occidental. En un contexto del sector objetivo marcado oleadas de cambios y nuevas tendencias, se estudia cómo las crecientes exigencias regulatorias en materia medioambiental —en particular, la aplicación del *FuelEU Maritime Regulation* impulsada por la Unión Europea (UE)— están redefiniendo las dinámicas operativas, la gobernanza y el posicionamiento estratégico de los puertos.

La investigación pone el foco en los puertos españoles, y seguidamente presta especial atención a los situados en Regiones Ultraperiféricas (RUPs) de la EU como el archipiélago canario, cuya competitividad se ve condicionada por la necesidad de cumplir estándares ambientales más exigentes que los aplicados en enclaves vecinos de África Occidental.

A partir de tres estudios empíricos interrelacionados, la tesis ofrece una evaluación integral del impacto de esta nueva regulación sobre la eficiencia y competencia portuaria y sus implicaciones en un entorno logístico global cada vez más competitivo.

El primer estudio introduce un enfoque innovador al considerar las emisiones de CO_2 como un insumo contaminante en la función de producción portuaria, y no como un subproducto no deseado. Basado en el Teorema del Balance Material (TBM), se demuestra una relación positiva entre las emisiones y la producción de carga, lo que evidencia la dependencia estructural del sector respecto a los combustibles fósiles (dado que la transición verde aún no se ha materializado al completo en la industria portuaria). Asimismo, se constata que los

puertos con mejores dotaciones de infraestructura y capital mantienen mayores niveles de eficiencia técnica ajustada ambientalmente, mientras que aquellos menos desarrollados podrían experimentar pérdidas de eficiencia ante las nuevas normativas si no reciben inversiones en tecnologías limpias. En este contexto, resulta pertinente complementar el análisis con una evaluación del posicionamiento estratégico de los puertos españoles frente a los puertos de países terceros no sujetos a la misma regulación, como los situados en la costa occidental africana.

Por consiguiente, el segundo estudio analiza el posicionamiento competitivo del Puerto de Las Palmas (situado en la isla de Gran Canaria) como nodo logístico estratégico en el Atlántico medio. A través de un modelo de análisis matricial de competitividad, se identifican sus principales fortalezas —seguridad jurídica, integración en la UE y oferta de servicios de valor añadido—, así como limitaciones estructurales derivadas de la gobernanza portuaria y las restricciones espaciales. Si bien la regulación medioambiental europea implica mayores costes operativos —lo que justifica una reconsideración minuciosa de posibles excepciones para regiones altamente dependientes del mar como es Canarias—, también representa una oportunidad para reconfigurar su ventaja competitiva mediante la transición hacia un modelo de puerto verde.

Tras el análisis del Puerto de Las Palmas como competidor clave frente a los puertos del África occidental, y con el objetivo de integrar los principales enclaves en un análisis conjunto, el tercer estudio compara la eficiencia técnica de una muestra representativa de puertos en Canarias y África Occidental, incorporando un indicador de calidad institucional —el índice de corrupción— mediante un modelo DEA con *bootstrapping.* Los resultados muestran que, aunque algunos puertos africanos alcanzan niveles similares de eficiencia técnica, los puertos canarios presentan un desempeño superior en términos de estabilidad institucional, fiabilidad normativa y atracción de inversiones. No obstante, las nuevas asimetrías en las cargas regulatorias ambientales podrían erosionar dicha ventaja, favoreciendo desvíos de tráfico e inversiones hacia regiones con normativas más laxas.

Los hallazgos de esta investigación permiten extraer implicaciones políticas relevantes. En particular, se subraya la necesidad de articular instrumentos diferenciados para los puertos de RUPs como Canarias, promover inversiones en tecnologías sostenibles que acompañen las exigencias regulatorias, y fortalecer los marcos de gobernanza portuaria como elemento clave de competitividad. Asimismo, se destaca la importancia de fomentar la cooperación internacional y la armonización regulatoria con terceros países, con el fin de evitar desequilibrios en el comercio marítimo internacional.

En síntesis, esta tesis doctoral realiza una aportación relevante en diversos planos, contrastados empíricamente: analiza el efecto operativo de las emisiones consideradas como insumo, detecta ventajas competitivas de un puerto insular en su interacción con África Occidental, y mide la eficiencia en una base de datos heterogénea para evaluar los efectos de distintos marcos regulatorios e institucionales. Todo ello se enmarca en un enfoque integral que vincula eficiencia, competitividad y gobernanza en un sector clave para la economía global. En definitiva, en un entorno caracterizado por crecientes exigencias de sostenibilidad ambiental y tensiones geopolíticas, esta investigación ofrece herramientas conceptuales y evidencia empírica para orientar el diseño de políticas portuarias más eficaces y resilientes.

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CHAPTER I – GENERAL INTRODUCTION

CHAPTER I - GENERAL INTRODUCTION

This doctoral dissertation explores the maritime-port sector within an international framework, with a particular focus on ports in Europe and West Africa. As a central enabler of global trade and a critical component of supply chain logistics, the sector faces mounting pressure to adapt to increasingly demanding environmental regulations. These challenges are especially acute in regions where economic activity is heavily dependent on maritime connectivity and the reliability of port operations, such as island regions.

Within this context, the thesis examines environmental policy developments—most notably the implementation of the European Union's (EU's) Maritime Regulation—as the industry enters an unprecedented phase of regulatory transformation. These regulatory shifts are expected to reshape not only the operational dynamics of ports but also their strategic positioning in a highly competitive international landscape.

The empirical analysis focuses primarily on Spanish ports, with particular emphasis on those located in the Canary Islands—a European outermost region situated on the doorstep of Africa. While ports in West Africa operate under more flexible and less demanding environmental regulations, Spanish ports must comply with EU standards, generating a structural asymmetry that may challenge their competitiveness vis-à-vis their regional counterparts.

To address this multidimensional issue, the dissertation is structured around three interrelated empirical studies, each presented as a standalone chapter. Together, they offer a comprehensive assessment of how environmental regulation—particularly the *FuelEU* Maritime Regulation—affects port performance, governance, and competitive positioning in an evolving and strategic context.

The first study assesses how the inclusion of greenhouse gas (GHG) emissions as a productive input impacts the performance —particularly the technical efficiency— of

Spain's 23 largest ports. It introduces a novel empirical approach by applying the Material Balance Theorem (MBT) to justify the treatment of CO_2 emissions as a polluting input within the stochastic production frontier model. Unlike traditional methods that treat emissions as undesirable outputs, this study aims to reflect the operational realities of the maritime-port sector. This approach offers a more accurate representation of the environmental and operational trade-offs inherent in port activities.

The findings indicate that incorporating CO_2 emissions into the production frontier model shifts the focus towards quasi-fixed inputs (infrastructure and capital investments) rather than variable inputs (labour and equipment). This shift implies that ports with a well-developed infrastructure are likely to achieve greater efficiency levels despite higher emissions, whereas ports with less developed infrastructure may experience decreased efficiency under the new environmental regulations.

Additionally, the study reveals that while the *FuelEU* Maritime Regulation aims to internalize externalities, it may also negatively affect traditional measures of technical efficiency due to increased compliance costs. In light of these findings, the chapter provides empirical evidence supporting the need for strategic investments in green infrastructure and energy-efficient technologies to reconcile environmental sustainability with operational performance.

The main idea is that the implementation of these environmental measures is likely to result in losses of efficiency and, consequently, in the competitiveness of Spanish ports, as they must adapt to a new regulatory environment that requires a reduction in the use of GHG-intensive energy sources, such as CO_2. Many of these ports face direct competition from nearby third-country ports that are not subject to the same regulatory constraints. This highlights the need to examine the competitive advantages of Spanish ports in relation to their closest regional competitors in West Africa.

Therefore, the second study shifts the focus to the Canary Islands, specifically examining the Port of Las Palmas (LPAP) also known as Port of La Luz, and its competitive positioning within the Mid-Atlantic region, a strategic hub connecting Europe, Africa, and the Americas. Using Porter's Extended Diamond Model and Competitive Matrix Analysis, the study explores the determinants of LPAP's competitiveness in relation to the rest of West African ports, which are emerging as significant competitors due to less stringent environmental regulations.

This study examines the geopolitical dynamics and economic interdependencies between the Canary Islands and West Africa, emphasizing how regulatory asymmetries shape competitive advantages. The findings show that regulatory frameworks, security, and legal stability are critical factors contributing to LPAP's competitive advantage, positioning it as "Europe in Africa." This strategic positioning enables LPAP to offer higher value-added services, including advanced logistics, manufacturing, and transhipment operations.

However, the study also identifies significant challenges, particularly related to Port Authority governance and spatial constraints that limit business expansion and infrastructure development. The research emphasizes that although EU environmental regulations increase compliance costs for LPAP, they also create opportunities for sustainability-driven innovation and green technology adoption, which could enhance its competitive positioning as a green port hub in the Mid-Atlantic. The analysis reveals that LPAP's competitive edge is largely influenced by its ability to adapt to these regulatory changes while leveraging its geopolitical position.

Following the analysis of LPAP as a key competitor to West African ports, the third study broadens the scope by integrating all these ports into a unified framework. The work includes an efficiency analysis on a heterogeneous sample comprising European ports in Africa (Canary Islands) and the major ports of West Africa, focusing on the impact of regulatory asymmetries and governance factors. This research tries to evaluate how compliance with the *FuelEU* Maritime Regulation could influence the competitive positioning of Spanish ports, particularly those in the Canary Islands. The study uses bootstrapped Data Envelopment Analysis (DEA) methodology including governance dimensions such as legality, security, and bureaucratic quality.

The analysis uses the Corruption Perception Index (CPI) as a proxy to measure governance quality, given its significant influence on operational efficiency and investment attractiveness. The findings reveal that while West African ports achieve technical efficiency levels in line with Canary Island ports, the latter consistently rank higher due to their robust regulatory frameworks and governance structures. Due to this, the stricter environmental regulations imposed on Canary Islands' ports by the *FuelEU* Maritime Regulation are expected to reduce their competitive edge, potentially diverting maritime traffic and investment to less regulated West African ports. The study highlights the need for strategic policy interventions to maintain the competitiveness of Canarian ports in an evolving international regulatory environment, especially given that the economies of these regions are highly dependent on the maritime transport industry.

The structure of this thesis is as follows: *Chapter 1* presents the general introduction, *Chapter 2* focuses on the efficiency study of Spanish ports, *Chapter 3* analyses the competitive positioning of the LPAP in the Mid-Atlantic, and *Chapter 4* examines efficiency levels in West African ports, particularly in the context of regulatory asymmetries. *Chapter 5* provides the general conclusions of the thesis, integrating the findings of the three empirical studies, while *Section 6* contains the appendix, including supplementary data and detailed methodological explanations.

CHAPTER II – THE EFFECT OF CO_2 EMISSIONS ON SPANISH PORT EFFICIENCY: AN ANALYSIS WITHIN THE CONTEXT OF THE FUELEU MARITIME REGULATION

CHAPTER II - THE EFFECT OF CO2 EMISSIONS ON SPANISH PORT EFFICIENCY: AN ANALYSIS WITHIN THE CONTEXT OF THE FUELEU MARITIME REGULATION[1]

2.1. INTRODUCTION

According to projections from the UN Conference on Trade and Development (UNCTAD), maritime transport is responsible for over 80% of global trade (UNCTAD, 2021). In 2023, a growth of 2.4% was recorded, marking a recovery from the contraction experienced in 2022 (UNCTAD, 2024). Although this mode of transport is often considered the least environmentally harmful per tonne of cargo, its emissions remain significant, at approximately 3% of global Greenhouse Gas (GHG) emissions.

The environmental concerns associated with maritime transport are primarily linked to its contribution to GHG emissions, particularly Carbon Dioxide (CO_2). Within the EU, maritime transport accounts for approximately 11% of CO_2 emissions from the transport sector and 3-4% of total EU CO_2 emissions (EU, 2022).

In response, the EU has introduced the *FuelEU* Maritime regulation (COM/2021/550 final: 'Fit for 55'), which aims to reduce this sector's emissions. It sets ambitious targets: a 55% reduction in emissions by 2030 (compared to 1990) and a 90% reduction by 2050[2]. It relies primarily on emission fees, which will take effect on 1 January 2025 (EU, 2022).

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[1] The results presented in this chapter are part of a manuscript currently under review.

[2] To date, no specific maritime transport-related regulation has existed. This initiative seeks to fill this gap by increasing the demand for renewable and low-carbon fuels (RLF) in maritime transport while maintaining a level playing field and an efficient EU market for marine fuels.

In ports, CO_2 emissions are generated by multiple sources, including ships at berth and auxiliary port activities using combustion engines, such as cargo handling equipment and support vessels. This paper focuses on emissions generated within the port area, including those from vessels regardless of their cargo operations, as well as from other combustion-based activities.

The main aim of this research is to propose a novel empirical specification for frontier production functions applied to ports. We use the Material Balance Theorem (MBT) framework to consider CO_2 emissions as an input in the port production function. This approach is particularly relevant nowadays, as fuel combustion remains the predominant energy source in the maritime industry, despite the existence of power alternatives that have yet to be fully implemented. Our research focuses on cargo handling services and estimates the frontier production function using the parametric approach of Stochastic Frontier Analysis (SFA). We present an application for the 23 largest ports in Spain between 2016 and 2020. Next, we assess the impact of CO_2 emissions on port production and port technical efficiency. We explore whether ports with higher CO_2 emissions could reach better results in terms of technical efficiency. Although emissions may contribute to productivity gains in strict operational terms, these gains are undesirable from an environmental perspective, further supporting the need for new Maritime EU legislation.

Despite the significance of port-related emissions, the literature on this topic remains scarce. To our knowledge, no previous studies have applied a parametric approach to analyse emissions from a productivity standpoint. This study makes several important contributions to existing literature. First, it introduces a novel framework for examining CO_2 emissions as a polluting input in port production, rather than treating them as an undesirable output. This approach provides insights that differ from prior studies that have focused solely on environmental performance.

Second, this research is a first attempt to understand better the complex relationship between port operations, environmental impact, and port technical efficiency. While emissions may provide short-term productivity gains through operational efficiency, these gains come at the expense of environmental sustainability. Exploring this trade-off is critical for informing policy decisions aimed at balancing economic and environmental objectives in the maritime sector.

This chapter is organized as follows: *Section 2.2* reviews the literature on port emissions and productivity analysis. *Section 2.3* addresses the Maritime *FuelEU* regulation. *Section 2.4* details the methodology, followed by the data in *Section 2.5* and the results in *Section 2.6*. *Section 2.7* provides the conclusions, while *Section 2.8* discusses the challenges and limitations of the study.

2.2. LITERATURE REVIEW

The literature on port emissions has expanded recently. Emissions of GHG, particularly CO_2, the impact of emission control areas (ECAs), and harmful particles such as those affecting human health, have been studied (Saxe & Larsen, 2004; Giuliano & O'Brien, 2007; Corbett *et al.*, 2009; Liao *et al.*, 2010; Tzannatos, 2010; Geerlings & Van Duin, 2011; Chang, 2013; Chang & Wang, 2014; Chang & Park, 2016; Zis & Psaraftis, 2017; Hsu & Huynh, 2023). However, environmental regulations, though less analysed, play a significant role in companies' decisions to relocate to regions with more lenient environmental standards (Eskeland & Harrison, 2003).

Concerning this issue, the International Maritime Organization (IMO) published the 'Port Emissions Toolbox' as the first official document designed to assess and regulate emissions from both ships and ports (IMO, 2018a, b). Although ports are relatively minor polluters compared to the transport sector as a whole (Acciaro & Wilmsmeier, 2015), they are critical nodes in the maritime transport network (Wang *et al.,* 2022). Various recommendations have been made for how ports can reduce their negative impact on both the climate and public health (Hoang *et al.,* 2022; Du *et al.,* 2019; Cullinane & Cullinane, 2019).

The economics of port operations, particularly productivity and efficiency, have traditionally been the focus of the port-maritime sector analysis (Notteboom & Verhoeven, 2010; González & Trujillo, 2009). This has been essential for planning port investment and operations. The need to include externalities, such as emissions, into port efficiency models is increasingly recognized, especially in the EU, where recent environmental regulations impose additional costs on emissions (Benamara *et al.,* 2019).

These regulations create a comparative cost advantage for ports in non-EU countries that are not subject to the same environmental controls, harming the competitiveness of some EU ports. In the Spanish context, several studies have specifically investigated the environmental impact of port emissions. For example, research by Villalba & Gemechu (2011), Mateo-Mantecón *et al.* (2011), and Martínez-Moya *et al.* (2019) explores how emissions from port activities contribute to local environmental degradation and the implications of regulatory policies on Spanish port operations.

In a critical review of analyses of port production, Rødseth & Paal (2015) pointed out that although significant advances have been made in understanding port productivity and efficiency, the inclusion of environmental variables, such as emissions, remains underdeveloped.

Further studies have built upon this need. Rødseth *et al.* (2020) analysed the growth of Norwegian seaport container throughput and its associated air pollution by applying the MBT. They highlight the complexity of balancing throughput growth with sustainability, as handling more volume usually leads to higher emissions. In a related study, Rødseth (2023) explored the issue of noise pollution from container handling operations in ports, addressing the costs of noise abatement and the environmental efficiency of various mitigation strategies.

Moving on to GHG emissions and focusing on Asia, Chin & Low (2010) employ a non-parametric method to examine 156 origin-destination pairs among 13 major East Asian ports, explicitly considering the environmental impacts of shipping, finding that the inclusion of external mitigation (measured as 'bad outputs' of gaseous emissions, such as NO_X, SO_2, CO_2, and particulate matter) can significantly influence efficiency. Building on this, Chang *et al*. (2013) argue that most Chinese provinces operate below 50% of the ideal level of environmental efficiency, a significant environmental inefficiency in the Chinese transport sector. This has been reinforced by studies such as Cui *et al.* (2023), which similarly underscore the lack of eco-efficiency in China's transport sector.

Further refining these approaches, Na *et al.* (2017) show that many Chinese ports display low environmental efficiency, with significant potential for improvement in emissions reduction without compromising overall productivity. Li *et al.* (2020) emphasizes the wide variation in environmental efficiency, suggesting the need for targeted technological and policy solutions to improve sustainability. Li *et al.* (2023) finds that while some ports are making progress, others still lag in achieving environmental efficiency, underscoring the importance of aligning port operations with the nation's decarbonization strategies.

Recently, in this geography area, Quoc & Quoc (2023) assessed the operational efficiency of container terminal operators at the Cai Mep-Thi Vai port. The analysis included undesirable outputs like CO_2 emissions and workplace accidents. Their results revealed that only 28.6% of operators reached full efficiency, while inefficient operators used up to 74.6% more input than necessary.

Similarly, Li *et al.* (2024) explores the relationship between port congestion and shipping emissions across four major Chinese ports. Using a time series model, they find that port congestion initially decreases emissions, but prolonged congestion leads to an eventual increase, particularly in large ports such as Shanghai and Ningbo.

Additionally, this focus on emissions in port efficiency is evident in Europe. For instance, Chang *et al.* (2017) explore the impact of ECAs in Europe and North America on port efficiency, finding a 15%-18% improvement in technical efficiency among ports within ECAs compared to those outside. These findings suggest that stricter environmental regulations can lead to enhanced efficiency. Similarly, Castellano *et al.* (2020) evaluate the economic and environmental efficiency of Italian ports using Data Envelopment Analysis (DEA), where CO_2 emissions are treated as undesirable output, revealing considerable disparities between the ports.

In the same vein, Tovar & Wall (2019) apply DEA to assess the environmental efficiency of 28 Spanish ports, considering their ability to reduce CO_2 emissions based on fleet activity estimations as proposed by the IMO. Building on this analysis, they later extended their model (Tovar & Wall, 2022a) to incorporate health costs as an undesirable output, thereby adding a public health dimension to the environmental efficiency evaluation.

Table II. 1 presents a comprehensive overview of selected studies examining productivity and efficiency, focusing on incorporating port-related CO_2.

Unlike previous studies that traditionally treat emissions as undesirable outputs, our approach explicitly incorporates them as a polluting input. This allows us to evaluate the effect of emissions on production frontiers, complementing the existing literature, which has primarily focused on an environmental perspective. In summary, examine the role of CO_2 as an energy-related factor.

Table II. 1. Summary of port emissions and port efficiency literature

Study	Methodology	Emissions variable	Main findings	Region
Chin & Low (2010)	Non-parametric (DEA)	NO_x, SO_2, CO_2, PM (in tonnes)	Environmental impacts of emissions significantly affect efficiency	East Asia
Chang *et al*. (2013)	Non-parametric (DEA)	CO_2 (in tonnes)	Significant eco-inefficiency in China's transportation sector	China
Na *et al*. (2017)	Non-parametric (Slacks-Based Measure (SBM))	CO_2 (undesirable output)	Low environmental efficiency in Chinese container ports	China
Tovar & Wall (2019)	Non-parametric (DEA)	CO_2 (IMO-based fleet estimations)	Environmental efficiency of Spanish ports assessed	Spain
Castellano *et al*. (2020)	Non-parametric (DEA)	CO_2 (undesirable output)	Disparities in economic and environmental efficiency across ports	Italy
Li *et al*. (2020)	Meta-frontier non-radial directional distance function	CO_2 (undesirable output)	Wide variation in environmental efficiency among Chinese ports	China
Li *et al*. (2023)	Non-parametric (DEA + Malmquist-Luenberger model)	CO_2 (undesirable output)	Mixed progress in achieving environmental efficiency	China

Cui *et al.* (2023)	Non-parametric (DEA)	CO_2 (in tonnes)	Significant eco-inefficiency in China's logistics and transportation sector	China
Quoc & Quoc (2023)	Non-parametric (Slacks-Based Measure (SBM)	CO_2 (undesirable output)	Only 28.6% of the operators achieve full efficiency; inefficient operators waste significant resources	Vietnam
Li *et al.* (2024)	Time series analysis	CO_2, NOx, SOx, $PM_{2.5}$ (emissions in tonnes)	Port congestion initially decreases emissions but increases them over time, especially in large ports	China

Source: Own elaboration.

2.3. *FUELEU* MARITIME REGULATION

The maritime sector plays a vital role in the European economy, handling 60% of exports and 85% of imports (Puertos del Estado, 2023). This sector is responsible for 13.5% of transport emissions in the EU, underscoring the need for effective regulation. According to the Global Carbon Project (2022), global CO_2 emissions reached 40.6 billion tons in 2022, highlighting the urgency of addressing maritime emissions as part of broader climate efforts.

In recent years, the EU has taken a leading role in setting environmental standards, starting with its Emission Trading System (ETS) and continuing with the more recent *FuelEU* Maritime regulation. Building on previous efforts, such as the MARPOL Convention (IMO, 1973)[3]. The *FuelEU* Maritime regulation represents a significant step in reducing GHG emissions from maritime transport, specifically targeting the energy consumed by ships and promoting the use of sustainable energy sources. Aligned with the EU's broader climate commitments under the

[3] This regulation introduces a more systematic and structured approach to ensure a gradual reduction in emission intensity over time

Paris Agreement (UNCTAD, 2015), the regulation seeks to cut GHG emissions at EU ports by 55% by 2030, compared to 1990 levels (EU, 2022). As a key instrument for achieving these ambitious goals, it ensures fairness and consistency across the maritime sector.

A crucial element of the regulation is the mandate to limit GHG emissions from ships entering EU-controlled ports, covering both docked vessels and those departing. Ships are required to use shore-side electricity or zero-emission technologies during port stays to reduce emissions, thereby promoting renewable energy and low-carbon technologies in line with the EU's general goal of achieving climate neutrality by 2050.

The regulation addresses this by focusing on operational efficiency while mandating a reduction in emissions. Notably, it targets ships over 5,000 gross tonnages, which are responsible for nearly 90% of CO_2 emissions in the sector, the law also includes provisions to prevent port avoidance and the potential relocation of operations outside the EU due to its stricter regulations).

To ensure compliance, the regulation establishes a rigorous and transparent framework for Monitoring, Reporting, and Verification (MRV), placing the responsibility on shipowners or other operating entities. Independent and qualified verifiers are tasked with ensuring that ships meet the requirements of the regulation. Ships that fail to comply will face *FuelEU* penalties, designed to discourage the use of high-emission energy sources. Penalties are calculated based on electricity costs, total energy demand, and the duration of non-compliance while in port. The proceeds from these penalties are reinvested in promoting the use of renewable fuels in the maritime sector.

An additional feature of the regulation is the inclusion of a reimbursement mechanism, allowing the purchasing body to compensate companies in cases where non-compliance is due to factors beyond their control. This provision helps ensure that penalties are fairly applied and do not disproportionately impact companies for issues outside their sphere of influence.

The regulation not only focuses on reducing emissions but also seeks to stimulate innovation and technological advancements within the maritime industry. By encouraging the adoption of zero-emission technologies and the use of clean fuels, the regulation is a cornerstone of the EU's broader strategy to achieve carbon neutrality by 2050.

The exposed regulatory framework for European ports underscores the pressing need to analyse GHG emissions management within the current operational landscape, where the port industry has not fully achieved its environmental objectives. In this context, this research proposes to recognize CO_2 as an input in the cargo handling services of port terminals. Since the discharge of goods in ports necessitates CO_2, these emissions represent costs that are incorporated into the production function of the terminals. Although it is primarily the shipping companies that generate these emissions, the recent EU regulation will facilitate the transfer of these costs to them, rendering the shipping companies responsible for the payment of the environmental fee stipulated by the regulation.

In the subsequent sections of this study, we will explore how to model CO_2 as a polluting input. This analysis aims to justify the potential effectiveness of the regulation as a future tool for internalizing the externalities associated with CO_2 emissions. Thereby enabling shipping companies to contribute to financing initiatives that assist terminals in meeting sustainability requirements.

2.4. METHODOLOGY

2.4.1. Modelling port emissions

Many externalities arise during port operations. They have a stochastic nature. So far, conventional production models of port activity have not adequately captured this form of joint production. However, the use of the Material Balance Theorem (MBT) should have the potential to capture this reality, as it allows employing other models drawn from the agricultural economics literature on production risk (Färe *et al.*, 1989).

Externalities are most commonly modelled as weakly disposable outputs in the majority of analyses of port production, where both desirable outputs and undesirable by-products, such as pollutants, are generated. However, this method has faced criticism due to its failure to adhere to the MBT. The MBT, grounded in the Law of Conservation of Mass, says that the mass of material inputs must equal the mass 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 the production processes (Coelli *et al.*, 2007).

Consequently, several physical approaches have been proposed to ensure the consistency of a production model with the MBT. These include the multi-wave production method (Førsund, 2009), which focuses on the sequential nature of the production process, allowing modelling the emissions and other outputs as they evolve through different stages of production. The 'cost function' approach (Coelli *et al.*, 2007) involves modelling the production process by incorporating the costs associated with undesirable outputs, such as pollutants. The concept of weak G-availability (Hampf & Rødseth, 2015) refers to the flexibility in the availability of resources 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 modelling emissions. The first specifies an explicit emission function, where emissions are treated as a by-product of the production process. These models show the amount of emissions based on the intended output level, emphasizing how emissions result from production activities.

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

The physical approaches (multi-wave production, cost function, weak G-availability) and the emission modelling approaches (explicit emission function, 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 apply the second approach, where emissions (polluting input) are incorporated within the production function. We rely on an adaptation of MBT's microeconomic approach. This allows us to account for the impact of emissions on production efficiency and output levels.

The use of natural resources is inherent in every industrial process whose outputs can be divided into two categories: desired outputs, which are the primary goal, and undesired outputs, e.g., 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:

$$M = Y + E \qquad \text{(II.1)}$$

Here, M represents the material inputs, Y represents the desired outputs (cargo), and E represents the undesirable outputs (for us, primarily CO_2 emissions).

Baumgärtner *et al*. (2001) assert that an incremental unit of material input cannot possibly be completely transformed into the intended output: a certain residual will inevitably persist. Consequently, the derivative of E with respect to M will always be positive. This suggests that within the context of 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. This implies that when a specific quantity of material inputs is used, a greater desirable output can be achieved.

We can describe the technology by a production function

$$Y = F(M, X), \qquad \text{(II.2)}$$

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

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

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

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

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

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

According the MBT, the undesirable output is determined by $E = M - Y = M - F(M, X)$. To introduce E modelled 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:

$$Y = G(E, X) \quad \text{(II.4)}$$

Following Ebert & 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 (II.3a) -(II.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 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, tonnes of CO_2 emitted in the port area is a proxy of port emissions (E).

2.4.2. Stochastic production frontier

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

$$Y_{it} = exp(X_{it}\beta + V_{it} - U_{it}) \quad \text{(II.5)}$$

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:

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

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

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. 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 technical efficiency 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 since in this industry even the labour input is of a quasi-fixed nature. In sum, it is considered that a port operator starts from a given level of input and tries to produce more output (Gonzalez & 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. (II.8)**, is what we call the traditional model without any consideration of CO_2 emissions. The second, **Eq. (II.9)**, includes the CO_2 emissions as a regressor of the production function, justified by MBT.

This second estimation allows us to see how the port technical efficiency ranking changes when this variable enters the analysis. The CO_2 variable can be used as a proxy for energy used and is inherent in the actual production process within the port industry.

The present study considers a translogarithmic specification to proxy the technology of the cargo handling port service. The simultaneous estimation of technological inefficiency consequences and the parameters of the stochastic frontier is through a Maximum Likelihood estimation.

Production Functions

$$lnY_{it}=\beta_0+\sum_{m=1}^{M}\beta_m lnX_{mit}+\frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M}\beta_{mn}lnX_{mit}lnX_{nit}+\sum_{t=1}^{T}\varphi_t f_t+\delta_c C_{it}+v_{it}-U_{it} \qquad \text{(II.8)}$$

$$lnY_{it}=\beta_0+\sum_{m=1}^{M}\beta_m lnX_{mit}+\frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M}\beta_{mn}lnX_{mit}lnX_{nit}+\gamma_0 lnE_{it}+\gamma_1 lnE_{it}^{\ 2}+\sum_{m=1}^{M}\gamma_m lnE_{it}lnX_{mit}+\sum_{t=1}^{T}\varphi_t f_t+\delta_c C_{it}+V_{it}-U_{it} \qquad \text{(II.9)}$$

Inefficiency Function

$$U_{it}=\delta_0+\delta_1 lnH_{it}+\delta_3 T_t+W_{it} \qquad \text{(II.10)}$$

Here, $Y_{it}$is the output vector of port i over a time period t (total cargo); $X_{mit}$is the m-th nonmaterial input of port i for the time period t; E_{it} is the CO_2 variable of port i over time period t; f represents temporal dummy variables; C_{it} includes the environmental variable for port i over time period t (index of cranes); H_{it} is the PLSCI inefficiency variable for port i over time period t; T is the trend variable.

2.5. 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*.

The National Port System (NPS) handles 60% of Spain's exports and 85% of its imports. 53% of Spain's trade is with other EU countries. Within the transportation sector, the NPS makes up 20% of the GDP (Puertos del Estado, 2023). Several of Spain's ports are among Europe's top 10.

To assess the port efficiency of its cargo handling service, a data panel is available, including 23 PAs, with all the biggest ports in terms of cargo movement, between 2016 and 2020. The PAs excluded from the sample are those considered too small or with problems in terms of data availability.

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.

The information used to construct the panel variables comes from the Annual Reports of the PAs, published on the official website of *Puertos del Estado*, and in some specific cases, provided directly by the statistical departments of the PA and *Puertos del Estado*. IHS Markit, UNCTAD, the public results of the OPS

Master Plan of Spanish Ports [4], and Activity Reports on State Stevedoring Companies have also been used[5].

2.5.1. 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.

2.5.2. Port emission variable

To better explain the different types of emissions generated in the port maritime sector, ***APPENDIX 1.*** shows that the emissions fall into two distinct

[4] Official web of OPS Master Plan Project http://poweratberth.eu/?lang=es
[5] In cases where actual data was unavailable for specific years, linear interpolation methods have been used.

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 compounds (SOx), Nitrogen, Carbon Oxide (CO), volatile organic compounds other than methane (NMVOCs), and particles of less than 10 μm in diameter, known as PM10[6]. Within the PM10 fraction, the smallest particles are < 2.5 μm, PM2.5[7].

- On the other hand, Greenhouse Gas emissions: Carbon dioxide (CO_2), Methane (CH4), Nitrous oxide (N2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF6). The most important contributor is CO_2. Furthermore, in most cases, GHG emissions are expressed in units of CO_2 (known as 'CO_2 equivalent').

For this analysis, the CO_2 emissions (E) generated within the port area, measured in tonnes, have been considered. The data for this variable were calculated and published as part of the Onshore Power Supply (OPS) Master Plan (2021) and have been used here without further modification. These emissions primarily come from all kinds of vessels berthed at the port; this accounts 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 Greenhouse Gas Study 2014 (IMO, 2015).

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[6] These have the greatest capacity to access the respiratory tract and therefore have the greatest effect on airways.
[7] These are deposited in the alveoli.

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 allow for a tailored calculation that reflects the unique characteristics of each vessel[8].

To measure emissions, the following equation is used:

$$E_i = AE \times t \times FE_i \qquad \text{(II.11)}$$

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 II. 2 presents the average CO_2 emissions for the top ten more polluted ports in the sample between 2016 and 2020, both in total emissions (tonnes) and in emissions per tonne of cargo handled. This allows 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 high absolute

[8] Additionally, emissions are recorded and verified through standardized monitoring systems implemented at ports, which track vessel activity and engine usage. This ensures consistency in data collection and improves the reliability of emission estimates.

emissions, its emissions intensity is lower than other ports. Similarly, for Valencia. 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 0.005584 and 0.005219 tonnes, intensities significantly higher than larger ports such as Barcelona and Valencia.

Table II. 2. Average CO_2 emissions for the top ten most polluted ports in the sample (between 2016 and 2020)

Port	Average CO_2 emissions in tonnes	Average CO_2 emissions in tonnes per total cargo (rank position)
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.

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 ten European ports with the highest CO_2 emissions that year, recording 3.3, 2.7, and 2.8 million tonnes, respectively.

2.5.3. Input variables

2.5.3.1. Infrastructure variables (fixed variables)

The terminal's infrastructure is represented by the total area of the port in square meters (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 meters. All these variables are treated as fixed, as no infrastructural expansions occurred during the period analysed.

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

Cranes (X_2) are one of the most controversial variables that measure the capital of the port terminal. Because of their nature these variables need to be considered with special care, as all cranes are not equal (Cullinane *et al.*, 2005; Cheon *et al.*, 2010; Yip *et al.*, 2011; Bichou, 2013; Yuen *et al.*, 2013 and 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[9].

In another hand, the labour variable (X_4) is measured by stevedore working man-days. In Spain, cargo can only be moved by stevedores, who work under the Port Workers' Organization, which is independent of the Ministry of Labour. This labour market over the years has seen the number of stevedores increase 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,

[9] 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.

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. As a result, the role of PAs was limited to supervising the work (Gobierno de España, 2010). This means that private companies, now responsible for stevedoring, do not provide transparently and straightforwardly any data on their stevedores, due to data protection principles and internal regulations.

The data about stevedores is highly debatable in Spain's port industry, not only due to the regulatory context of this activity but also because of the complexity of obtaining reliable data (Arrillaga Canedo, 2022). This difficulty arises because such data is not managed by a single administrative body and is often not consolidated or publicly available, particularly over extended periods. The literature notes that this issue is also prevalent in other countries with similar regulatory frameworks.

In this context, as Pérez *et al.* (2020) point out, the study of cargo handling services often assumes an inflexible relation between the actual number of stevedores at a terminal and the number of cranes, sometimes specifying their features. Although direct data on stevedores would be ideal for efficiency modelling, previous studies have validated the use of cranes as a statistically sound proxy. 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.

2.5.4. Control variable

Additionally, as a new contribution, a control variable that captures the intensity of cranes in each port and about the whole NPS has been considered as a control variable in the model (C)[10]. To measure this variable, a Bird Index has been defined. This index, developed by Frémont & Soppé (2007), shows port specialization in each type of crane with respect to the other cranes in the same port but also in terms of the cranes in the rest of the ports in our sample.

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 certain segments of the production frontier. However, due to the high specialization observed in Spanish ports, this effect may not be uniformly negative[11]. This 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.

[10] 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 variables and the output, ensuring that the observed effects are not biased by omitted variable influences.

[11] 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.

2.5.5. Inefficiency variable

As some studies have highlighted, it is important to consider the Connectivity index (H) when analysing port efficiency. The Liner Shipping Connectivity Index (LSCI) was created by UNCTAD in 2004 to measure a nation's locations in global liner shipping networks and its changes over time by using a gravity equation model (Fugazza & Hoffmann, 2017).

Connectivity indices are considered useful in assessing the efficacy of investments made to improve ports in accomplishing their desired goals (Martínez-Moya & Feo-Valero, 2020). The primary aim of connectivity indices is to distinguish the relevant characteristics of ports that are crucial for evaluating the level of their connectivity. Martinez-Moya *et al*., (2024) provides a comprehensive collection of connection indices, outlining their characteristics. 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 gaining greater prominence (Ducruet, 2020). For this purpose, we employ the Port Liner Shipping Connectivity Index (PLSCI) as a measure of inefficiency in our model. The PLSCI was published by UNCTAD in 2019 and was employed as an inefficiency variable for Spanish ports by Tovar & Wall (2022b). This work was further substantiated by research employing this factor at the national level (Figueiredo De Oliveira & Cariou, 2015; Serebrisky *et al*., 2016; Suárez-Alemán *et al*., 2016).

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

Table II. 3. Summary statistics of the data

Variable	Name	Description	Mean	Std. Dev.	Min	Max
			Output Variable			
Total Cargo	Y	Tonnes	21,300,000.00	24,900,000.00	1,105,782.00	105,000,000.00
			Input Variables			
Area	X_1	Square meters	3,692,954.00	3,786,686.00	573,419.00	17,500,000.00
Cranes	X_2	Capacity in tonnes	1,221.43	1,734.30	40.00	8,646.00
Draught	X_3	Meters	15.51	4.48	7.20	30.00
Labour	X_4	Working man-days	83,603.32	152,634.50	1,473.28	576,710.90
CO_2	E	Tonnes	22,096.00	24,040.62	461.50	109,176.70
			Control Variable			
Int. cranes	C	Index	1.00	0.33	0.13	1.44
			Inefficiency Variable			
PLSCI	H	Percentage	15.27	18.78	0.70	67.24

Source: Own Elaboration with data from the Annual Reports of the PAs, IHS Markit, UNCTAD, public results of the OPS Master Plan of Spanish Ports, and Activity Reports on State Stevedoring Companies.

2.6. RESULTS

The estimated production functions meet the expected theoretical requirements, with the first-order parameters displaying the expected signs and statistical significance. The estimation, conducted using Stata17, presents the parameters for both the stochastic frontier model and the technical inefficiency model, as shown in ***Table II. 4.***

On average, all input variables satisfied the traditional production conditions of having a positive marginal effect on port output at the sample mean.

Table II. 4. Estimations of the production functions

*Model (1): Equation **II.8***			*Model (2): Equation **II.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***	.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			**Inefficiency model**		
Parameters in mean of u			*Parameters in mean of 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

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2.6.1. Crane variables

In the context of crane capacity, a negative marginal effect may arise if we consider only the cargo capacity that can be moved. To address this, a crane intensity control variable is included in the model to capture the relative level of crane inputs within the overall port infrastructure. This variable is not intended to directly assess crane specialization; rather, it reflects the relative position of crane capacity in the production function.

The crane capacity at Spanish ports should not be viewed merely as a standard input variable. The 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, we can assess how efficiently cranes, as key inputs, are utilized relative to the total port capacity. 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 in terms of crane intensity is positive. This is particularly true based on the nature of the superstructure of a port, having a specific number of cranes implies that they are being fully utilized (Squires & Segerson, 2020).

2.6.2. Time effect variables

Focusing on the year dummy variables, these are all statistically significant in the first model, **Eq. (II.8).** These variables reflect a type of event that affected all ports in the sample in the same way over the years 2016-2020. The reference year to compare this effect is 2020, and the effect of all years on production is positive, although not with the same average. It could be said that while the panel limits any analysis of the pandemic, the effects concerning 2020 (when the COVID shock had already occurred and congestion in the ports) were already beginning to be experienced (Liu *et al*., 2023). All the years before the shock show positive values relative to 2020, as the decline in production began during the period 2019-2020.

2.6.3. CO_2 emission variable

The CO_2 emission variable included in **Eq. (II.9),** aims to identify how port area emissions can be modelled within the context of port production. First order parameter of CO_2 is positive and statistically significant. Then, we find a positive marginal productivity of CO_2 regarding total cargo at the sample mean as it was 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 port area and marginal productivity of CO_2 regarding 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 marginal productivity of CO_2 regarding total cargo. Thus, it can be inferred that a greater port draught is associated with higher marginal productivity of CO_2 concerning total cargo (this may be because larger draughts enable bigger 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[12]. This is because, as explained, CO_2 is a non-desirable output of the industry that functions 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 with respect to output shows 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 until now.

2.6.4. Comparison of the two frontier production function models

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

[12] 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.

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

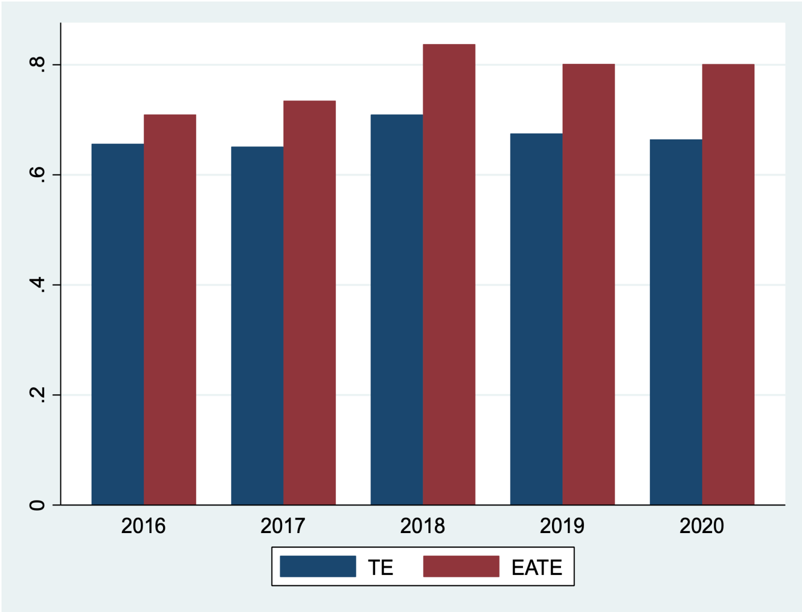
2.6.5. Technical efficiency

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 II. 4,*** the variables PLSCI and Trend, which describe inefficiency, were both negative and substantially different from zero. This indicates 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 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 Technical Efficiency (TE) is used to refer to efficiency 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 percentage points (See ***Figure II. 1***).

Figure II. 1. Mean Technical Efficiency for the period of study

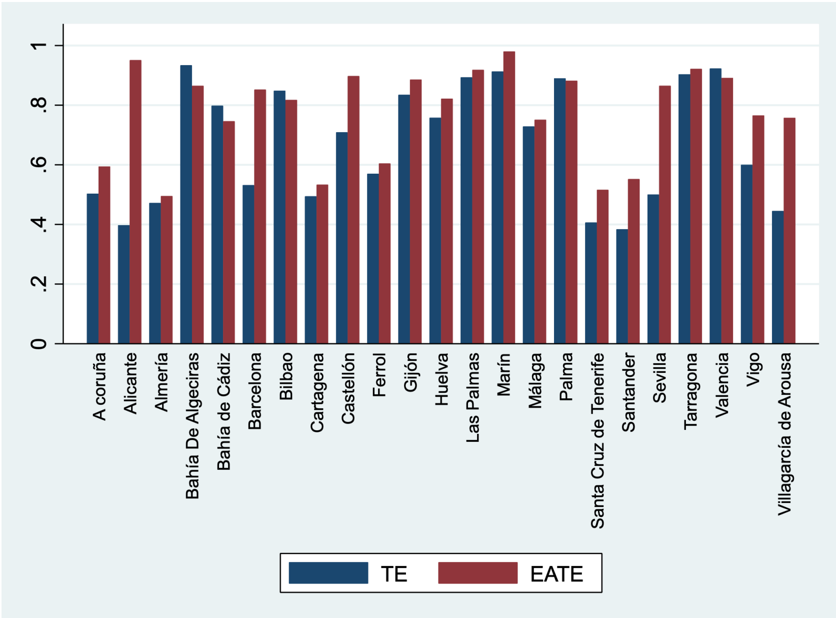


Source: Own Elaboration.

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

As shown in ***Figure II. 2,*** the distribution of technical efficiencies 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 variable alters the traditional ranking of port technical efficiency without a clear pattern. Generally, larger ports in terms of cargo volume rank higher. This 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.

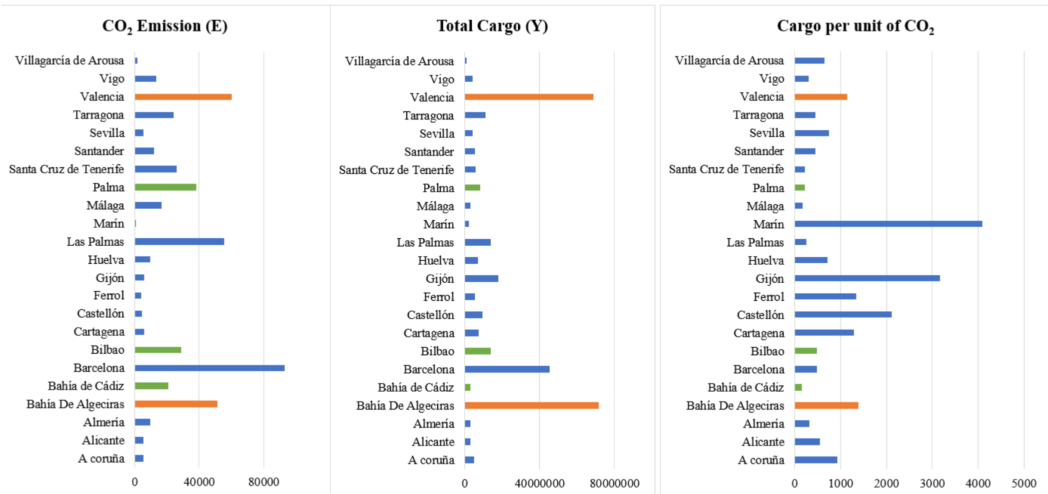
Figure II. 2. Technical Efficiency by port



Source: Own Elaboration.

While the reason for the negative impact of emissions on certain 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 ***Figure II. 3***).

Figure II. 3. CO_2 emissions, Total Cargo, and Cargo per unit of CO_2



Source: Own Elaboration.

This reality supports the great concern for emission restrictions in port areas from a classical production point of view. This is because the treatment of this variable, now more than ever, should be considered in the analysis of efficiency to evaluate not only the TE but also EATE.

2.7. CONCLUSIONS

Although policy interventions in the transport sector often focus on external costs, the economic impact of externalities from port operations has received little attention to date. In contrast, the EU's latest environmental policies (EU, 2022) now acknowledge the need to internalize the maritime sector's externalities. The present study has evaluated the trade-offs involved in recognizing CO_2 as an essential energy input within the port production framework, before a complete green transition, with findings suggesting that positive policy outcomes are a distinct possibility.

It is essential to acknowledge that a port's CO_2 emissions can be perceived not only as an environmental issue but also as a catalyst for economic growth. Nonetheless, in this ever-changing landscape, efficient environmental regulation management is key.

Since the world as a whole has not enforced a globally consistent set of environmental regulations, concerns have arisen regarding the competitive disadvantages faced by ports in the EU. Failure to resolve this may lead to the relocation of businesses to regions with less stringent regulations, undermining the competitive standing of the EU.

With this issue in mind, two models have been developed, demonstrating that emissions are a process polluting input variable according to the Material Balance Theorem (MBT), satisfying the conditions of a positive relation between CO_2 emissions and production. The analysis shows a significant difference between TEAE (which takes CO_2 into account) and TE (which does not), with empirical evidence suggesting that a 1% increase in CO_2 emissions is related to a 0.33% increase in port total cargo moved, ceteris paribus.

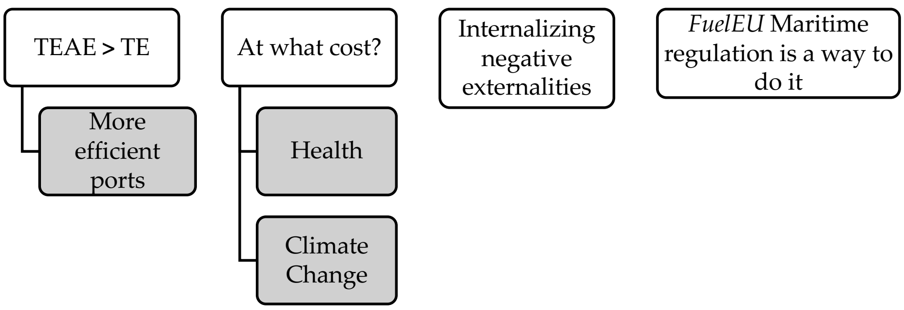
In sum, "the more I pollute, the more I can produce." However, this trade-off between production and environmental cost does not align with society's best interests. Once externalities are internalized, reducing production at a higher cost may prove to be the optimal solution.

It must be emphasized 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? Damage to public health and damage to the climate (see ***Figure II. 4***).

This 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.

Finally, 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 a strong partnership between the EU, IMO, and other international organizations. Such collaboration would involve the exchange of key information on the implementation of any regulations and working jointly to develop international standards for maritime transport, with the ultimate goal of addressing the global environmental challenge.

Figure II. 4. Key ideas of findings and conclusions



Source: Own Elaboration.

2.8. CHALLENGES AND LIMITATIONS

Our research is based on a microeconomic model, which considers the Material Balance Theorem framework to justify the inclusion of CO_2 emissions as an input. Then, we propose an empirical specification based on a frontier production function which just consider an aggregate output. To our opinion, this proposal could be especially useful in those cases in which the units of observation are not so long to use a multioutput approach.

This study has some specific limitations, primarily due to the lack of available CO_2 data for Spanish ports, which restricted the temporal scope of the analysis. Broader access to more comprehensive data would enable a deeper exploration of trends and correlations in this area. 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 could still represent a concern. However, as explained earlier in the manuscript, the CO_2 emissions variable account for all ships arriving at the port, regardless of whether they are engaged in cargo unloading or not. This means 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. It would be valuable for future studies to explore these two variables' interdependent patterns and potential causality. The use of advanced econometric techniques, such as instrumental variable models like the one proposed by Karakaplan (2022), could offer valuable tools for this.

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 cease to be a necessary input. A comparative analysis of scenarios with and without CO_2 could offer valuable insights into future research, addressing questions not fully covered in this study.

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CHAPTER III - GEOPOLITICAL AND COMPETITION ANALYSIS: THE CASE OF WESTERN AFRICAN PORTS AND THE PORT OF LAS PALMAS IN THE MID-ATLANTIC EUROPEAN ISLANDS

CHAPTER III - GEOPOLITICAL AND COMPETITION ANALYSIS: THE CASE OF WESTERN AFRICAN PORTSAND THE PORT OF LAS PALMAS IN THE MID-ATLANTIC EUROPEAN ISLANDS[13]

3.1. INTRODUCTION

The maritime industry plays a crucial role in global trade by enabling the transportation of goods across long distances and maintaining the smooth operation of international supply chains and import-export activities (Saeed *et al.*, 2021). United Nations Conference on Trade and Development (UNCTAD) data shows that in 2021 the maritime sector experienced a 3.2% increase in global maritime trade, reaching 11.0 billion tons (UNCTAD, 2022a). However, this favourable trajectory did not continue in 2022, as trade volumes experienced a contraction of 0.4% (UNCTAD, 2023). The industry's operational effectiveness and dependability have been impeded by obstacles such as port congestion, logistical delays, and equipment shortages, which have affected the movement of goods and economic stability (Alamoush *et al.,* 2022). Despite this, UNCTAD (2024) reported a 2.4% increase in 2023, anticipating ongoing, albeit tempered, growth in the long term (2024–2028).

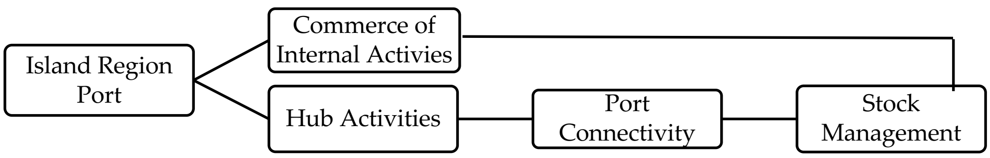
Regions that predominantly rely on maritime transit, particularly islands, require special attention due to their geographical characteristics (Zittis *et al.*, 2023). Around 90% of the products in these areas are transported by sea due to their limited industrial development (Ducret, 2020; Trujillo *et al.*, 2025). Consequently,

[13]The results presented in this chapter have been published in: Rodríguez, A., Cerbán, M. M., & Trujillo, L. (2025). Geopolitical and competition analysis: The case of Western African ports and the port of Las Palmas in the mid-Atlantic European Islands. *Journal of Transport Geography, 123,* 104141. https://doi.org/10.1016/j.jtrangeo.2025.104141.

this research focused on the Port of La Luz y Las Palmas (hereafter referred to as Las Palmas Port; LPAP), located on the island of Gran Canaria within the Spanish Canary Islands. It is the most important outermost island port under the European Union (EU) jurisdiction EU (2024), as it is geographically situated off the African coast.

The economic activity of these island regions stems from two primary sources (See ***Figure III. 1***). First, these ports are critical for importing goods, as these regions typically have lower industrialization rates and are net importers. This dependency is heightened in areas with significant tourism, such as the Canary Islands, where external goods are essential to meet local demand. Second, some island ports serve as strategic hubs in global logistics chains, with a significant portion of their traffic dedicated to transhipment. This establishes them as 'Hub ports', marked by intense competition with their closest rivals. This dynamic, in turn, drives regional economic growth. Moreover, the increase in transhipment traffic boosts port connectivity, reducing trade costs by streamlining stock management.

Figure III. 1. Characterisation of the process of LPAP economic activities



Source: Own Elaboration.

Analysing port competitiveness has always been crucial to enhancing operational performance compared to rivals (Baştuğ *et al.,* 2022) and is key to understanding the effects of new regulatory limitations on specific ports (Kent & Ashar, 2001). Building on this, the objective of this article is to investigate the factors that influence the LPAP's competitiveness in container traffic (handling service), compared to competitors within the Western African region.

This study offers a novel contribution to the literature by addressing critical gaps in the analysis of port competitiveness between the two regions (West Africa and the LPAP) which, although geographically proximate, operate under distinct regulatory frameworks. While previous studies have examined various aspects of port competitiveness, they have rarely focused specifically on West African ports and emphasized the perspectives of the multiple stakeholders involved in port services.

This work gives special consideration to the role of geopolitical factors, which are essential in shaping maritime trade dynamics. Geopolitics directly influences the regulatory and economic environment governing port operations, affecting trade routes, market access, and the competitive positioning of ports in strategically important regions like the Mid-Atlantic. The study aims to identify key areas where geopolitical interventions are necessary to support resilience and maintain competitive advantages for ports facing regulatory challenges and shifting trade patterns.

A relevant example of the geopolitical influence on maritime trade is the EU's recent environmental legislation, including the Emissions Trading System (ETS) and the *Fit for 55-FuelEU Maritime* initiative, introduced in 2023, which aims to reduce emissions by 55% by 2030 and 90% by 2050 (EU, 2021). These regulations present competitive challenges for ports in regions such as the Canary Islands, which rely heavily on maritime activity for economic stability (Carballo Piñeiro *et al.*, 2021). Specifically, the EU's environmental laws could place these ports at a disadvantage compared to non-EU ports that are exempt from such regulations (e.g., African ports), with potential repercussions for the economic and social well-being of these regions.

This study seeks insights into the LPAP's dynamics and makes strategic recommendations to improve its competitive position in the face of changing environmental and regulatory conditions, considering competition from continental African ports. In light of these findings, it aims to highlight the competitive advantages and disadvantages within this geopolitically significant area, emphasizing critical points where geopolitical strategies might mitigate potential adverse effects on the economies of regions highly dependent on maritime transport—such as the Canary Islands—by adapting to regulatory changes that impact port-based trade flows.

To achieve the objective, the 'extended diamond' model has been applied, first created by Porter, to identify and measure the primary determinants that comprise port competitiveness. This framework encompasses various elements, such as resource and factor circumstances, demand conditions, linked and supporting industries, company strategy, structure, and rivalry, as well as the responsibilities of government and chance events. The data were gathered via interviews and questionnaires specifically aimed at organizations and enterprises engaged in LPAP port operations. This was supplemented with additional statistical sources to accurately depict the progression of container traffic.

The structure of this chapter is as follows: *Section 3.2* offers a comprehensive review of the relevant literature. *Section 3.3* examines the global container market, highlighting the distinctive characteristics of the LPAP and West African ports. *Section 3.4* examines the key determinants of LPAP's competitiveness in comparison to its regional counterparts. *Section 3.5* presents the conclusions and discussion, while *Section 3.6* outlines policy implications and strategic recommendations. Finally, *Section 3.7* discusses the study's limitations and proposes directions for future research.

3.2. LITERATURE REVIEW

Within the maritime port sector, numerous research topics have emerged around the analysis of competitiveness, reflecting the sector's diverse range of activities. Recent studies suggest that several common factors influence port competitiveness, though their significance may vary depending on the specific port and type of traffic analysed (Acosta *et al.,* 2011; Notteboom & Langen, 2014). Additionally, Notteboom (2008) argues that, beyond these traditional factors, excellence in the logistics chain that includes the port is becoming increasingly important.

Focusing on port performance studies, such as those by Lirn *et al.* (2003, 2004), explore the factors influencing shipping companies' port selection by employing methodologies, like stakeholder interviews and surveys, to ascertain the most salient considerations in port preference. This methodological approach, along with the studies' overarching objectives, characterizes a leading genre of scholarly inquiry concerning port competitiveness and selection, replicated in diverse geographical contexts, such as Asia (Tongzon, 2007; Yeo & Song, 2005; Tai & Hwang, 2005) and specific regions like the Strait of Gibraltar (Acosta *et al.*, 2011) and Western Africa (Van Dyck & Ismael, 2015).

Another prevalent genre of academic inquiry involves comparative port analyses within the same region to ascertain their competitive advantages and disadvantages. Research, for example, by Kammoun & Abdennadher (2022), Kalgora (2019), and Yeo *et al.* (2011), exemplifies this approach in Western Africa and Asia. Other studies focus on individual ports, evaluating their relative strengths and weaknesses vis-à-vis competitors, as evidenced by works focused on Antwerp (Haezendonck *et al.,* 2000) and the Angolan port system (Campos, 2023).

In the realm of container traffic, research has mirrored broader inquiries into port competitiveness, probing factors that confer competitive advantages in containerized cargo operations (Acosta *et al.,* 2007; Yuen *et al.*, 2012; Kaliszewski *et al.,* 2020). It has also compared service quality among major transhipment ports both regionally (Kalgora, 2019) and globally (Ha, 2003).

A separate research strand has focused on the relative weight of the determinants of port choice to include service quality. For example, Murphy & Hall (1995) emphasized that quality is more important than service cost, while Wong *et al*. (2008) confirmed the importance of reliability in port selection. In this same context, Magala & Sammons (2008) identified several qualitative and quantitative factors as being important in port choice. Chang *et al.* (2008) concurred on the existence of these factors but argued that major shipping lines are more sensitive to costs than feeders. Notteboom & Vernimmen (2009) contended that specifically, bunker costs constitute a considerable expense to container shipping lines, significantly impacting costs per Twenty-foot Equivalent Unit (TEU), even when using large post-Panamax vessels.

It can be argued that these studies have reached a consensus regarding the pivotal factors influencing port selection: costs, available infrastructure, geographic positioning, and the quality of services offered. Specifically, service quality has increased in significance in recent years, concomitant with the proliferation and increasing complexity of logistic chains (Kaliszewski *et al.,* 2020).

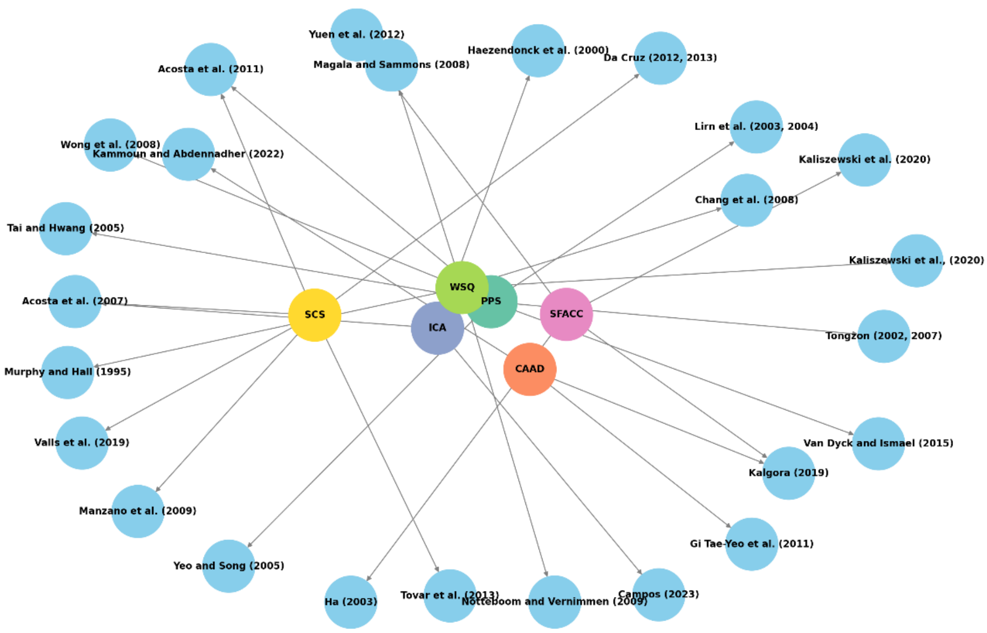
Within the context of Spain and its environs, scholarly investigations parallel global trends, examining port competitiveness and selection criteria. Pire *et al.*, (2013), for example, scrutinizes the strategic positioning and determinants of competitiveness for ports in the Iberian Peninsula, highlighting disparities in priorities among port authorities, terminal operators, and maritime transporters. Castillo-Manzano *et al.* (2009) constructed an index to rank Spanish port authorities based on various competitiveness factors, while Garcia-Alonso *et al.* (2019) explored port selection criteria for container traffic in Spain, shedding light on the impact of transhipment orientation on hinterland market access.

Focusing on the Canary Islands, Tovar *et al.* (2015) evaluate the infrastructure, accessibility, and hub port potential of major ports in the archipelago. Their analysis underscores the need for differentiation among ports to enhance overall competitiveness and suggests that the LPAP stands out as a hub port within the insular context.

Under the African scope, there is also a notable focus on other common analyses such as port efficiency and service quality measures, among others. Researchers have underscored the importance of examining these dimensions in less explored regions, where seaport performance has critical implications for economic development. For instance, Ayesu *et al.* (2024) emphasize how improvements in port efficiency can drive trade performance across African seaports, while Trujillo *et al.* (2013) discuss how reform processes impact efficiency and quality by incorporating critical variables, such as corruption in the model. Similarly, Sakyi (2020) conducts a comparative analysis of service quality across the Economic Community of West African States (ECOWAS) seaports, highlighting the need to enhance service quality to reduce delays and boost regional competitiveness.

The competitive studies can be summarized into seven categories to facilitate visualization of the state of the art on the topic. ***Figure III. 2*** shows the breadth and focus areas of existing research, while also highlighting the gaps that this study aims to address. Specifically, it underscores the lack of detailed analysis of Western African ports and, in methodological terms, the limited consideration of the diverse perspectives of all agents operating within specific port services.

Figure III. 2. A visual summary of the competitiveness literature review



Source: Own Elaboration.

Note: PPS (Port Performance and Port Selection); CAAD (Comparative Analysis - Advantages and Disadvantages); ICA (Individualized Competitiveness Analysis); SFACC (Specific Factor Analysis in Containerized Cargo); WSQ (Weights and Service Quality); SCS (Spanish Case Studies).

3.3. Competitive context of container cargo in the Western Africa ports

The LPAP, under the administrative control of the Port Authority of Las Palmas, holds a prominent position in container traffic within the Spanish network and in the Mid-Atlantic port context. In 2022, the LPAP achieved a record total traffic of 28.29 million tons, confirming its position as the eighth largest within Spain's national port system (Puertos del Estado 2024). This milestone reflects a significant recovery from the pandemic, surpassing pre-pandemic levels (Puertos del Estado 2022).

Regarding general merchandise, the port handled 17.58 million tons, marking a 1.92% increase compared to the previous year. Of this general merchandise, 12.8 million tons (72.7%) were containerized, which aligns with national trends. This performance gave the LPAP fourth ranking in the nation for containerized traffic, with a total of 1.16 million TEUs processed in 2022 (Puertos del Estado, 2024).

The port's overall significance is emphasized by its leading role in the Canary Islands, where it handled 69% of the total cargo volume in the region. On a European scale, the port ranked 15th in TEUs in 2022 (EuroStat, 2024). Globally, World Bank data from 2019 indicates that the total volume of TEUs was 808.8 million, with Spain and Africa each contributing approximately 2% of this total (World Bank, 2024).

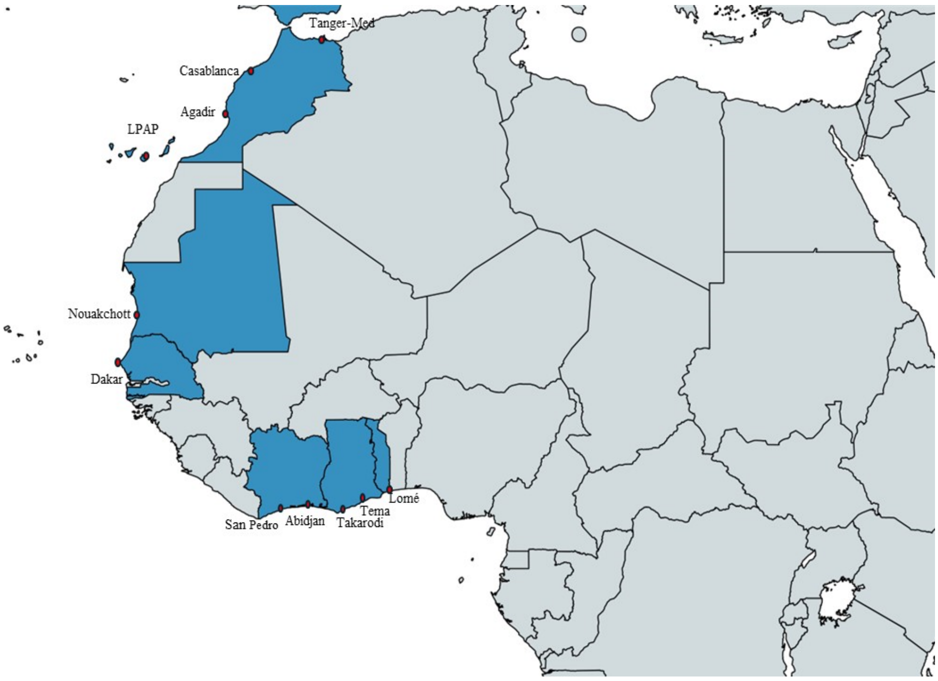
Additionally, the LPAP plays a prominent role in transhipment operations, ranking fourth among Spanish ports in this category. In 2022, the Port Authority of Las Palmas recorded 8.46 million tons of transhipped containers, accounting for approximately 70% of its total transhipment cargo, affirming its critical role in this highly competitive sector (Puertos del Estado, 2024).

The LPAP's strategic importance is accentuated by its role as a major maritime hub, often referred to as the "Gas Station of the Mid-Atlantic." This nickname reflects its pivotal function in providing bunkering services, and critical support for the extensive regional maritime traffic. The port's advantageous geographical location, high-quality services, and advanced infrastructure contribute significantly to giving it its competitive edge.

The main ports that constitute the subset of competitors for the LPAP were identified through direct interviews with high-level agents involved in its port performance and cargo handling services (Abidjan, San Pedro, Takoradi, Tema, Nouakchott, Agadir, Casablanca, Tanger-Med, Dakar and Lomé). These ports were selected based on their geographical proximity, operational capacities, and relevance as direct competitors in cargo traffic within the Mid-Atlantic region. Located in Western Africa, they represent potential rivals that could divert traffic from the LPAP, offering a comprehensive view of the competitive landscape and underscoring LPAP's strategic importance in this context (see ***Figure III. 3***).

The ports included in this sample represent a diverse cross-section of West Africa. The port's governance primarily tends to be under landlord port models, many of these ports focus on container and bulk cargo operations, serving both domestic and international trade needs. Ports such as Abidjan, Tema, and Lomé are positioned as critical gateways, connecting landlocked regions in Burkina Faso, Mali, and Niger to global supply chains. High-connectivity hubs like Tanger-Med and Lomé, which rank highly on the Port Liner Shipping Connectivity Index (PLSCI) of the UNCTAD, benefit from advanced digital systems and strong private sector involvement, establishing them as key transhipment centres. Other ports, like San Pedro and Nouakchott, support specialized export activities or domestic needs, respectively, with tailored investments to enhance operational efficiency.

Figure III. 3. Maps of selected West African Ports for the analysis



Source: Own elaboration.

The main characteristics of these ports—including hinterland, port connectivity, investment levels, digitalization, and operator involvement—are summarized in ***Table III. 1***, highlighting their roles within the broader regional trade network and the maritime logistics landscape in West Africa.

Table III. 1. The main features of the subset of ports

Country	**Port**	**Average Port Liner Shipping Connectivity Index (PLSCI) between 2010-2020**	**Mian Hinterland**	**Kind of port**	**Level of investment development in recent years**	**integration of digitization measures**	**Available infrastructure for container management**	**International Operators**
Ivory Coast	Abidjan	18.37	Burkina Faso, Mali	Landlord	High	Digital cargo tracking	2	APM Terminals, Bolloré

Ivory Coast	San Pedro	14.28	Ivory Coast's cocoa regions	Landlord	Moderated	Limited	1	Bolloré Africa Logistics MSC
Ghana	Takoradi	7.55	Burkina Faso, Mali, Niger	Landlord	High	Cargo tracking, automation	1	Meridian Port Services
Ghana	Tema	32.33	Ghana's mining regions	Landlord	Moderated	Oil and gas terminals	2	APM Terminals-Maersk Bolloré Africa Logistics
Mauritania	Nouakchott	6.85	Domestic	Mixed	High	Digitalization in planning	1	Maersk CMA CGM
Morocco	Agadir	9.54	Southern Morocco	Service Port		Limited	1	Marsa Maroc
Morocco	Casablanca	17.21	Morocco's industrial regions	Service Port	High	Some digitalization	4	Marsa Maroc
Morocco	Tánger-Med	63.60	International transhipment	Landlord	High	Full Seaport 4.0 integration	4	Port of Singapur APM Terminals-Maersk
Senegal	Dakar	16.73	Mali	Landlord	Moderated	Cargo tracking in progress	3	Dubai Ports World Bolloré Africa Logistics
Togo	Lome	35.52	International transhipment	Landlord	High	Partial Seaport 4.0 integration	1	China Merchants Bolloré Africa Logistics MSC
Spain	LPAP	30.08	International transhipment	Landlord	High	Full Seaport 4.0 integration	3	Maersk, MSC Boluda

Source: Own elaboration based on information from Shipping Guides Books, UNCTAD data centre https://unctadstat.unctad.org/datacentre/*), direct inquiries to relevant port experts, and consultations on the official websites of each port, where available.*

According to accumulated historical data on cargo traffic between the LPAP and key West African countries, the flow from Las Palmas to West Africa generally exceeds that in the opposite direction. In 2021 alone, 1,562,660 tons were unloaded at the LPAP from West African ports, while 3,936,948 tonnes were loaded at the LPAP for shipment to West Africa, underscoring the substantial level of trade between the LPAP and this region. Analysing specific destinations within our subset of interest, Senegal emerges as the primary recipient of maritime cargo from LPAP, while the largest volumes of cargo arriving at the LPAP come from Morocco (Puertos del Estado, 2024).

Moreover, ***Table III. 2*** provides a comparative overview of key indicators for the objective areas of study at country/region level on average between 2010 and 2020 (used as a proxy of patterns). The significant difference in Gross Domestic

Product (GDP) per capita between the Canary Islands (21,100.32 USD) and the West African countries can be appreciated, where Morocco has the highest at 3,038.27 USD. This substantial economic asymmetry suggests that the LPAP primarily serves as a central export hub, with lower purchasing power in West Africa driving more outbound traffic from the Canary Islands.

Population figures also offer context for trade patterns, with Morocco's population of 34.6 million partly explaining its role as the top origin for incoming cargo at the LPAP. In contrast, the Canary Islands' smaller population (2.1 million) aligns with its role as a strategic logistics centre rather than a large-scale consumer. Furthermore, the Logistic Performance Index (LPI) places the Canary Islands at a distinct advantage (3.80), indicating a more developed internal transport infrastructure than the West African countries.

Lastly, container traffic data highlights the LPAP's role in regional commerce. Morocco, with 4,251,026.18 TEUs, demonstrates substantial port activity, while the LPAP handles 1,363,955.80 TEUs, solidifying its status as a major node for trade redistribution to and from West Africa.

Table III. 2. Average key data from the evaluated area between 2010 and 2020

Region	GDP per capita	Population	LPI	TEUS by sea
Cote d' Ivoire	1,357.55	14,632,459.09	2.49	905,305.81
Ghana	1,944.70	27,882,402.45	2.43	934,622.90
Mauritania	1,754.19	3,952,476.91	2.14	75,952.68
Morocco	3,038.27	34,641,614.27	2.68	4,251,026.18
Senegal	1,173.42	10,610,307.27	2.34	525,772.45
Togo	700.80	7,487,409.55	2.16	837,830.45
Canary Islands (Spain)	21,100.32	2,123,136.63	3.80	1,363,955.80

Source: Own elaboration based on information from World Bank (https://data.worldbank.org/) and Puertos del Estado databases (https://www.puertos.es/).

An additional factor to consider is the regulatory framework in the region, which significantly influences trade dynamics. While the Canary Islands operate under EU regulations (EU, 2024), providing a high level of security and standardized protocols, West African ports follow different regulatory standards. This distinction can play a crucial role in shipping companies' decisions, as many prioritize the regulatory stability and security provided by EU jurisdictions, making the Canary Islands an attractive option for port calls.

However, African ports have also sought a competitive edge by enhancing their infrastructure and performance. Many are implementing strategies to attract shipping lines and investing in port facilities to increase their appeal and capacity. These efforts are supported by regional organizations, such as the African Union (AU)[14] and the ECOWAS[15], which promote regulatory reforms and standards aimed at facilitating trade and improving port efficiency.

In addition to regulatory aspects, the geopolitical environment heavily shapes port competitiveness in the region. The EU-Africa partnership framework[16], for instance, emphasizes collaboration in trade, security, and infrastructure, potentially favouring EU-linked ports like those in the Canary Islands as gateways between Europe and Africa. At the same time, AU policies aim to bolster regional integration, promoting direct intra-African trade and transport networks to reduce dependency on external ports. This has led to investments in West African port

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[1] The AU is a continental organization that fosters unity, cooperation, and socio-economic development across Africa, particularly emphasising the African Continental Free Trade Area (AfCFTA). This initiative aims to reduce trade barriers among its 55 member states, creating the world's largest free trade area and significantly enhancing intra-African trade and economic integration. See the official website for more details https://au.int/

[15]ECOWAS is a regional organization that promotes economic integration, stability, and development among its 15 West African member states. ECOWAS aims to establish a unified economic and trading bloc, fostering regional collaboration through policies on trade liberalization, free movement, and shared infrastructure to enhance prosperity and reduce poverty across the region. See the official website for more details https://www.ecowas.int/

[16] See the official website of the European Commission https://international-partnerships.ec.europa.eu/policies/africa-eu-partnership_en

infrastructure and enhancements, aiming to strengthen the region's logistical autonomy (ElGanainy *et al*., 2023).

Further complicating the geopolitical landscape, China’s Belt and Road Initiative (BRI) has expanded its influence over key African ports through extensive investment. Ports in countries such as Djibouti, Nigeria, and Kenya have received significant Chinese capital, enabling infrastructural improvements that increase their attractiveness to shipping companies. These investments also reflect China’s strategic interest in establishing a foothold across major African trade routes, which influences the competitive dynamics with EU-regulated ports.

Moreover, regulatory frameworks in African ports increasingly emphasize safety and security, in part due to the influence of the International Maritime Organization (IMO) and its conventions, such as the International Ship and Port Facility Security (ISPS) Code (IMO,2003). Compliance with international standards like ISPS is essential for many ports to gain the trust of global shipping companies, which rely on consistent security measures.

This regulatory and strategic contrast creates a competitive landscape, where vessels must choose between ports in close geographical proximity but with distinctly different regulatory and operational conditions, influenced by broader geopolitical interests. These dynamics shape regional trade flows and further strengthen the role of the LPAP as a preferred hub. Its EU-compliant regulatory environment and robust infrastructure offer stability and predictability, making it a strategic point of reference in the West African maritime corridor amidst complex geopolitical influences.

3.4. PORT OPERATORS' INTERNAL PERSPECTIVE ABOUT CONTAINER CARGO COMPETITIVENESS

This section identifies the factors that affect the LPAP's competitiveness from the perspective of all the individuals, entities and companies that participate in container traffic port services, both from the standpoint of demand and supply.

After identifying the various agents involved in the process of containerization, a representative sample was extracted. The selection of this sample for the survey was not random but rather intentional, based on the specific significance of each company or institution in port activities. To ensure the reliability and rigour of the study, the interviews were conducted in person and recorded, with the consent of the interviewees, to capture essential information.

For methodological clarity, two groups were formed. The first, the "Traditional" analysis, did not assign any weight to the interviews, while the second "Weighted" analysis highlighted certain results and provided a more relative analysis, and was developed to give a comprehensive view of the insights gathered. The latter analysis assigned a specific weight to each interview based on the number of employees in the company, the area of activity, and the length of time the company has operated in the LPAP.

The sample aims to cover all facets of port operations related to container transportation, including governmental entities, associations, customs and freight forwarders, container terminals, ship and cargo agents, stevedores, suppliers, land transportation businesses, and tugboats. Specifically, a total of 20 entities were selected, representing approximately 55% of all institutions and enterprises. The survey was administered to the director or highest-ranking member in charge of each organization's main office.

A structured questionnaire was given to all of these organizations, split into three components, similar to prior studies conducted by Acosta *et al.* (2007, 2011). The initial section comprises inquiries regarding the company's identification or status, staff count, subsector classification within the port industry, and the scope and duration of the LPAP operations.

The survey's highly significant second component was structured according to the competitiveness matrix. As said, the questions in this section are categorized according to Porter's (1990) extended diamond framework[17], which includes factor conditions, demand conditions, support industries, port competence, and the role of the public sector at different levels. This methodology was first applied to ports by Rugman & Verbeke (1993).

The variables in the questionnaire were rated on a scale of estimated intensity, ranging from -2 to +2, based on whether they were perceived as a disadvantage or an advantage for the competitiveness of the Port. The scale used to evaluate the variables that affect the competitiveness of the LPAP is as follows: -2 indicates a very unfavourable situation, -1 indicates an unfavourable situation, 0 indicates a neutral situation, +1 indicates a favourable situation, and +2 indicates a very favourable situation.

The third part of the survey consists of a series of open questions to explain in detail the data of the preceding part and to qualitatively corroborate them. This

[17]Porter's Diamond Model is an analytical framework for assessing the competitive advantage of an industry within a specific geographic area. Traditionally it identifies four key determinants: 1) factor conditions, such as labour and infrastructure; 2) demand conditions, referring to the nature of local demand; 3) related and supporting industries, or the presence of complementary sectors; and 4) firm strategy, structure, and rivalry, which considers how companies are organized and compete. These elements interact to shape industry competitiveness, influenced further by external factors like government and chance. This model has been widely adapted to analyse sector-specific competitive dynamics across different regions. For a more in-depth exploration of this methodology, refer to the source: Porter, M. E. (1990). *The Competitive Advantage of Nations.* New York: The Free Press.

last part of the interview was the most useful to properly explain the results after applying the calculations to the data.

The survey matrix displays the perceptions acquired from the second section of the questionnaire. It refers to the integration of various operational tasks inside a port, focusing on the logistics process, and considering the factors that contribute to the port's ability to compete. The operational tasks carried out in a port (the horizontal axis of the matrix) are further classified into:

- **Activities Related to the Foreland:**
  - **Maritime Accessibility (ACCESS):** Measures the ease of access for ships to enter the port.
  - **Maritime Transport (SHIP):** Evaluates the efficiency and availability of maritime transport services.
- **Activities Concerning the Port Sector:**
  - **Cargo Loading and Unloading (LOAD):** Assesses the port’s capability in handling cargo operations.
  - **Storage (WARE):** Evaluates the facilities and services for storing goods.
  - **Value-Added Logistics (VAL):** Looks at services that add value to the cargo, such as packaging and labelling (usually related to activities developed in free zones).
  - **Manufacturing Industry (MANU):** Considers the presence and efficiency of manufacturing activities within the port area (activities such as ship repairs, bunkering, offshore activities etc.)
- **Activities Linked to the Hinterland:**
  - **Road Transport (ROAD):** Measures the connectivity and efficiency of road transport services linking the port to the hinterland.

The determinants of port competitiveness are represented on the vertical axis. These determinants are structured according to the components of Porter's extended diamond, as follows:

- **Factor Conditions:**
  - **Infrastructure (INFR):** Evaluates the physical structures supporting port activities (those referring to the infrastructure such as draught, linear meters of quay, terminal area, etc.)
  - **Superstructure (SUP):** Assesses the additional facilities and equipment beyond basic infrastructure (those referring to the infrastructure above ground such as offices, warehouses, cranes etc.)
  - **Human Capital (LAB):** Looks at the availability and quality of labour within the port.
  - **Technology and Communication Systems (LOG):** Measures the technological advancements and communication systems in place.
- **Competition in the Port:**
  - **Internal Competition (ICO):** Examines the state of competition among entities within the port community.
  - **External Competition (ECO):** Evaluates competition from other ports considered as competitors.
  - **Cooperation within Port Institutions (ICOOP):** Assesses the level of cooperation among institutions and companies involved in port activities.
- **Demand Conditions:**
  - **Customer Relations (ICLI):** Measures the relationship between the port community and its current customers.
- **Government or Public Sector:**

- **Port Authority (GOAP):** Evaluates the intervention or position of the Port Authority.
- **Canary Islands Government (GOREG):** Assesses the involvement of the regional government.
- **Central Government (GONAT):** Looks at the national government's stance on port-related political decisions.
- **Local Authorities (GOLOC):** Measures the intervention of municipal authorities in port activities.
- **Supranational Organizations (GOSUPRA):** Evaluates the involvement of international organizations, except the EU as it is analyzed on an individual basis.
- **European Union (GOEU):** Assesses the EU's role and its policies impacting the port.

This matrix is a modified version of the original Antwerp matrix for the LPAP, adjusted to the specific parameters of our case study. A matrix $X^{(m)}$ has been generated for each firm or institution questioned, using the findings acquired from the surveys. The matrix comprises 14 rows and 7 columns, and 'm' represents the number of companies or institutions interviewed, which is equal to 20. Certain respondents in the survey may provide ratings that are more inclined towards the highest or lowest possible values compared to others. This discrepancy may be attributed to variances in the individual's personality or attitude during the interview, rather than an actual disparity linked to the competition of the port. To mitigate these distortions, the responses to each question have been categorized thus:

$$z_{ij}^{(m)} = \frac{[x_{ij}^{(m)} - AVE_{IJ}\left(X_{ij}^{(m)}\right)]}{SD_{ij}(X_{ij}^{(m)})} \qquad \text{(III.1)}$$

Where i=1, 2…14 and j=1,2…,7.

Next, the 'm' matrices were consolidated into a single matrix (Z) by computing the average of each intersection value from the standardized data. An examination of the primary determinants of competitiveness reveals the specific rows and columns that are associated with a favourable or unfavourable evaluation, as well as any potential interplay between them. The detection of extreme factors can be achieved by computing the departure of each cell in the response matrix, which has previously been standardized, from the overall mean behaviour of all cells, as proposed by Hubert & Rousseeuw (1997). To determine the average behaviour of rows and columns, the values of the matrix will be associated with two sets of predictors consisting of fictitious variables. The first group represents the average behaviour of each column, which pertains to the functional operations carried out in the port. The second group represents the average behaviour of each row, which pertains to the factors influencing the port's competitiveness. The model includes thirteen fictitious variables for the rows and six variables for the columns to prevent issues related to collinearity. The model is structured in the following way:

$$z_{ij} = \acute{e}_0 + \sum_{k=2}^{14} \acute{a}_{ij}^{(k)} \, I_{ij}^{(k)} + \sum_{l=2}^{7} \hat{a}^{(l)} J_{ij}^{(l)} + u_{ij} \qquad \text{(III.2)}$$

where $I_{ij}^{(k)}$ =1, for $i = k$, and $I_{ij}^{(k)}$ =0 for the rest of the various possibilities. Similarly, $J_{ij}^{(l)}$ =1 for $j = l$, and $J_{ij}^{(l)}$ =0 for the other values. The independent term is $\acute{e}_0$ and $u_{ij}$is the random perturbation.

To verify the consistency before developing the objective model, we conducted a reliability analysis using Cronbach's alpha on the items included in our dataset. The result, an alpha near 0.7, demonstrates an acceptable level of internal consistency among the variables. This reliability assessment ensures that the items consistently measure the intended construct, thus supporting the robustness of the model's foundation.

Estimating the model using Ordinary Least Squares (OLS) is a straightforward process. However, it is important to note that this method is very susceptible to the presence of extreme observations. To mitigate the impact of external factors on the outcomes, the model has been calculated by minimizing the sum of the absolute residuals. The equation obtained corresponds to the formula known as L1 regression:

$$\hat{z}_{ij} = \hat{\theta}_0 + \sum_{k=2}^{14} \hat{\alpha}^{(k)} I_{ij}^{(k)} + \sum_{l=2}^{7} \hat{\beta}^{(l)} J_{ij}^{(l)} = \hat{\theta}_0 + \hat{\alpha}^{(i)} + \hat{\beta}^{(i)} \quad \text{(III. 3)}$$

The residuals are computed by subtracting the actual values of the standardized scores matrix from the values estimated by the model: $e_{ij} = z_{ij} - \hat{z}_{ij}$. The model's estimation generates several residuals equal to the number of boxes in the competitiveness matrix, which is 98. By analyzing the residuals, taking into account their uncommon or unusual nature and their position in the matrix, we may determine the competitive advantages and disadvantages.

If any of the residuals e_{ij} found are exceptionally big, this indicates that the actual value of the dependent variable is not fully accounted for by the average impact of the rows and columns. According to Haezendonck *et al.* (2000), there is a relationship between row i and column j, namely between the functional activities carried out at the port and the resources required for port operations.

Hence, identifying exceptionally large residuals, whether positive or negative, allows for the identification of corresponding advantages or disadvantages in terms of competitiveness. To identify the observations where interactions occur, the most effective method is to visually show the standardized residuals graphically denoted as $\hat{e}_{ij}$, which is equal to e_{ij} divided by σ_e, against the estimated values $\hat{z}_{ij}$. If the residuals follow an almost normal distribution, around 95% of them will be located approximately within the range of -2 to +2. Observations that fall outside of the specified range can be considered extreme, suggesting either positive or negative interaction, depending on whether they are above or below the range.

The matrix of competitiveness of the Traditional and Weighted, presented in ***Table III. 3*** and ***Table III. 4*** respectively, is obtained by employing the methodology described above. From these data, the regression model is estimated, which will enable us to identify the competitive advantages and disadvantages (See ***APPENDIX 2***[18]). The residuals of the econometric model are presented in the following ***Table III. 5*** and ***Table III. 6*** for each Traditional and Weighted model.

Table III. 3. Matrix of Competitiveness of the Traditional Approach

	ACCESS	LOAD	MANU	ROAD	SHIP	VAL	WARE
ECO	-0,3498	-0,1889	-0,6482	-0,4755	-0,2677	-0,5104	-0,1562
GOAP	0,2316	0,1805	-0,9519	-0,2508	0,4102	-0,1220	-0,1697
GOEU	-0,3429	-0,5720	-0,1771	-0,3724	-0,7271	-0,3236	-0,4152
GOLOC	-0,5387	-0,6467	-0,8119	-0,8119	-0,5800	-0,7582	-0,9051
GONAT	-0,3498	-0,3572	-0,6554	-0,4140	-0,3759	-0,6412	-0,5368
GOREG	-0,3204	-0,3210	-0,7901	-0,6460	-0,1995	-0,3224	-0,4169
GOSUPRA	-0,3760	-0,3602	-0,2716	-0,3129	-0,1493	-0,2320	-0,3144
ICLI	0,3956	0,5420	-0,2344	-0,0085	0,3389	0,3557	0,4043
ICO	0,5476	0,5367	-0,1456	0,0615	0,4475	0,6356	0,4615
ICOOP	0,0651	0,5007	-0,4320	0,0901	0,0903	0,5264	0,1591
INFRA	1,2238	1,2091	-0,1000	0,1098	0,9947	1,1088	0,6416
LAB	0,7685	0,6056	-0,3361	0,2690	0,3712	0,5610	0,3256
LOG	0,8211	0,8211	0,0053	0,1798	0,6800	0,5469	0,4900
SUPRA	0,7790	0,8000	-0,3080	-0,0382	0,7804	0,6125	0,3539

Source: Own Elaboration.

[18] Note that the econometrical estimation of the OLS is the same for both models

Table III. 4. Matrix of Competitiveness of the Weighted Approach

	ACCESS	LOAD	MANU	ROAD	SHIP	VAL	WARE
ECO	-0,0431	0,0191	-0,0490	0,0053	0,0162	-0,1052	0,0195
GOAP	0,0223	0,0187	-0,0616	-0,0605	0,0199	0,0140	-0,0536
GOEU	-0,0063	-0,0073	0,0699	-0,0008	-0,0090	-0,0004	-0,0014
GOLOC	0,0039	-0,0049	-0,0141	-0,0228	-0,0016	-0,0132	-0,0738
GONAT	0,0092	0,0015	-0,0024	-0,0010	0,0046	-0,0023	-0,0014
GOREG	0,0163	0,0233	0,0002	-0,0717	0,0169	0,0156	-0,0481
GOSUPRA	0,0151	0,0147	0,0159	0,0105	0,0165	0,0746	0,0153
ICLI	0,0206	0,0165	0,0163	-0,0622	0,0064	0,0157	0,0100
ICO	0,0172	0,0174	0,0056	-0,0590	0,0125	0,0759	0,0031
ICOOP	0,0180	0,0216	-0,0004	-0,0607	0,0188	0,0775	0,0111
INFRA	0,0459	0,0481	0,0242	-0,0571	0,0364	0,0971	-0,0391
LAB	0,0219	0,0157	0,0004	-0,0474	-0,0499	0,0168	-0,0440
LOG	0,0192	0,0192	0,0152	-0,0537	-0,0405	0,0177	-0,0409
SUPRA	0,0288	0,0244	0,0132	-0,0571	0,0240	0,0222	-0,0458

Source: Own Elaboration.

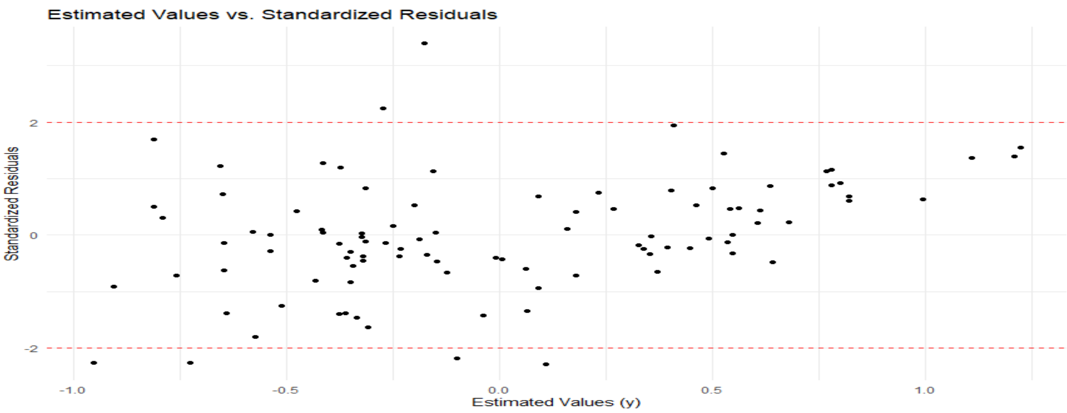
The extremely standardized residuals will be those that fall outside the bands of ±2 in ***Figure III. 4*** for the Traditional model and ***Figure III. 5*** for the Weighted model. Following those values, ***Table III. 5*** and ***Table III. 6*** show the position of the extreme residuals and their sign. The residuals selected are those whose values exceed approximately ±2 standard deviations and are placed and ranked to analyse their position concerning the functional activities undertaken in the port (columns) and the resources needed to operate the port (rows).

Table III. 5. Standardized residuals exceeding ±2 for the Traditional Model

	Position	
Order	**Positive residuals**	**Negative residuals**
1	GOEU-MANU (3,3979)	INFRA-ROAD (-2,2872)
2	GOSUPRA-MANU (2,239)	GOEU-SHIP (-2,2558)
3	-	GOAP-MANU (-2,253)
4	-	INFRA-MANU (-2,1768)

Source: Own Elaboration.

Figure III. 4. Values estimated against standardized residuals (±2 lines) for the Traditional Model



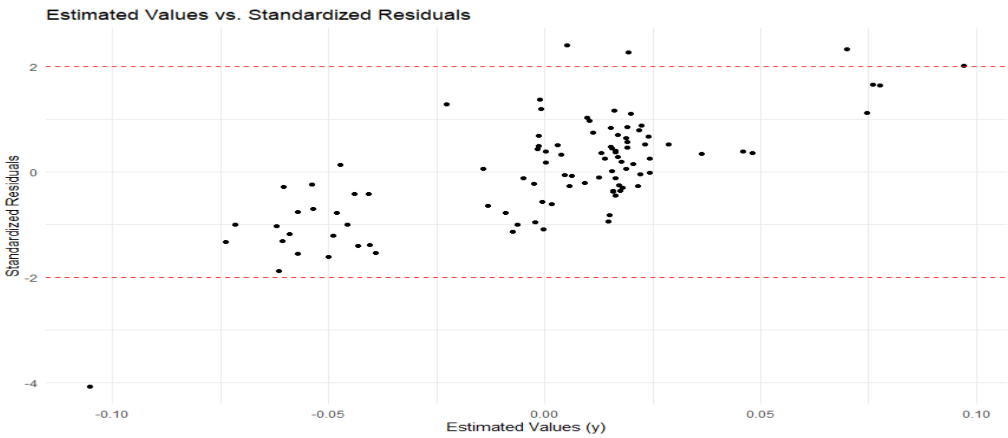
Source: Own Elaboration.

Table III. 6. Standardized residuals exceeding ±2 for the Weighted Model

	Position	
Order	**Positive residuals**	**Negative residuals**
1	ECO-ROAD (2,4021)	ECO-VAL (-4,075)
2	GOEU-MANU (2,3197)	
3	ECO-WARE (2,2658)	
4	INFRA-VAL (2,0096)	

Source: Own Elaboration.

Figure III. 5. Values estimated against standardized residuals (±2 lines) for the Weighted Model



Source: Own Elaboration.

Based on the examination of these points and the interactions they represent; the findings of the approach can be determined. To improve the analysis, it is useful to complement the results of the Traditional model with those of the Weighted model. In the latter case, by weighting according to the number of employees, greater emphasis is placed on companies or institutions, such as container terminals or stevedoring associations, whose reliance on transhipment container traffic is crucial and which employ large workforces.

3.4.1. Competitive advantages

3.4.1.1. Government or public sector

Regarding the primary competitive advantages identified from the results of valuing all surveys equally (Traditional model), respondents emphasize the significant role of actions taken by EU governments (GEOEU-MANU: 3.3979, takes first place in the Traditional model and second in the Weighted) and other international organizations (GOSUPRA-MANU: 2.3197, takes second place in the rank of the Traditional model), such as the International Maritime Organization (IMO), in promoting the presence and efficiency of manufacturing activities within the port area.

The GEOEU-MANU competitive advantage is further underscored in the Weighted model, suggesting that companies closely associated with terminal operations, which rely heavily on transhipment container traffic and employ large numbers of workers, view the management of these entities positively in terms of their competitiveness. The LPAP benefits from being classified as an outermost EU region, enhancing its status as a high-quality European port ‘within Africa’. This positioning offers a competitive advantage, as vessels looking for a port can rely on the safety and regulatory protections associated with the EU, in the sense of providing complementary services, in contrast to those available in African ports.

3.4.1.2. Competition in the port

Continuing with the analysis of competitive advantages, the Weighted model reveals that external competition, particularly concerning the ports within the target sample, is a critical factor. The model highlights two key areas where this competition is particularly intense: road transport (ECO-ROAD: 2.4021, takes first place in the Weighted model) and the availability of facilities and services for storing goods (ECO-WARE: 2.2658, takes third place in the rank).

ECO-ROAD refers to the strategic advantage the LPAP holds in offering highly competitive road transport services, which are essential for ensuring seamless operations and strong connectivity between the port and its hinterland. The efficiency of these transport services is crucial for the Port's ability to compete effectively with its West African counterparts. This advantage is primarily driven by the large number of transport providers operating within the Port, creating a competitive environment that leads to more favourable pricing for businesses. While the abundance of providers may occasionally introduce challenges such as congestion, it also fosters an atmosphere of continuous improvement, compelling providers to enhance their services to stay competitive. Consequently, the LPAP's capability to deliver efficient and cost-effective road transport services makes it particularly attractive to companies requiring reliable and economical logistics solutions.

In contrast, ECO-WARE highlights the LPAP's competitive edge in its warehousing facilities and related services, which are pivotal in attracting and retaining global shipping lines and logistics companies. This strength lies in its extensive availability and high quality of logistics and warehousing companies, enabling it to meet the diverse needs of its clients. The Port's ability to provide dependable and flexible storage solutions is especially important for handling goods that require precise and efficient management, such as transhipment container traffic.

3.4.1.3. Factor conditions

Lastly, as a competitive advantage, the Weighted model highlights the significance of the physical infrastructure that supports port activities, particularly in terms of value-added logistics services, such as packaging and labelling (INFRA-VAL: 2.0096, takes last place in the rank).

The emphasis on INFRA-VAL in the Weighted model underscores the recognition among stakeholders, particularly those from larger enterprises within the port, of the critical role that value-added services play in maintaining a competitive edge. These services extend beyond basic cargo handling and storage, incorporating additional processes that enhance the value of goods before they reach their destination. Such capabilities are crucial for attracting high-value cargo and clients who require more than just standard port services, especially in the context of retaining transhipment traffic.

For the LPAP, investing in and maintaining advanced infrastructure that supports these value-added activities is vital. The ability to offer comprehensive logistics services—such as packaging, labelling, and other forms of cargo customization—not only differentiates the LPAP from its West African competitors but also enhances its appeal to global shipping lines and logistics providers. These services contribute significantly to the overall efficiency and effectiveness of the supply chain, making the Port a more attractive hub for international trade.

However, it is important to recognize that this competitive advantage likely stems from the LPAP's position as a key port in a more developed region. This advantage could rapidly diminish in the coming years as African ports continue to develop their infrastructure, driven by increasing investments and the establishment of enterprises from around the world. As these ports improve their facilities, the competitive landscape could shift, challenging the LPAP's current standing. Therefore, the Port's strategic focus on expanding its value-added services, supported by robust and adaptable infrastructure, is essential for sustaining its competitive advantage amidst the growing competition from rapidly developing West African ports.

3.4.2. Competitive disadvantages

Unlike the case of advantages, the Traditional and Weighted models show no overlap when it comes to competitive disadvantages; however, despite this, the results from both models are complementary.

The primary competitive disadvantage identified by the traditional model is linked to the infrastructure supporting road transport (INFRA-ROAD: -2.2872) at the LPAP. This disadvantage arises from the significant atomization within the road transport sector, where a high density of trucks operates daily within a constrained space. The available infrastructure is inadequate to accommodate the volume of traffic, leading to inefficiencies in the distribution of resources among the numerous transport companies.

This mismatch between the number of transport providers and the capacity of the existing infrastructure frequently results in severe traffic congestion, overcrowding, and extended waiting times. These logistical challenges are exacerbated by the Port’s location, where the overflow of traffic and associated disruptions often extend into the urban centre, further complicating the situation. As a result, the Port's ability to maintain smooth and efficient operations is hindered, diminishing its competitiveness relative to other ports with better infrastructure management. This issue underscores the urgent need for infrastructure improvements to support the Port's operational demands and mitigate the negative impact on both the Port and the surrounding urban area.

The second place of the ranking goes to the EU government’s role in maritime transport services (GEOEU-SHIP: -2.2558) highlights its significant impact on the LPAP. This influence is particularly evident with implementation of the new Emissions Trading Systems’ (ETS) regulations, which will apply to the LPAP as an EU member, but not to its competitors in Western Africa.

On the other hand, the results indicate that respondents perceive the infrastructure related to manufacturing activities as inadequate to maintain competitive standards (INFRA-MANU: -2.1768). This deficiency is further exacerbated by the role of the Port Authority Government (GOAP-MANU: -2.253), which has been a critical factor in this context. The lack of support from the Port Authority Government of the LPAP has hindered the establishment and development of manufacturing enterprises within the Port’s public domain or its surrounding areas. As a result, the Port's ability to attract and sustain manufacturing activities has been significantly compromised, limiting its overall competitiveness in this sector.

Lastly, in the Weighted model, only one competitive disadvantage is identified, which relates to external competition in providing value-added services to cargo (ECO-VAL: -4.075). This finding reinforces the observation that, in the Weighted model, companies with larger workforces—those more closely involved in cargo management—tend to prioritize internal port factors. This concern may stem from deficiencies in the free trade zone, which aligns with the previously mentioned GOAP-MANU disadvantage identified in the Traditional model. Unlike other parts of the country, the free trade zone in Gran Canaria is located within the port area, meaning that its suboptimal functioning is perceived as a disadvantage.

The inability to offer a conducive environment for value-added services is particularly concerning, as these services are a key method for retaining cargo loyalty. The absence of a robust framework for managing and enhancing cargo thus represents a significant competitive shortfall. However, it is important to note that the LPAP has traditionally secured vessel loyalty by facilitating excellent services to ships. This historical strength highlights the Port's capability to attract and retain maritime traffic, even as it faces challenges in expanding its value-added offerings for cargo.

3.5. CONCLUSIONS AND DISCUSSION

The analysis of key competitive factors for the LPAP in comparison to the ports on the West Coast of Africa has led to the development of two distinct models. Both models are designed to enrich the analysis and examine the specific scenario from the most realistic perspective possible. The difference between these models, highlighted in the results, arises from the specific activities related to container traffic. In the Weighted analysis, the focus is on companies or institutions exclusively involved in container traffic—such as container terminals or stevedoring firms—which typically employ the largest number of workers. This approach offers a concentrated perspective on port traffic. Conversely, the Traditional analysis considers all companies and institutions equally, including those not solely dedicated to container traffic, such as shipping agents or freight forwarders. From this perspective, the results, as shown, provide a more comprehensive or holistic view of the competitive analysis in a specific case of an island region.

The EU plays a pivotal role in providing the LPAP with a significant advantage over its competitors, as observed in both models. This influence serves as a safeguard against issues such as corruption, extended waiting times, and legal uncertainties, which are more prevalent in neighbouring African regions. Despite sharing the same strategic geographical space in terms of maritime routes, the Canary Islands benefit from this comparative advantage, leading vessels to continue to select the LPAP over African ports.

In the Traditional model, this advantage is further reinforced by the LPAP's second position in the ranking, highlighting the role of supranational governments outside the EU, which underscores the importance of external support. Conversely, the Weighted model emphasizes internal operational factors, with the first position occupied by the competitive advantage derived from road transport. This suggests that companies with larger workforces, particularly those involved in cargo management, prioritize internal port operations.

However, this competitive edge is challenged by the implementation of the EU ETS, which imposes regulations on the LPAP that its African competitors are not required to follow. This regulatory disparity, indicated by the GEOEU-SHIP factor, creates a comparative disadvantage, presenting a significant challenge for both regional and supranational authorities. While increased competition typically fosters productivity and market efficiency, the potential social damage caused by such regulatory imbalances must be carefully addressed. The Canary Islands, an outermost region heavily reliant on maritime trade, faces unique challenges.

Strategic responses are critical to maintaining the region's competitive positioning, particularly given the social costs that could arise from these regulatory pressures and the opportunities that companies might seek in Africa.

Additionally, the perception of administrative bodies involved with the Port is notably negative. This sentiment is particularly strong in port-related matters, such as the Port Authority's handling of manufacturing activities, and extends to supranational levels concerning maritime transport. The analysis suggests that the LPAP struggles to attract and establish new business, especially those that could add value to cargo. Respondents explicitly highlighted these challenges, pointing out that the manufacturing sector is administratively disadvantaged.

Lastly, external competition is perceived ambivalently. High levels of competition in road transport and storage activities are seen as an advantage, despite infrastructure limitations in road terms being seen as a disadvantage because of congestion. Moreover, when it comes to the provision of value-added services, external competition is also seen as a disadvantage. The scarcity of industrial activity in the Canary Islands, coupled with inadequate facilities—such as the underutilized free trade zone—further exacerbates this issue. Respondents emphasize the lack of sufficient infrastructure and support of the administration for fostering value-added activities, highlighting a significant challenge for the Port's overall competitiveness.

In sum, from a geopolitical perspective that considers competition and maritime transport in the case study presented, it is crucial to acknowledge that existing competitive advantages must effectively compensate for or mitigate current disadvantages, especially if these challenges persist. In the present context, strategically important regions like the Canary Islands, which rely heavily on the development of the port industry, could face significant negative impacts if these issues are not addressed. Based on the results, it is essential to highlight the competitive advantages of the LPAP over the ports of the West African coast; this remains true despite the imposition of emissions charges resulting from European regulations.

While the EU’s protection and support provide a substantial competitive advantage, they may not, shortly, be sufficient to ensure the selection of the LPAP over its competitors. Therefore, substantial efforts in infrastructure, external competition, and value-added services are essential to maintain the Port's traditional position in the face of emerging pressures. This challenge requires a coordinated effort by the relevant port authorities and could serve as a significant case study in strategic protectionism.

3.6. POLICY IMPLICATIONS AND STRATEGIC RECOMMENDATIONS

The findings of this study underscore the critical need to address the challenges and opportunities facing the LPAP to ensure its sustained competitiveness in the maritime transport sector. By aligning the results with Sustainable Development Goals (SDGs), developed as part of the 2030 Agenda for Sustainable Development proposed by the United Nations (2015)—a comprehensive framework aimed at eradicating poverty, protecting the planet, and ensuring peace and prosperity for all by 2030—along with specific maritime strategy goals and regional policies, several strategic recommendations emerge.

3.6.1. Encourage Technological Modernization and Environmental Sustainability

Aligning with SDG 13 (Climate Action) and the European Green Deal (European Commission, 2019), which targets a significant reduction of greenhouse gas (GHG) emissions in the maritime sector, the LPAP should promote the adoption of green technologies by providing economic incentives, such as subsidies or tax reductions. These measures would facilitate compliance with EU emission regulations (*FuelEU* Maritime), including the EU ETS, and address the comparative disadvantage created by these regulations for the LPAP (EU, 2021). However, this regulatory burden places LPAP at a competitive disadvantage compared to West African ports, which are not subject to such stringent emission control regulations. While the IMO's strategy for GHG reduction aims for a 40% reduction in carbon intensity by 2030, the regulatory disparities between the LPAP and its West African competitors may encourage shipping companies to prioritize cost-effective, less regulated options (IMO, 2018). This could undermine the LPAP's competitive positioning, particularly in the face of emerging global sustainability trends. Additionally, the roadmap outlined by UNCTAD for decarbonizing the shipping industry emphasizes the need for technological innovation and consistent policy frameworks. However, in the absence of regionally coordinated efforts, the LPAP may face difficult trade-offs between sustainability and preserving its market share (UNCTAD, 2022b).

3.6.2. Strengthen Port Governance and Space Management

Governance reforms are essential to optimizing the port's spatial resources and attracting logistics activities that add value to cargo handling. Collaborative efforts between public and private stakeholders, through Public-Private Partnerships (PPPs), could address limitations in infrastructure, contributing to SDG 9 (Industry, Innovation, and Infrastructure**)** and fostering regional economic growth.

3.6.3. Develop Support Infrastructure and Value-Added Services

The diversification of port activities is critical to maintaining the LPAP's competitiveness. Programmes aimed at developing value-added services, such as light manufacturing and container repair, can enhance the port's capacity to compete on a global scale. These initiatives support SDG 8 (Decent Work and Economic Growth) by generating employment and increasing economic productivity in the Canary Islands.

3.6.4. Enhance Regional Integration and Supranational Partnerships

Collaboration with West African ports and alignment with policies from the EU and ECOWAS can improve regional integration. This strategy might include the establishment of logistics corridors and tailored trade agreements, contributing to SDG 17 (Partnerships for the Goals). Strengthened ties between these regions would facilitate mutual growth while leveraging the Canary Islands' geographic and strategic advantages.

3.6.5. Facilitate Adaptation of Land Transportation to Port Sector Needs

Efficient connectivity between the port and inland transportation is critical to addressing the competitive pressures identified. Investments in road and rail infrastructure tailored to port operations can optimize cargo movement, reduce bottlenecks, and support SDG 11 (Sustainable Cities and Communities).

3.6.6. Leverage Geopolitical Analysis in Decision-Making

In light of global shifts in maritime policies and investment patterns, the LPAP should establish units dedicated to geopolitical analysis. These units might proactively address challenges, such as Chinese investments in Africa or EU regulatory changes, ensuring that port operations remain resilient and adaptive. This aligns with maritime strategy goals emphasizing foresight and adaptability in governance.

Addressing the policy implications derived from this analysis requires coordinated efforts between local, regional, and supranational authorities. These recommendations emphasize the dual need to maintain competitiveness and align with global sustainability objectives. For the LPAP, strategic action in these areas will not only mitigate current disadvantages but also leverage its geographic and operational strengths to achieve long-term resilience and success.

3.7. LIMITATIONS AND FUTURE PROPOSALS

This analysis has inherent limitations due to its specific time focus. It reflects only the reality at the time of execution without encompassing a longer temporal perspective for broader assumptions. Additionally, the reliance on direct interaction with agents through field activities poses challenges in ensuring comprehensiveness, veracity, and reliability, which together require careful control to mitigate biases.

To enhance its scope, this type of competitive analysis should be supplemented with econometric methods for a more integrated understanding of the port scenario. Future research could compare the findings with the port's performance over a one- to two-year period, capturing the effects of anticipated regulatory changes. These insights could support decision-making by supranational entities, aiding regional protection and fostering competitive markets. Advanced quantitative techniques, such as factor analysis or principal component analysis (PCA), could further refine the evaluation of influencing factors, identifying the most significant components affecting competitiveness.

Integrating longitudinal data would also enable a dynamic perspective, tracking the impacts of regulatory shifts, infrastructure upgrades, and evolving market demands over time.

Moreover, scenario analysis offers another promising avenue, simulating the effects of geopolitical, regulatory, and technological changes on port competitiveness to inform strategic planning. Expanding the geographic scope to include comparative studies between Las Palmas and other West African ports could provide valuable benchmarking insights, highlighting opportunities for collaboration and best practices. These insights might also serve as a reference for applying similar strategies to other island regions with comparable challenges and opportunities, fostering knowledge transfer and tailored solutions in analogous contexts.

Finally, incorporating Seaport 4.0 metrics, such as digitalization, automation, and environmental performance indicators, would align future research with global trends in port management, offering a holistic view of competitiveness in a rapidly evolving and sustainability-driven industry.

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CHAPTER IV – EXAMINING THE INFLUENCE OF CORRUPTION ON PORT EFFICIENCY IN WEST AFRICA AND THE MID-ATLANTIC: A BOOTSTRAPPED DEA ANALYSIS

CHAPTER IV - EXAMINING THE INFLUENCE OF CORRUPTION ON PORT EFFICIENCY IN WEST AFRICA AND THE MID-ATLANTIC: A BOOTSTRAPPED DEA ANALYSIS[19]

4.1. INTRODUCTION

In recent years, Africa has demonstrated considerable progress both economically and demographically, inspiring growing scholarly interest in domains such as trade and infrastructure (Schwab, 2018). Within this context, maritime transport—responsible for more than 90% of global trade—plays a pivotal role in fostering commerce, driving economic expansion, and connecting African economies to worldwide markets (Fugazza & Hoffmann, 2017; Ducruet, 2020). Nonetheless, the continent's economic landscape remains complex, marked by significant disparities across countries, sectors, and social groups (Robinson, 2002; Cramer *et al.*, 2020).

Against this backdrop, governance quality—and the issue of corruption—has drawn increasing scrutiny, given its far-reaching implications for port performance. Several authors have highlighted how corruption index levels significantly affect port quality, productivity, and investment decisions (Trujillo *et al.*, 2013; Sequeira & Djankov, 2010). Comparable studies in Latin America emphasize that systemic corruption inflates shipping costs, undermines competitiveness, and curtails container throughput (Suárez-Alemán *et al.*, 2016; Serebrisky *et al.*, 2016; Seabra *et al.*, 2016). While these findings illustrate the adverse consequences of corruption on maritime logistics, few investigations explicitly

[19]The results presented in this chapter are part of a manuscript currently under review.

integrate corruption measures into multi-country frameworks encompassing both shared geography and varied governance regimes.

Building on these insights, the present research contributes to the literature by systematically incorporating Transparency International's (1995) Corruption Perceptions Index (CPI)[20] into a bootstrap Data Envelopment Analysis (DEA). Although previous work has explored the role of corruption in port inefficiencies (Trujillo *et al.*, 2013), limited attention has been paid to its direct impact on efficiency rankings within a single, heterogeneous sample of ports. Specifically, this study considers two main ports from the Canary Islands (Spain)—which, despite their proximity to Africa, benefit from European Union (EU) regulatory stability—and 14 main seaports across West Africa, where operational and bureaucratic conditions often diverge substantially.

Intense competition among these ports for transhipment traffic and maritime trade destinations underscores the need for a unified analytical framework. According to Rodriguez *et al.*, (2025), while some African ports are steadily enhancing their infrastructure and cargo-handling capabilities, Canary Island ports often maintain a competitive edge due to more stringent security standards and stricter regulatory oversight. Building on this contrast, recent studies highlight the importance of addressing governance and political factors in port efficiency. In this regard, Mlambo (2021) found that higher operational efficiency strongly supports national trade relations, reinforcing the connection between governance, efficiency,

[20] Further information on the data and methodology is available on Transparency International's official website: http://www.transparency.org. The CPI calculation incorporates alternative approaches developed by Professor Andrew Gelman (Department of Statistics and Department of Political Science, Columbia University) and Dr Piero Stanig (Fellow, Methodology Institute, London School of Economics and Political Science). It is worth noting that Transparency International has revised both the sample and the methodology for the CPI multiple times since the index was first introduced in 1995. The present study comprise data from 2011 to 2020, downloaded in 2024.

and trade competitiveness. Similarly, Buor (2024) identified nationalism and political considerations as major drivers of efficiency outcomes, confirming that regulatory and political issues are critical to a unified analytical approach.

In practical terms, we examine how incorporating the CPI—using as proxy of legacy environment and for instance time-congestion problems—reshapes efficiency rankings among ports that, although geographically proximate and linked by similar shipping routes, operate under distinct legal, regulatory, and bureaucratic conditions. Such a comparative analysis is particularly relevant for West African ports, which compete directly with Atlantic and Mediterranean gateways. In contrast to studies confined to a single region or reliant on broad structural indicators, our approach illuminates the specific mechanisms through which corruption influences port performance and produces flexible results, thus enabling the construction of a realistic comparative framework for this sample.

By employing a bootstrap DEA methodology, we mitigate bias in efficiency estimates and provide robust, data-driven insights into how governance capacity, infrastructure development, and maritime logistics intersect. Moreover, by capturing political and legislative heterogeneity within a single framework, this work refines our understanding of how differing institutional environments shape operational effectiveness. To our knowledge, no previous research has explicitly integrated the CPI as a contextual factor in a consolidated dataset of multiple ports—European and African—competing along similar trade routes.

The structure of this paper is as follows. *Section 4.2* reviews the existing literature on port efficiency in line with the study's objectives. *Section 4.3* outlines the methodological rationale behind the bootstrap DEA approach. *Section 4.4* describes the dataset and highlights legislative disparities between the EU-regulated Canary Islands and West African ports. *Section 4.5* presents and discusses the empirical findings, focusing on implications for port administrators and policymakers. *Section 4.6* synthesizes the main conclusions, while *Section 4.7* addresses the study's proposed avenues for future research.

4.2. STATE OF THE ART

4.2.1. Bootstraps efficiency analysis

In recent decades, efficiency estimation has evolved significantly, driven by the development of non-parametric methodologies. Among these, the bootstrap method has emerged as a fundamental tool, enabling robust statistical inferences without the need to assume specific parametric distributions. This approach has been widely adopted across various fields, including economics, management, and the social sciences, where the goal is to evaluate the relative efficiency of productive units or firms. Through a series of key studies, the advantages of bootstrap in estimating standard errors, confidence intervals, and other accuracy measures have been demonstrated, expanding the analytical possibilities in complex contexts.

The evolution of this methodology has been shaped by foundational works. Efron & Tibshirani (1986) introduced the bootstrap as a key technique for estimating standard errors and confidence intervals, while Manski (1988) brought new perspectives by incorporating analogue estimation methods in econometrics. Simar (1992) adapted these concepts to the analysis of panel data, proposing a semi-parametric approach that improved the statistical significance assessment of efficiency estimators. Later, Simar & Wilson (1998) advanced the field by introducing non-parametric tests for returns to scale, utilizing bootstrap procedures to reinforce statistical inference.

In 1999, Lothgren & Tambour applied the bootstrap to calculate confidence intervals for Malmquist productivity indices, revealing significant productivity changes. Simar & Wilson (1999) refined this approach with an iterative bootstrap procedure, enhancing confidence interval estimates in DEA models. In their 2007 study, Simar and Wilson integrated several preceding approaches, developing novel bias corrections and interpolation techniques to enhance the reliability of non-parametric estimators (Simar & Wilson, 2007).

In the port-maritime sector, non-parametric approaches can be found in a wide range of studies, demonstrating its versatility and applicability. In terms of a more global unit of analysis, studies such as Gutierrez *et al.* (2014) evaluated the efficiency of major international container shipping lines using a bootstrap DEA approach. Their study highlighted the presence of oversized operations and inefficiencies within strategic alliances. Following this, Chang *et al.* (2017) shifted focus to the cruise industry, using a network DEA model to reveal operational efficiency among major cruise lines, but also identified significant inefficiencies in non-operational aspects due to high debt and poor financial risk hedging.

Moving to cargo activities, Gil-Ropero *et al.* (2019) analysed the efficiency of the main container ports in Spain and Portugal using a DEA bootstrap-based approach. Their findings indicated that inefficiencies were present, but they were not necessarily due to a lack of infrastructure, as the bootstrapped results suggested that future investments in port expansion were not required. More recently, Danladi *et al.* (2024) extended the methodology to container ports in lower-middle-income countries, identifying that poor efficiency was mainly due to pure technical inefficiency rather than scale inefficiencies.

Following geographical criteria, Barros & Managi (2008) analysed the drivers of efficiency in Japanese seaports using a DEA bootstrapped two-stage approach. Their study highlighted the importance of identifying key efficiency drivers, offering valuable insights for policy strategies aimed at improving port productivity. Similarly, Hung *et al.* (2010) investigated the operational efficiency of Asian container ports by integrating a comprehensive DEA framework with bootstrap methods. Their research focused on determining scale efficiency targets and assessing the variability of efficiency estimates, providing crucial guidance for port managers to optimize resource allocation and improve operational performance. Nguyen *et al.* (2015) further extended this approach by applying bootstrapped DEA to assess the efficiency of 43 major Vietnamese ports, stressing that standard DEA tends to produce biased results—particularly sensitive to sample size—while bootstrapped DEA yields more consistent and unbiased efficiency scores.

Relevant studies have also expanded these approaches to other regions. In Europe, Carvalho *et al.* (2010) analysed the governance and performance of 33 seaports in the Iberian Peninsula, revealing significant inefficiencies due to mismanagement, political interference, and labour challenges, and highlighting the importance of governance models in improving port efficiency. In the Americas, Wanke & Barros (2015) investigated the role of public-private partnerships in enhancing scale efficiency in Brazilian ports. Their two-stage DEA analysis demonstrated that partnerships with private terminal operators significantly improved coordination, technology use, and connectivity, leading to greater efficiency. In a subsequent study, Wanke & Barros (2016) used bootstrapped DEA to confirm these findings, emphasizing the positive impact of connectivity infrastructure and private management on port performance, particularly in reducing costs and queuing times.

4.2.2. African efficiency analysis

Studies estimating the efficiency of African ports have increased since the early 21st century, predominantly utilizing non-parametric methods. Nonetheless, Zhang *et al.* (2024) notes in a recent literature review that Middle Eastern and African ports collectively accounted for only 6.6% of all port-efficiency research as of 2024. This discrepancy underscores the relative scarcity of in-depth analyses focused on African contexts, even as scholars acknowledge the region's growing economic and infrastructural significance.

One of the pioneering works in this area is by Al-Eraqi *et al.* (2008), which evaluates the efficiency of 22 cargo seaports across East Africa and the Middle East. The study employs DEA with a Window Analysis to assess both standard and super efficiency scores, drawing on panel data from 2000 to 2005. The findings indicate that the number of efficient decision-making units (DMUs) under the super-efficiency model exceeds those identified under the standard efficiency model. A follow-up study further applied both Standard DEA and Window Analysis to the same dataset, offering deeper insights into port efficiency and revealing the distinct advantages and disadvantages of each approach over time (Al-Eraqi *et al.*, 2010).

Subsequent research has continued to apply DEA Window Analysis to evaluate port efficiency across Africa. Gamassa & Chen (2017) used this method to compare major ports in East and West Africa, finding that West African ports, despite their larger size and higher throughput, were generally less efficient than their East African counterparts. Tema in Ghana was identified as the most efficient, while Dar es Salaam ranked the least efficient over seven years. The study recommended port development strategies based on these efficiency rankings. Kalgora *et al.* (2019) assessed the efficiency of five major commercial ports in West Africa, reporting a scale efficiency score of 89.53%. Ports like Abidjan and Cotonou were found to require adjustments in operational scale, and the study highlighted the impact of external factors such as pandemics and security threats on port efficiency. Most recently, Mwendapole *et al.* (2022) provided a recent example of this methodology, evaluating the operational efficiency of seaports in Southern and Eastern Africa over 10 years (2010–2019). They concluded that East African ports, despite being smaller, were generally more efficient than their South African counterparts.

By contrast, Barros *et al.* (2010) introduced a bootstrapped DEA approach to analyse the technical efficiency of 25 African seaports. Their findings revealed that the original efficiency scores were biased, making bootstrap methods essential for providing more reliable estimates. The results indicated that Nigerian seaports exhibited the greatest efficiency, followed by those in Mozambique and Angola. Diallo *et al.* (2022) likewise employed DEA bootstraps at the Autonomous Port of Dakar, identifying inefficiencies and offering insights for improved decision-making. Although these studies demonstrate the value of bootstrapped DEA, relatively few have integrated external governance variables—such as corruption—into their models.

Regarding standard DEA applications, Okeudo (2013) analysed the impact of reforms on the ports of Onne and Rivers, finding a continuous improvement in efficiency since 2006, with faster cargo handling, increased ship traffic, and higher berth occupancy. Carine (2015) extended the approach to 16 container ports in Sub-Saharan Africa, concluding that inefficiencies were primarily scale-related rather than technical. Van Dyck (2015) similarly assessed six major West African ports, reporting average efficiency scores above 76% for most. Focusing on East Africa, Ngangaji (2019) found comparable technical efficiency for Dar es Salaam and Mombasa, suggesting that "coopetition" strategies could further enhance overall port performance. Moreover, Birafane & Abdi (2019) focused on Moroccan seaports through the application of two DEA models (Standard with Charnes-Cooper-

Rhodes (CCR) and Banker-Charnes-Cooper (BCC); and scale of efficiency analysis), demonstrating that port expansions do not necessarily yield proportional gains in operational performance

Other non-parametric productivity methodologies have also been explored. Barros & Peypoch (2012) used the Luenberger productivity indicator, concluding that Nigerian ports were the most efficient, followed by Angola and Mozambique. Nwanosike *et al.* (2016) employed the Malmquist Productivity Index on six Nigerian seaports, revealing post-reform gains in technical efficiency but a decline in technological progress. Adeola Osundiran *et al.* (2020) further examined 19 Sub-Saharan African ports (from 2008 to 2015), identifying technical efficiency as the main driver of productivity and recommending a continuous port improvement framework.

In contrast, parametric analyses are relatively scarce. Trujillo *et al.* (2013) employed a Stochastic Production Frontier (SPF) to examine reforms in 37 African ports, finding moderate yet consistent efficiency improvements. The study identified corruption, port size, Gross Domestic Product (GDP), and the landlord port model as influential determinants. Similarly, Akinyemi (2016) focused on Nigeria's port reforms using a SPF approach, reporting notable gains in cargo throughput and berth occupancy. More recently, Ayesu *et al*. (2023) used a System-Generalised Method of Moments to assess seaport efficiency for 28 African countries, concluding that higher performance in these dimensions strongly correlates with economic growth. Subsequently, Ayesu *et al.* (2024) took a gravity-based approach to 33 African countries, demonstrating that improved seaport efficiency significantly boosts trade performance.

Table IV.1 summarizes the principal works on African port efficiency. Notably, none of these studies combine African ports with those operating under different political and legislative contexts. To our knowledge, only Trujillo *et al.* (2013) have incorporated corruption as a contextual variable in efficiency analyses of African ports, focusing primarily on the impact of reforms on productivity. Considering this gap, the present article proposes an integrated assessment that examines major West African ports alongside key Atlantic ports from the Canary Islands, which operate under EU regulations. By including corruption as a contextual variable, our approach aims to offer new insights into how governance disparities shape port efficiency, thereby contributing to the broader literature on maritime performance.

Table IV. 1. Summary of the Literature Review on Efficiency Studies in Africa

Year	Authors	Unit of analysis	Methodology
2008-2010	Al-Eraqi *et al*.	22 cargo seaports across East Africa and the Middle East	Standard DEA and DEA Window Analysis
2010	Barros *et al*.	25 African seaports 2004-2006	DEA bootstraps
2013	Okeudo	Onne and its river ports from 2001 to 2010	Standard DEA
2013	Trujillo *et al.*	1998 and 2007 across 37 African ports.	SPF
2015	Carine	16 container port of Sub-Saharan Africa over the year 2012	Three DEA models: CCR, BCC, and Super-Efficiency
2015	Van Dyck	Six major West African ports for the period 2006-2012	Standard DEA
2016	Akinyemi	Nigerian seaports from 2000 to 2011	SPF
2016	Nwanosike *et al.*	Six major Nigerian seaports from 2000 to 2011	Malmquist Productivity Index
2017	Gamassa & Chen	Eastern and Western African ports from 2008 to 2014	DEA Window
2018	Wanke *et al.*	Six major Nigerian ports from 2007 to 2013	Two-Stage Fuzzy-DEA models

2019	Kalgora *et al.*	West-Africa Ports over the years 2005-2016	DEA Window
2019	Ngangaji	Dar es Salaam and Mombasa Port from 2008 to 2018	Standard DEA
2019	Birafane & Abdi	Eight seaports in the Kingdom of Morocco from 2014 to 2017	Two DEA models (Standard with CCR and BCC, and scale of efficiency analysis)
2020	Adeola Osundiran	19 Sub-Saharan African ports from 2008 to 2015	Malmquist Production Index
2022	Diallo *et al.*	Autonomous port of Dakar for the year 2021	DEA bootstraps
2022	Mwendapole *et al.*	Six South and East African seaports from 2010 to 2019.	DEA Window
2023	Ayesu *et al.*	28 African countries, using data from 2010 to 2018	Generalized Method of Moments

Sources: Own Elaboration.

4.3. METHODOLOGY

One of the significant characteristics of the standard Data Envelopment Analysis (DEA) method is its deterministic nature, which precludes the derivation of statistical properties for the efficiency scores. A more attractive solution involves the application of bootstrap methodology, which preserves the advantages of DEA while enabling the extraction of statistical properties from a data-driven scheme. Accordingly, this analysis adopts a fully non-parametric approach, wherein an iterative bootstrapped procedure characterizes the production set. The estimation of non-parametric efficiencies using bootstrap methodology not only yields more consistent efficiency measurements but also facilitates the detection of extreme values. Under the standard DEA method, some ports are deemed efficient (i.e., they receive an efficiency score of one); however, the bootstrapped DEA is particularly effective in addressing this overestimation problem (Barros *et al.*, 2010). According to Simar & Wilson (2000), the application of bootstrap methodology results in more robust and consistent outcomes.

Consequently, this study employs the DEA methodology to measure pure technical efficiency. In a subsequent stage, the DEA-Bootstrap-BCC model is utilized to derive more reliable efficiency rankings for the Spanish ports. All calculations were performed using software developed by the authors. The methodological details are provided in *Sections 4.3.1* and 4.*3.2*.

4.3.1. Data Envelopment Analysis (DEA) methodology

The DEA methodology is a non-parametric technique and does not assume any functional form for the relationship between inputs and outputs, or any distribution of inefficiency. Furthermore, it is capable of handling situations with multiple inputs and outputs, expressed in different units. It is precisely these advantages that have favoured the extensive use of DEA. Applying DEA methodology, the efficient frontier can be defined by either an input orientation (minimal achievable input level for a given output) or an output orientation (maximal achievable output given the input level).

In this study, an output-oriented DEA model is employed to estimate Pure Technical Efficiency (PTE) under Variable Return Scale (BCC–VRS), commonly referred to as the BCC-VRS model. Suppose that there are ***n*** Decision Making Units (DMUs)- in this context, the port under analysis-each using ***m*** inputs X_{ij} ($i = 1\ldots, m$) to produce ***s*** outputs Y_{rj} ($r = 1\ldots, s$). Let $X_{ij} > 0$ denote the amount of input i used by DMU j and Yrj > 0 the amount of output r produced by DMUj.

Following Charnes *et al.* (1978) and Banker *et al.* (1984), the output-oriented VRS (BCC) model can be formulated in matrix form as follows:

$$\text{Max } \theta + \varepsilon \left(\sum_{i=1}^{m} S_i^- + \sum_{r=1}^{s} S_r^+\right) \quad \text{(IV.1)}$$

subject to:

$$\sum_{j=1}^{n}(\lambda_j x_{ij}) + S_i^- = x_{io} \qquad i = 1,2,\ldots,m;$$

$$\sum_{j=1}^{n}(\lambda_j y_{rj}) - S_r^+ = \theta y_{ro} \qquad r = 1,2,\ldots,s;$$

$$\lambda_j \geq 0 \qquad j = 1, 2\ldots, n.$$

$$\sum_{j=1}^{n}\lambda_i = 1$$

Where:

- Y_{ro} and X_{io} the r_{th} output and i_{th} input for a DMU_o under evaluation
- λj the decision variables that represent the weights DMU *j* would place on DMU_o in constructing its efficient reference set
- θ the proportional distance in inputs to the envelope and therefore the measurement of the index of technical efficiency
- ε the smallest real positive number
- S_i and S_r the potential slacks or excess factor for each input

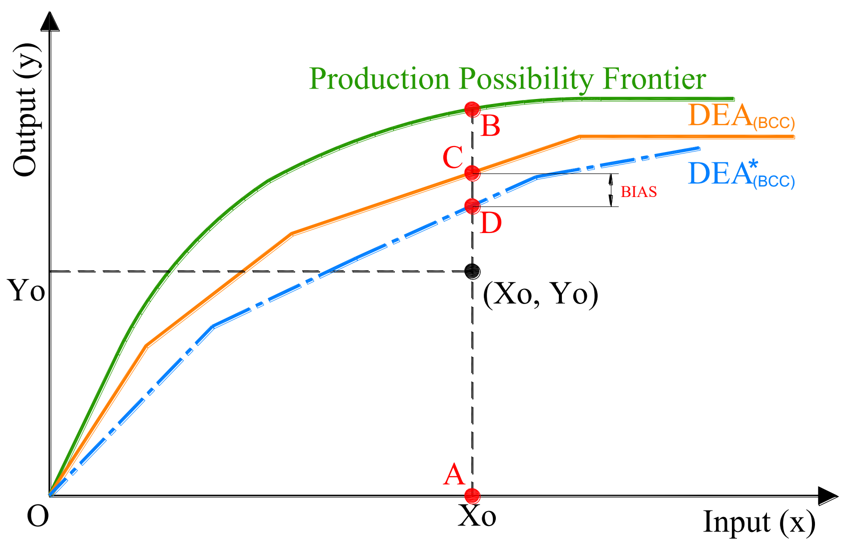
In brief, the output-oriented BCC model thus provides a measure of how much each DMU (port) can proportionally increase its outputs, given its current input levels, before reaching the efficient frontier.

4.3.2. Bootstrapped DEA methodology

Simar & Wilson (1999) proposed an algorithm to obtain bootstrap estimates of confidence intervals, bias, and other statistical properties for the output distance function $\theta_{(x_0,y_0)}$ evaluated for a particular, arbitrary point $(x_0, y_0) \in R_+^{p+q}$, provided that the corresponding estimate $\hat{\theta}_{(x_0,y_0)}$ exists.

The concept discussed above is illustrated in ***Figure IV. 1***, which depicts the production possibility frontier under variable returns to scale, along with the standard DEA and bootstrap DEA frontiers. Under the assumption that the smooth bootstrap holds, it is expected that: $[\widehat{\theta^*}_{(x_0,y_0)} - \hat{\theta}_{(x_0,y_0)}] \sim [\hat{\theta}_{(x_0,y_0)} - \theta_{(x_0,y_0)}]$

Figure IV. 1. Graphic representation of Bootstrap Output-Oriented



Source: Gil-Ropero et al., (2019).

4.4. CHARACTERISTIC OF THE SAMPLE

The dataset used to estimate efficiency scores comprises 16 seaports: two Spanish ports—Las Palmas and Santa Cruz de Tenerife (St. Cruz Tfe.), both in the Canary Islands Archipelago—and 14 seaports located across the West African mainland (see ***Table IV. 2***). As previously noted, including the two Spanish ports introduces a distinctive dimension to the analysis. Although these ports are geographically situated off the African coast, they operate under EU regulations, thereby creating a regulatory contrast within the sample. This contrast sheds light on the competitive advantages and governance disparities across the ports, ultimately allowing for a more realistic comparison of efficiency scores. Moreover, despite belonging to different countries, these ports share overlapping spheres of commercial influence, further underscoring the relevance of their joint assessment.

Table IV. 2. Ports, Port Authorities and Countries

Port	Port Authority	Country
Cape Town	Transnet National Port Authority	South Africa
Casablanca	Agence Nationale des Ports	Morocco
Cotonou	Port Autonome de Cotonou	Benin
dÀbidjan	Port Autonome of Abidjan	Cote d' Ivoire
Dakar	Port Autonome de Dakar	Senegal
Doula	Port Autonome de Douala	Cameroon
Durban	Transnet National Port Authority	South Africa
East London	Transnet National Port Authority	South Africa
Luanda	Empresa Portuaria de Luanda UEE	Angola
Las Palmas Port	Port Authority of Las Palmas	Spain
Onne	Nigerian Ports Authority	Nigeria
Port Elizabeth	Transnet National Port Authority	South Africa
St Cruz Tfe. Port	Port Authority of St. Cruz Tfe.	Spain
Tanger Med	Tanger Med Port Authority	Morocco
Tema	Ghana Ports and Harbours Authority	Ghana
Walvis Bay	Namibian Ports Authority	Namibia

Source: Own Elaboration.

The ports (see ***Figure IV. 2***) were selected based on their geographical proximity, operational capacities (movements of Twenty-Foot Equivalent Units (TEUs) by port), traditional main port of the area and competitive relevance within the Mid-Atlantic cargo traffic network (Rodriguez *et al.*, 2025). This sample represents a diverse cross-section of West African ports, which include hubs such as Dakar, Tema, and Tanger Med. These ports exhibit varying governance structures, infrastructure capabilities, and investment levels. Ports like Tanger Med and Tema stand out for their advances in digitalization and high connectivity, as demonstrated by their strong rankings in the Port Liner Shipping Connectivity Index (PLSCI) by the United Nations Conference on Trade and Development

(UNCTAD). Conversely, ports like Abidjan and Dakar serve as critical gateways for landlocked countries, connecting them to global trade networks despite operational inefficiencies.

Figure IV. 2. Maps of selected Ports for the analysis

Source: Own Elaboration.

The Spanish ports are administered under the centralized framework of *Puertos del Estado*[21], ensuring uniform operational standards and benefiting from a regulatory regime, which emphasizes security, transparency, and efficiency (European Commission, 2020). This governance model stands in marked contrast to that of many African ports, where operations are often overseen by private

[21] Official website https://www.puertos.es/

concessions or decentralized authorities. Such arrangements can give rise to challenges, including corruption and bureaucratic inefficiencies in port performance.

Although significant dichotomies exist between EU-compliant ports and those managed under diverse national or private regimes, numerous initiatives have been undertaken to support the African continent in various areas. For example, China's Belt and Road Initiative has driven substantial investments in ports such as Tema and Lomé, leading to notable infrastructural enhancements. Moreover, regional trade policies championed by the African Union [22] and Economic Community of West African States (ECOWAS)[23] aim to reduce reliance on external hubs, like the Canary Islands, by strengthening intra-African trade. Nevertheless, prevailing indicators—including the corruption index and other socio-economic measures—suggest that much progress remains to be made.

Covering the period from 2011 to 2020, this analysis captures a decade of evolving dynamics within this competitive maritime landscape. Data were sourced from the Transparency International, World Bank, IHS Markit SeaWeb, UNCTAD, and Shipping Guides publications, providing a robust foundation for a nuanced comparison of port efficiency[24].

4.4.1. Variables of the empirical model

In this study, the analysis is confined exclusively to the container handling service—specifically, the loading and unloading operations carried out at port

[22] See the official website for more details https://au.int/

[23] See the official website for more details https://www.ecowas.int/

[24] It is important to note that significant challenges remain in obtaining reliable data from African ports for accurate efficiency analysis. Consequently, constructing a comprehensive data panel has required direct engagement with port agents, the procurement of specialized data collections—including the purchase of data—and contributions toward developing new databases. In this study, these measures have been implemented to effectively address the inherent difficulties in data acquisition.

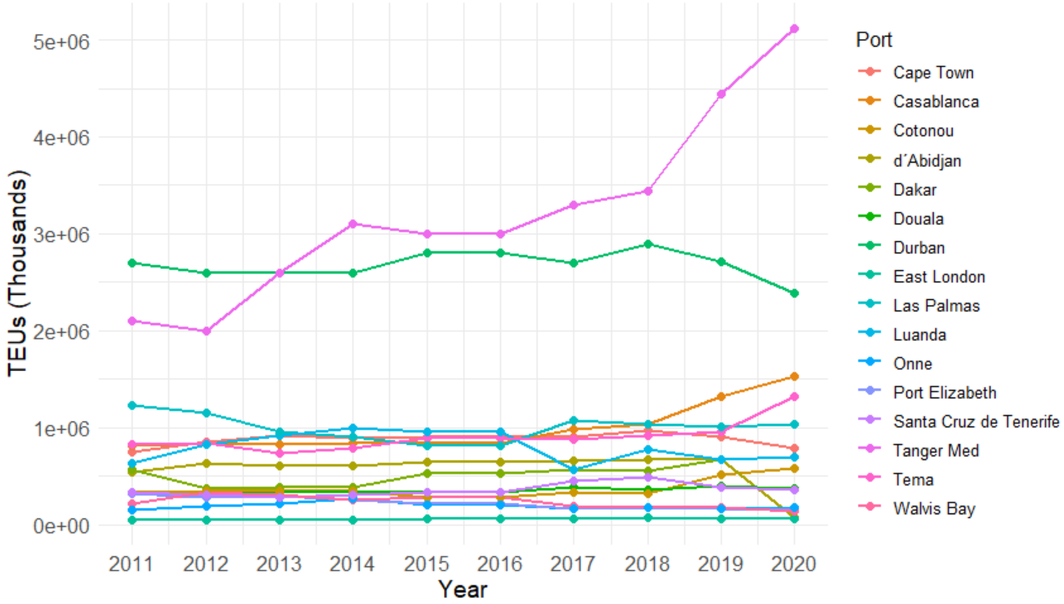
terminals. This focus is crucial for accurately selecting the appropriate output and input data, as ports function as multi-service entities and a clear delineation of the evaluated service ensures methodological rigor. A robust framework for defining variables in port efficiency studies has been extensively developed in the literature, with seminal contributions by Cullinane *et al.* (2004, 2006). Building on these foundations, the variables selected for the present analysis adhere to widely accepted inputs and outputs in the field.

4.4.1.1. Output variable

The output variable (Y) is defined as container throughput, measured in TEUs. This indicator is universally recognized as the most critical metric in port efficiency studies, as it encapsulates the volume of cargo processed by a terminal and serves as a key proxy for productivity and operational effectiveness.

The ***Figure IV.3*** illustrates the evolution of container throughput (in thousands of TEUs) across the sample (from 2011 to 2020). The data reveal notable differences in both absolute volumes and growth trajectories: while certain ports exhibit a pronounced upward trend—surpassing five million TEUs by 2020—others have more modest figures, reflecting diverse operational scales and investment levels. Such variation underscores the importance of contextual factors, including infrastructure capacity, geographic location, and trade routes, in shaping port performance and container handling efficiency.

Figure IV. 3. TEUs (Thousands) Evolution by Port



Source: Own Elaboration.

4.4.1.2. Infrastructure variable (Fixed Variables)

The primary input variable (X_1) is the total length of berths designated for container handling, expressed in meters. This measure reflects a port's capacity to accommodate large vessels, particularly those with drafts exceeding 14 meters, and is regarded as a crucial determinant of port infrastructure and operational efficiency.

4.4.1.3. Capital variable (Quasi-Fixed Variables)

The secondary input variable (X_2) is the total number of quay gantry cranes at the port, recorded as a unit count. These cranes are integral to container operations, directly influencing the speed and efficiency of loading and unloading processes. Consequently, the number of quay gantry cranes serves as an indicator of the capital investment in port equipment and the terminal's capacity to handle containerized cargo.

4.4.1.4. Control variable

In the estimate, port connectivity (C) is included as a control variable. In this specific case, including a connectivity variable is indispensable. Although African ports have not yet reached the development levels of their European counterparts—due to security restrictions and other constraints—many exhibit robust connectivity in terms of trade routes and commerce. This reality underscores the need to incorporate a measure that reflects the degree to which ports are integrated into global maritime networks.

The rationale for incorporating connectivity into productivity and efficiency analyses lies in the pivotal role of ports as intermodal hubs, bridging maritime and land-based logistics while addressing increasingly complex supply chain demands (Ducruet, 2020). Despite its recognized importance, relatively few studies have integrated connectivity measures into port efficiency models.

Among the earliest contributions, Suárez-Alemán *et al.* (2016) employed the Liner Shipping Connectivity Index (LSCI), developed by UNCTAD, to evaluate how effectively ports integrate into global maritime networks. Their findings revealed a direct influence of connectivity on container throughput, particularly in developing regions. Building on this work, Serebrisky *et al.* (2016) applied the LSCI at a national scale in a stochastic frontier analysis, corroborating its positive impact on port productivity. In a similar vein, Schøyen *et al.* (2018) used the LSCI within a DEA framework to assess port efficiency in the North Sea/Baltic region.

Moreover, Tovar & Wall (2022) introduced the Port Liner Shipping Connectivity Index (PLSCI) as an explanatory variable in the inefficiency term of a stochastic output distance function. Their results indicated a direct correlation between heightened connectivity and increased efficiency, with even marginal enhancements in the PLSCI yielding substantial gains in output. Further advances include Yen *et al.* (2023), who investigated the influence of smart port designs on shipping efficiency using the PLSCI, and Nadarajan *et al.* (2023), who incorporated the LSCI as a dependent variable alongside GDP to examine seaport network efficiency.

Recent studies further enhance this perspective. Nguyen & Kim (2024) have provided empirical evidence that the COVID-19 pandemic significantly impacted port connectivity, operational efficiency, and resilience in major container ports in Southeast Asia. Their application of social network analysis reveals that even amidst disruptions, robust connectivity is essential for maintaining competitive performance. Similarly, Jin *et al.* (2024) have demonstrated that the LSCI is dynamically linked not only to port performance but also to broader economic indicators, such as energy trade and inclusive growth, thereby highlighting the multifaceted implications of connectivity in maritime economics.

For this analysis, the PLSCI—expressed as an index ranging from 0 to 100, following the UNCTAD methodology prior to 2023—is employed to capture a port's connectivity and its bearing on operational efficiency. A higher index value indicates stronger integration into global shipping networks.

4.4.1.5. Objective Variable

As mentioned, the objective variable of this study (Z) is the Corruption Perceptions Index Score (CPI). Developed by Transparency International in 1995, the CPI measures public sector corruption at the national level by aggregating data from 13 independent sources provided by 12 institutions, including the World Bank. It captures perceptions of corruption from business executives and country experts, assessing its impact on public sector institutions. Countries are scored on a scale from 0 to 100, where 0 indicates high perceived corruption and 100 represents a corruption-free public sector[25].

In the context of this study, the CPI is used as a proxy for the national institutional and bureaucratic environment, reflecting broader administrative and security conditions that influence port operations. This approach recognizes that ports operate within national governance frameworks that shape operational environments, including regulatory efficiency, political stability, rule of law, and public sector integrity. These elements indirectly impact port performance by influencing dwell times, customs processing, security risks, and logistics reliability.

Unlike port-specific metrics, the CPI captures country-level governance dynamics, providing a comprehensive view of the environment in which ports function. It reflects the quality of public administration and security standards that affect port competitiveness and integration into global maritime networks. This influence is significant not only for public ports but also for privately operated ports, as they are equally embedded within the broader national governance context. Regardless of ownership structure, the efficiency, security, and overall performance of ports are shaped by the regulatory and institutional climate of the host country. Therefore, the CPI is not merely a corruption measure but an indicator of the overall institutional climate.

Recent literature reinforces this broader interpretation of the CPI. Budsaratragoon & Jitmaneeroj (2020) argue that the CPI captures complex governance dimensions, including political stability, regulatory quality, and institutional trust. Their study highlights how these factors interconnect to

[25] The CPI's calculation methodology involves selecting credible sources that provide valid, comparable, and reliable data based on expert opinions. To enhance reliability and minimize biases, the CPI averages at least three different sources per country.

influence the business climate and governance efficiency, validating the use of the CPI in assessing national administrative conditions affecting port operations.

When analysing the global landscape, the CPI reveals significant regional disparities. Sub-Saharan Africa continues to have the lowest average CPI score, with a regional average of 33, highlighting the persistent challenges of governance and rule of law in the region. Democracy is under pressure in many African nations, where corruption and weak institutional frameworks exacerbate the lack of accountability and hinder effective governance.

In contrast, Western Europe and the EU continue to maintain the highest regional averages, with the CPI score dropping to 65 in recent years. This decline signals a weakening of political integrity, erosion of checks and balances, and the growing threat of corruption in even traditionally strong institutions. While some countries in the region show improvements, the overall trend reflects concerns over transparency and accountability, undermining their long-held status as the global leaders in governance and anti-corruption efforts.

The rest of the world, including regions like Eastern Europe and Central Asia, faces stagnation in corruption reduction efforts. In these regions, systemic corruption, the rise of authoritarian governance, and the dysfunctional rule of law have led to limited progress in governance reforms. Similarly, the Middle East and North Africa show little improvement, with countries continuing to struggle with political corruption, conflict, and a lack of transparency in governance processes. Asia Pacific also faces long-term stagnation, although some historically top-ranking countries, such as Singapore, have seen a reversal in their progress.

In the Americas, the weak rule of law and lack of judicial independence continue to enable widespread impunity, affecting governance and contributing to corruption in public institutions. While some countries show small improvements, overall, the region struggles to make meaningful progress.

Despite the global challenges, some countries, including a few in Africa, have significantly improved their CPI scores over the last decade, showing that progress is possible even in environments with entrenched corruption. However, the overall trend indicates that most regions face substantial barriers to curb corruption, with impunity, weak judicial systems, and poor governance continuing to plague efforts to fight corruption.

For the purposes of this study, the CPI has been inverted to facilitate interpretation in the model. In its transformed form, higher values reflect worse levels on the index (i.e., higher perceived corruption and weaker governance), while lower values indicate better index scores (i.e., lower perceived corruption and stronger governance). This adjustment ensures a more intuitive understanding of the variable's influence on port performance, aligning with conventional interpretations of institutional and administrative quality.

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

Table IV. 3. Statistical summary of data used (2011-2020)

Variable	Name	Description	Mean	Std. Dev.	Min	Max
			Output Variable			
TEUs	Y	Number	834,630.00	895,183.80	41,957.00	5,122,630.00
			Input Variables			
Length of berths	X_1	Metres	1,982.69	1,481.12	256.00	5,336.00
Cranes	X_2	Number	11.56	11.60	0.00	37.00
			Control Variable			
PLSCI	C	Index	20.79	12.00	2.30	64.98

Objective Variable						
CPI	Z	Invert Index	0.027	0.01	0.02	0.07

Source: Own Elaboration.

4.5. RESULTS

An output-oriented DEA bootstrap methodology, as described in *Sections 4.3.1* and 4*.3.2* of, has been applied to the sample of 16 ports, detailed in *Section 4.4.* The efficiency index measures the distance of each port to the nearest most efficient DMU (port) located on the frontier. This approach allows for a robust and consistent estimation of efficiency scores by addressing the potential overestimation problem inherent in the standard DEA method.

As investments in port infrastructure are typically lumpy and port expansion projects usually take several years to complete, the amounts of these inputs may remain constant over extended periods, followed by a sudden addition of port capacity. Compared to the low variation in inputs, container throughput tends to change rapidly over the years (Wan *et al.,* 2012). Therefore, the output-oriented model is the most suitable for obtaining operating efficiency in this context.

First, the Variable Returns to Scale (VRS – BCC) model is used to estimate pure technical efficiency (PTE). At a second stage, an output-oriented bootstrapping approach was applied to evaluate the presence of scale inefficiency (the simulations were replicated 2,000 times, ensuring the robustness of the efficiency estimates).

To achieve the analytical objective, two main estimations have been developed:

- The first estimation, called the *Base Model* (BM), excludes consideration of the CPI. This estimation focuses solely on the traditional operational characteristics of each port related to cargo handling services. It evaluates operational efficiency without considering regulatory or institutional factors.

- The second estimation, named the *Adjusted Model* (AM), incorporates the CPI as an additional variable. This model considers the impact of the regulatory environment, including aspects related to corruption, on the efficiency scores of ports. By including the CPI alongside traditional operational variables, this approach provides a more comprehensive view of the factors influencing port efficiency.

4.5.1. Estimation analysis

Table IV. 4 presents the values obtained for both DEA and bootstrap DEA efficiencies for BM and AM models. The results indicate that to achieve efficiency with the same input values (i.e., maintaining the existing facilities and infrastructure), ports would require increased production. Over the entire period studied and for both approaches (DEA and DEA bootstrap), substantial reductions in efficiency were observed.

Table IV. 4. Efficiencies Average BCC DEA and BOOTSTRAP (2011-2020) for BM and AM models

BM					AM				
Port Name	***Rank***	***BCC DEA***	***Rank***	***BOOTSTRAP***	**Port Name**	***Rank***	***BCC DEA***	***Rank***	***BOOTSTRAP***
Tanger Med	**1**	1.00000	**1**	0.76595	Tanger Med	**1**	1.00000	**1**	0.84830
Durban	**2**	1.00000	**2**	0.75532	Durban	**2**	1.00000	**2**	0.84202
Casablanca	**3**	1.00000	**3**	0.74201	Walvis Bay	**3**	1.00000	**3**	0.84017
East London	**4**	1.00000	**4**	0.74187	Las Palmas	**4**	1.00000	**4**	0.83964
Onne	**5**	1.00000	**5**	0.74095	St Cruz Tfe.	**5**	1.00000	**5**	0.83903

Luanda	**6**	0.69989	**6**	0.60360	Onne	**6**	1.00000	**6**	0.83893
St Cruz Tfe.	**7**	0.61932	**7**	0.57665	East London	**7**	1.00000	**7**	0.83814
Tema	**8**	0.59861	**8**	0.53174	Casablanca	**8**	1.00000	**8**	0.83806
Douala	**9**	0.58486	**9**	0.48480	Port Elizabeth	**9**	0.91630	**9**	0.77283
Cape Town	**10**	0.52726	**10**	0.47443	Tema	**10**	0.70328	**11**	0.65270
Cotonou	**11**	0.51375	**11**	0.46540	Luanda	**11**	0.69989	**10**	0.65711
Las Palmas	**12**	0.49588	**12**	0.45655	Cape Town	**12**	0.62536	**12**	0.58665
d´Abidjan	**13**	0.48728	**13**	0.44609	Douala	**13**	0.58486	**13**	0.53614
Dakar	**14**	0.44677	**14**	0.42130	d´Abidjan	**14**	0.53468	**14**	0.51402
Walvis Bay	**15**	0.30940	**15**	0.28421	Cotonou	**15**	0.51375	**15**	0.49282
Port Elizabeth	**16**	0.22201	**16**	0.18514	Dakar	**16**	0.45299	**16**	0.43808

Source: Own Elaboration.

The estimation revels that during the period 2011–2020, only five seaports—Casablanca, Durban, East London, Tanger Med, and Onne—achieved a PTE score of 1, indicating optimal operational performance under the standard BCC DEA model. However, the bootstrapped efficiency scores reveal that none of the ports maintain full efficiency, demonstrating the bootstrapped DEA's ability to provide a more conservative and reliable estimation by addressing the overestimation present in the standard approach. These scores are consistently lower than the standard DEA results, especially in ports previously deemed fully efficient, reflecting adjustments for statistical noise and bias. Despite this, the bias in inefficient ports remains minor and substantially below 1 percent, suggesting consistent inefficiencies unaffected by random variations, thereby reinforcing the robustness of the findings.

Over the period 2011–2020 (*See **APPENDIX 3** and **4***), the BCC DEA results indicate a relatively stable trend in efficiency scores for the most efficient ports, which consistently appear on the efficiency frontier. These ports demonstrate operational stability and optimal resource utilization. In contrast, the other ports exhibit fluctuating efficiency scores, reflecting operational inconsistencies and variations in performance over time. The bootstrapped results, however, reveal a more dynamic pattern, with no port maintaining full efficiency throughout the decade. Ports like Durban and Tanger Med consistently achieved relatively high scores, although below 1, highlighting near-optimal performance when adjusted for statistical noise. Conversely, Port Elizabeth and Walvis Bay persistently displayed low efficiency scores, reflecting structural inefficiencies.

These differences can certainly be attributed to the fact that the estimation of efficiency scores by DEA analysis depends on the discretization in the frontier estimation. Similarly, the results are sensitive to data sampling. Consequently, the port efficiency values averaged from the DEA analysis tend to be overestimated. In contrast, the bootstrapped DEA methodology proves to be a fundamental tool for obtaining more realistic efficiency scores by addressing this peculiarity while retaining the advantages of traditional DEA. Moreover, bootstrapped DEA provides more robust efficiency results, enhancing the reliability of the analysis.

The efficiency gap between the estimations remained significant throughout the period, with average differences ranging from 15% to 20%. This discrepancy is particularly noticeable in years of economic fluctuations and trade disruptions, suggesting that the standard DEA model is more sensitive to external shocks, whereas the bootstrapped DEA offers a more consistent evaluation.

As shown in ***Table IV.4***, the two European ports included in the sample are positioned at the bottom of the efficiency rankings. However, in practice, shipping lines more commonly choose European ports over those in Africa due to safety and regulatory considerations. This highlights the paradox that, despite their medium-low efficiency scores, European ports in Africa maintain a competitive advantage linked to their robust regulatory frameworks.

It is also important to note that, efficiency rankings are typically calculated based on TEUs handled relative to quay length and the number of fixed quay cranes. However, many vessels operating in African ports are equipped with their own cranes for loading and unloading containers, effectively increasing the available lifting capacity. This factor may contribute to unexpectedly high efficiency scores for some ports with limited infrastructure, potentially distorting comparisons with European ports such as Las Palmas and Santa Cruz de Tenerife.

4.5.2. BM and AM comparative analysis

To better understand this discrepancy, ***Figure IV. 4*** shows graphically the Hierarchical ordering of the bootstrapped model. Including the CPI provides a more accurate and realistic reflection of port efficiency by considering the legal and regulatory environment influencing port operations. This approach acknowledges that the competitive edge of European ports is not solely due to operational efficiency but is also significantly influenced by their institutional and regulatory contexts.

Moreover, the results show that African ports perform similarly to European ports in terms of infrastructure and operational capacity, which reinforces the idea that the real differentiating factor lies in the regulatory and legal environment.

By incorporating the CPI, the analysis accounts for non-operational factors that shape port choice and efficiency, enhancing the relevance and interpretability of the results. This not only aligns efficiency scores with real-world dynamics but also quantifies the impact of the regulatory environment on port performance, bridging the gap between operational efficiency and market perception.

The most significant change in the ranking occurs with the two European ports in the sample, Las Palmas and Santa Cruz de Tenerife. These ports move from medium-low positions to high positions when the CPI is considered. In the case of the bootstrap estimation—which provides a more robust interpretation—Santa Cruz de Tenerife advances from 7th to 5th place, while Las Palmas makes a remarkable leap from 13th to 4th place.

In the case of Las Palmas, this result is particularly revealing, as the inclusion of the CPI accounts for more than 50% of the reason for its rise to the top of the ranking. This illustrates how these ports benefit from being part of a stronger institutional system, which—when objectively measured—proves to be their most decisive comparative advantage.

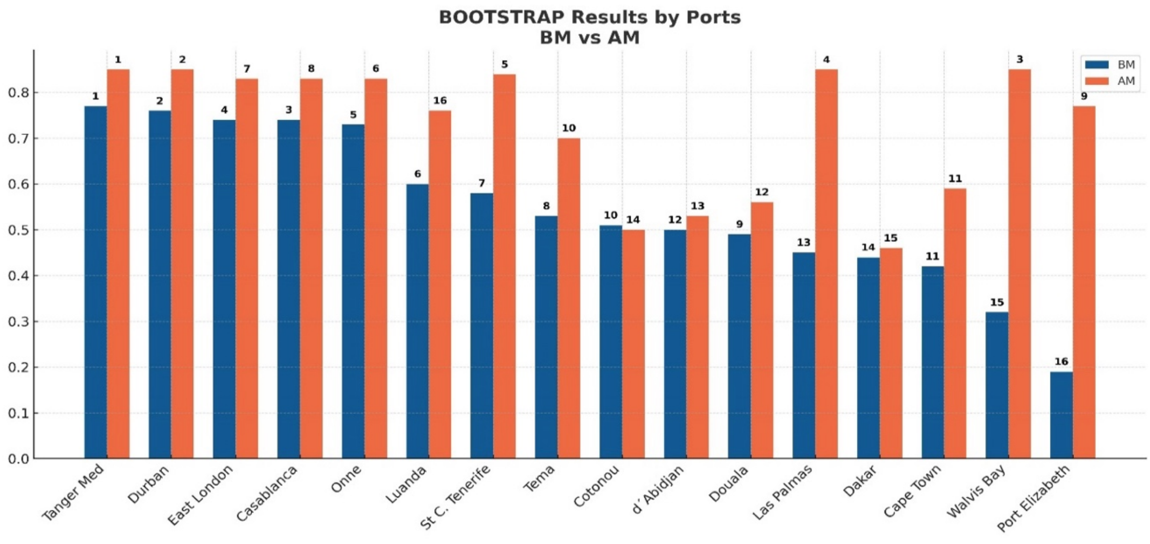
Turning to the African ports, the results indicate a structural advantage for some ports regardless of the CPI inclusion. Specifically, Tanger Med and Durban consistently maintain the top positions, underscoring their operational efficiency and strategic importance. However, it is also evident that most African ports suffer a relative decline in the adjusted model, not due to technical or logistical deficits, but because of their more fragile institutional and regulatory frameworks. This suggests that African ports do not lag behind in capacity or functionality, but in governance indicators that weigh heavily in comparative assessments.

It may appear paradoxical that the port of Tanger Med maintained its leading position in both the BM and the AM, while the port of Casablanca experienced a significant drop—from third to eighth place—despite both being located in Morocco. This divergence can be explained by their differing governance structures. Tanger Med is considered a national strategic project, directly managed by the Tangier Med Special Agency (TMSA), a fully state-owned public company endowed with governmental powers. In contrast, Casablanca is regulated by the

Agence Nationale des Ports (ANP), which oversees port safety and environmental issues and manages an additional 33 Moroccan ports. This distinction in governance highlights how institutional configuration can decisively shape performance outcomes, even within the same national context.

A noteworthy positive impact is observed for Walvis Bay, which moves from the lower end of the BM to an impressive 3rd place in the AM. This highlights the port's significant improvement when regulatory and institutional factors are considered, suggesting a competitive advantage linked to its governance and legal framework. This case exemplifies how improvements in institutional quality can dramatically shift a port's perceived efficiency and reinforce its attractiveness in international logistics networks.

Figure IV. 4. Hierarchical ordering according to BOOTSTRAP Efficiency values/Average 2011 – 2020 for BM and AM model



Source: Own Elaboration.

This analysis is particularly relevant given the emerging trade dynamics affecting European ports, including those located in Africa, as they face increasing pressure to reduce carbon emissions in the maritime sector. The *Fit for 55-FuelEU* Maritime initiative, implemented by the EU, aims to reduce emissions by 55% by 2030 and 90% by 2050 (EU, 2021). In response, new trade routes are being developed to minimize the carbon footprint, potentially altering logistics patterns and influencing port choice. While necessary for climate goals, these regulatory shifts introduce asymmetric burdens that may disproportionately affect outermost regions.

These changes are likely to impact the comparative advantages of European ports in Africa, as they must comply with restrictions that their direct competitors are not required to follow, leading to a potential decline in port activity. This impact is particularly significant for European ports located in island regions, where port activity is a crucial industry, given that around 90% of goods arrive by sea (Trujillo *et al.*, 2025). This reality poses a threat not only to the industry but also to the specific social and economic fabric of the Canary Islands.

In this context, if future environmental or bureaucratic requirements were to compromise the current levels of legal stability or increase administrative complexity in these ports, they could lose their institutional edge. This could cause a diversion of maritime traffic to less regulated and more agile West African ports, altering regional balances in port competition.

In contrast, African ports are not subject to the same regulatory pressures related to carbon emissions, which may enhance their competitive position relative to European counterparts. If the regulatory landscape becomes more stringent for European ports—including those geographically located in Africa—they could lose their comparative advantages, and experience declines in efficiency levels.

This raises a broader policy dilemma: while the EU advocates for free competition and environmental ambition, it must also ensure that this does not come at the expense of regions that, due to their insularity and economic dependence on maritime trade, require a differentiated approach. The Canary Islands could serve as a paradigmatic case for future discussions about regulatory adaptation and territorial equity.

4.6. Conclusion and discussion

This study presents an updated efficiency analysis of West African ports using the bootstrap DEA approach, recognized as the most robust methodology for addressing overestimation issues in standard DEA models. The research contributes to the literature by updating the efficiency calculations for African ports, a topic that remains underexplored, and establishes a comparative framework with European ports on the African West coast. This framework provides valuable insights into the competitive dynamics between African and European ports, especially given their geographical proximity and overlapping hinterlands.

The findings reveal that, when using the bootstrap approach to obtain a more realistic and robust estimation, none of the ports reach the efficiency frontier, suggesting that there is no immediate need for further investments to expand port infrastructure unless container traffic demand significantly increases. This result challenges the conventional notion that African ports require continuous capacity expansion and instead suggests a more strategic approach to resource allocation.

The comparison between the ports in the sample (including those from Africa and the EU) reveals a critical insight: there are no significant differences in terms of infrastructure and TEU movements between the two groups. This finding suggests that operational efficiency in African ports is not primarily constrained by infrastructure limitations but rather by non-operational factors. Notably, when the Base and Adjunct models were considered (both with and without the inclusion of the CPI), the regulatory and institutional environment emerged as a decisive factor influencing efficiency levels. The results demonstrate that the competitive advantage of European ports is significantly strengthened by their robust regulatory frameworks, which enhance security, transparency, and operational consistency. This observation is consistent with previous studies that emphasize regulatory stability as a key competitive advantage for European ports.

However, the study also reveals that African ports have the potential to achieve better efficiency levels, comparable to their European counterparts, if non-operational barriers such as policy and bureaucracy-related constraints are addressed. This underscores the importance of institutional reforms to enhance competitiveness, particularly as African ports face increasing competition from European ports geographically located in Africa.

The regulatory landscape plays a crucial role in shaping competitive dynamics. As emerging environmental policies, like the Emissions Trading System (ETS) and the *Fit for 55-FuelEU* Maritime initiative are implemented exclusively in the EU, ports in Africa will not face the same compliance costs or operational restrictions. This regulatory asymmetry could shift the competitive balance, providing Africa ports with a cost advantage. Conversely, European ports competing directly with African counterparts could face significant competitive pressures, particularly in regions where they share overlapping trade routes and hinterlands.

This study offers valuable information for policymakers. As European ports are increasingly subject to stringent environmental regulations, it is essential to consider the competitive impact on EU ports geographically located in Africa (also because the Canary Islands are considered outermost regions of the EU). Policymakers should weigh the long-term consequences of regulatory asymmetries on trade flows, competitiveness, and the strategic positioning of European ports. In this regard, the study highlights the need for a coordinated regulatory strategy that considers the unique competitive dynamics faced by European ports operating in African contexts.

4.7. FUTURE RESEARCH

A key constraint we encountered—common to many empirical studies on African ports—is the difficulty of accessing reliable and comprehensive data across countries in the region. In particular, first-hand feedback from stakeholders in the African port sector has confirmed that some of the official sources used for data collection may be affected by manipulation or misreporting, raising concerns about the accuracy of the available information.

This constraint restricts the number of ports and variables that can be included in cross-country comparative studies. Nevertheless, we remain optimistic that continued efforts devoted to the African maritime-port sector, combined with improved collaboration with regional authorities, will lead to future datasets with greater coverage and quality, thereby enabling more robust and detailed evaluations.

In addition, we identify a natural continuation of this research in the form of a longitudinal reassessment once the environmental regulations discussed—particularly the *FuelEU* Maritime Regulation—have been fully implemented and enforced. While this study offers a forward-looking perspective based on projected regulatory impacts, it would be especially valuable to replicate this analysis in the coming years, drawing on data from periods in which the new framework is already in effect.

Such a follow-up study would allow for the empirical identification of the actual impact of environmental regulation on port efficiency, particularly in the case of ports located in unique institutional and geographic contexts, such as those in the Canary Islands. This would further enrich the understanding of how sustainability goals interact with port competitiveness in an increasingly regulated global maritime environment.

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CHAPTER V – GENERAL CONCLUSIONS

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This doctoral thesis provides a comprehensive and empirically grounded exploration of how environmental regulation, institutional quality, and geopolitical dynamics interact to shape port efficiency and competitiveness in a globalized context characterized by continuous shocks affecting global logistics. Through three interconnected empirical studies, it delivers novel insights into the specific vulnerabilities and strategic opportunities faced by the EU port-maritime industry—particularly for island regions and areas near third countries—within an increasingly asymmetric regulatory environment with West African ports.

In an international regulatory landscape increasingly shaped by climate imperatives, the ability of ports to remain competitive will depend not only on compliance but also on institutional adaptability, innovation capacity, and the strategic use of governance tools. This is especially relevant for outermost European regions such as the Canary Islands, which face unique challenges due to their geographic location, exposure to global trade routes, and obligation to meet EU environmental standards.

The empirical results of *Chapter 2* reveal a positive relation between emissions and cargo throughput, reflecting the sector's current reliance on fossil fuels. Once CO_2 is consider as an input, the relative importance of infrastructure and capital increases, underscoring the role of quasi-fixed inputs in maintaining environmentally adjusted technical efficiency. The findings point to a transitional efficiency loss under the *FuelEU* Maritime Regulation, especially for ports with limited financial or technological resources, and emphasize the need for targeted investment in green infrastructure and low-carbon technologies.

This chapter shows how emissions affect the efficiency of different Spanish ports. In this context, it would be worth asking whether the internalization of externalities in European ports, through emission taxes, affects the competitiveness of EU ports compared to those that are not affected by this regulation. The following chapter addresses this question by comparing a European port in Africa with its closest competitors in the West African region.

Chapter 3, which assesses the competitive positioning of LPAP as a strategic node in the Mid-Atlantic, suggests that EU environmental regulations, although increasing compliance costs, may also catalyse sustainable innovation. By aligning environmental obligations with smart investment strategies and improved governance, LPAP could reposition itself as a regional hub for green maritime logistics. However, this transition requires proactive institutional coordination and forward-looking spatial planning.

Thus, among the most interesting results of this chapter, it is worth highlighting that the LPAP has competitive advantages over its competitors in the West African region. Building on this, the next chapter presents an efficiency ranking of ports in the West African region.

Chapter 4 conducts a comparative efficiency analysis of ports in the Canary Islands and West Africa, with the aim of integrating the main ideas developed in the first two chapters. The results show that while some West African ports display high technical efficiency, Canary Island ports consistently outperform them in terms of institutional stability, regulatory predictability, and investment appeal. Nevertheless, environmental regulatory asymmetry could undermine this advantage, with stricter EU standards potentially leading to traffic and capital shifts toward less regulated competitors. These findings stress the importance of differentiated regulatory strategies and international cooperation to ensure competitive equity and prevent market distortions.

Collectively, the results yield several strategic and policy-relevant insights. First, the successful implementation of environmental regulation in the port sector hinges on synchronized investment in sustainable technologies and adaptive capacity, especially in geographically and economically constrained regions. Second, a uniform application of EU standards, without considering regional disparities, may generate unintended inefficiencies and competitiveness losses. Third, institutional quality emerges as a critical factor in buffering the effects of regulatory stress and enhancing long-term performance. Fourth, global regulatory harmonization—particularly between the EU, IMO, and key African partners—is essential to mitigate competitive imbalances and support sustainable maritime trade.

From a scientific standpoint, this thesis contributes to the literature in several significant ways. Methodologically, it offers a novel framework for integrating emissions as productive inputs in efficiency analyses, addressing a critical gap in existing frontier modelling approaches. Empirically, it pioneers a cross-regional comparative evaluation of ports by incorporating both environmental and institutional variables into performance assessments. Strategically, it advances an integrated perspective on port competitiveness, weaving together economic, regulatory, and geopolitical dimensions.

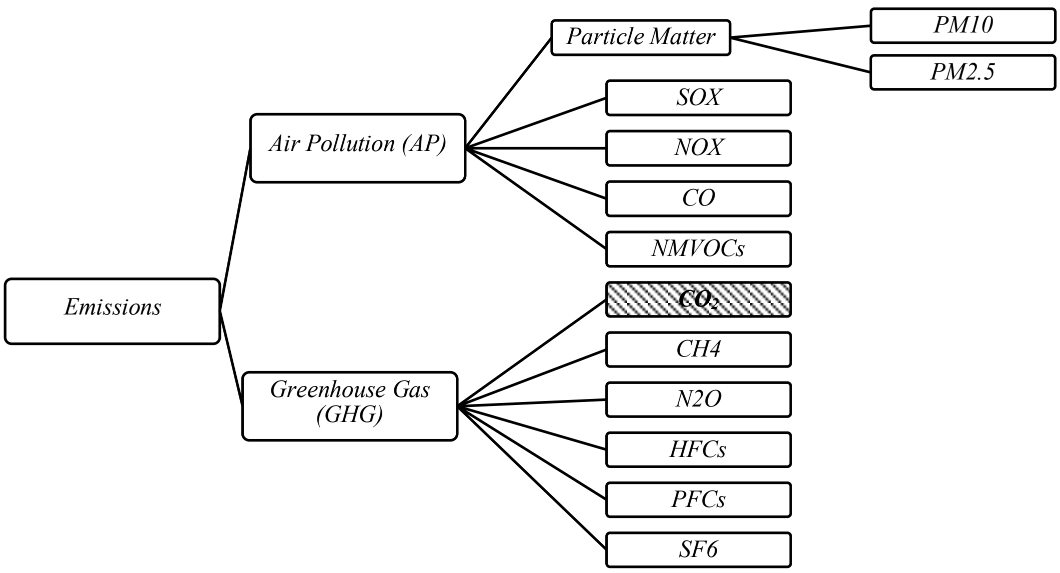
This background highlights the structural tensions between environmental ambition and competitive balance, particularly in contexts characterized by institutional constraints and regulatory asymmetries. While competition is a core principle of the European Union and a cornerstone of market economies, there are circumstances in which exceptions and protective measures are necessary—especially for vulnerable regions, both within the EU and beyond.

In sum, the findings emphasize the need for adaptive, inclusive, and regionally sensitive maritime policies. These should promote investment in green infrastructure, strengthen governance frameworks, and foster international regulatory alignment as essential pillars for sustainability and long-term competitiveness. In light of ongoing disruptions in maritime logistics, the sector's capacity to adapt—both environmentally and geopolitically—emerges as a critical challenge for the years ahead.

APPENDIX

APPENDIX

APPENDIX 1. Different emission types



Note: CO_2 is highlighted because it is the variable used in this study.
Source: Own elaboration.

APPENDIX 2. Estimations of the L1 model

Variable	Coefficient	Std. Deviation	Error t	P Value
Intercept	-0.18846	0.09783	-1.926	0.05770
LOAD	0.01394	0.08185	0.170	0.86525
MANU	-0.60083	0.08185	-7.341	1.76e-10 ***
ROAD	-0.36962	0.08185	-4.516	2.21e-05 ***
SHIP	-0.05292	0.08185	-0.647	0.51979
VAL	-0.07984	0.08185	-0.975	0.33234
WARE	-0.18807	0.08185	-2.298	0.02426 *
GOAP	0.27492	0.11575	2.375	0.02000 *
GOEU	-0.04768	0.11575	-0.412	0.68155
GOLOC	-0.35084	0.11575	-3.031	0.00331 **
GONAT	-0.10482	0.11575	-0.906	0.36797
GOREG	-0.05995	0.11575	-0.518	0.60597
GOSUPRA	0.08289	0.11575	0.716	0.47610
ICLI	0.62716	0.11575	5.418	6.49e-07 ***
ICO	0.73448	0.11575	6.345	1.35e-08 ***
ICOOP	0.51374	0.11575	4.438	2.95e-05 ***
INFRA	1.11206	0.11575	9.607	7.20e-15 ***
LAB	0.73734	0.11575	6.370	1.21e-08 ***
LOG	0.87725	0.11575	7.579	6.13e-11 ***
SUPRA	0.79658	0.11575	6.882	1.32e-09 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1
Residual standard error: 0.2166 on 78 degrees of freedom
Multiple R-squared: 0.8631, Adjusted R-squared: 0.8298
F-statistic: 25.89 on 19 and 78 DF, p-value: < 2.2e-16
Mean of the dependent variable= 5.20527675e-19
SD of the dependent variable=0.52492956
Sum of absolute values of the residuals=14.34652253
Sum of squares of the residuals=3.65788128
Source: Own Elaboration.

APPENDIX 3. Efficiency results by years (2011-2015)

Port Name	2011				2012				2013				2014				2015			
	DEA		BOOTSTRAP		DEA		BOOTSTRAP		DEA		BOOTSTRAP		DEA		BOOTSTRAP		DEA		BOOTSTRAP	
	BM	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*
Cape Town	0,57111	0,84073	0,50382	0,78664	0,61832	0,80611	0,54472	0,75827	0,57417	0,65842	0,50250	0,62779	0,55904	0,63658	0,49494	0,59827	0,56232	0,67574	0,49404	0,63864
Casablanca	1,00000	1,00000	0,75320	0,83771	1,00000	1,00000	0,75850	0,84712	1,00000	1,00000	0,75995	0,86478	1,00000	1,00000	0,73783	0,84842	1,00000	1,00000	0,75040	0,85326
d´Abidjan	0,46253	0,46253	0,42622	0,43986	0,54531	0,54531	0,50047	0,51642	0,52218	0,57230	0,49343	0,55805	0,46887	0,50134	0,44165	0,48174	0,49420	0,56207	0,46280	0,54304
Dakar	0,45786	0,45786	0,42806	0,44502	0,38989	0,38989	0,37064	0,37849	0,50450	0,50450	0,47998	0,48844	0,42811	0,42811	0,40909	0,41198	0,43282	0,43282	0,40242	0,41206
Douala	0,38322	0,38322	0,33363	0,36486	0,32141	0,32141	0,27275	0,30286	0,39534	0,39534	0,34178	0,37864	0,34798	0,34798	0,29361	0,32800	0,68546	0,68546	0,58539	0,65056
Durban	1,00000	1,00000	0,75517	0,84982	1,00000	1,00000	0,76054	0,84695	1,00000	1,00000	0,76281	0,86364	1,00000	1,00000	0,75018	0,84389	1,00000	1,00000	0,74656	0,85892
East London	1,00000	1,00000	0,75426	0,83886	1,00000	1,00000	0,75952	0,85350	1,00000	1,00000	0,76183	0,86444	1,00000	1,00000	0,74383	0,84569	1,00000	1,00000	0,74960	0,85242
Port Elizabeth	0,36763	1,00000	0,30715	0,84634	0,31659	1,00000	0,26665	0,85116	0,32388	1,00000	0,27264	0,86076	0,28392	1,00000	0,23470	0,84512	0,23934	1,00000	0,19982	0,86090
Tanger Med	1,00000	1,00000	0,78379	0,85455	1,00000	1,00000	0,80247	0,86612	1,00000	1,00000	0,77805	0,87355	1,00000	1,00000	0,75552	0,84685	1,00000	1,00000	0,75919	0,86665
Tema	0,57525	0,57525	0,51096	0,54365	0,66807	0,71532	0,60525	0,66946	0,64353	1,00000	0,59071	0,87405	0,58401	0,85090	0,53305	0,79005	0,54040	0,83712	0,46730	0,78495
Walvis Bay	0,34350	1,00000	0,31242	0,84197	0,50457	1,00000	0,46656	0,85270	0,43879	1,00000	0,40681	0,86725	0,32212	1,00000	0,29311	0,84147	0,35514	1,00000	0,32469	0,85874
Cotonou	0,62176	0,62176	0,57461	0,59490	0,62583	0,62583	0,58672	0,60457	0,58690	0,58690	0,55178	0,57187	0,51120	0,51120	0,46909	0,48953	0,42712	0,42712	0,39292	0,40905
Luanda	0,81155	0,81155	0,69592	0,76100	0,86691	0,86691	0,75886	0,81678	0,91418	0,91418	0,78995	0,87523	0,88000	0,88000	0,75237	0,82538	0,86610	0,86610	0,74445	0,81429
Onne	1,00000	1,00000	0,74673	0,84265	1,00000	1,00000	0,75789	0,85165	1,00000	1,00000	0,76447	0,86460	1,00000	1,00000	0,74174	0,84236	1,00000	1,00000	0,74901	0,85327
Las Palmas	0,65709	1,00000	0,57798	0,84482	0,59284	1,00000	0,51790	0,84602	0,49926	1,00000	0,45138	0,86793	0,50270	1,00000	0,45826	0,83926	0,41115	1,00000	0,36925	0,85971
St C. Tenerife	0,58000	1,00000	0,53992	0,84156	0,54787	1,00000	0,51580	0,84567	0,64535	1,00000	0,60672	0,86643	0,66628	1,00000	0,62945	0,83878	0,61269	1,00000	0,56251	0,86012

Source: Own Elaboration.

APPENDIX 4. Efficiency results by years (2016-2020)

Port Name	2016				2017				2018				2019				2020			
	DEA		BOOTSTRAP		DEA		BOOTSTRAP		DEA		BOOTSTRAP		DEA		BOOTSTRAP		DEA		BOOTSTRAP	
	BM	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*	*BM*	*AM*
Cape Town	0,50837	0,67464	0,43927	0,62449	0,51545	0,56113	0,45838	0,52519	0,63841	0,63841	0,57573	0,59930	0,40252	0,41105	0,35116	0,38070	0,32284	0,35081	0,28948	0,32718
Casablanca	1,00000	1,00000	0,73934	0,84367	1,00000	1,00000	0,75029	0,84331	1,00000	1,00000	0,74460	0,80928	1,00000	1,00000	0,72435	0,82072	1,00000	1,00000	0,70163	0,81236
d´Abidjan	0,52910	0,62638	0,49561	0,60217	0,61261	0,72609	0,57724	0,70005	0,65237	0,73536	0,61100	0,70412	0,53968	0,56572	0,51375	0,54673	0,04596	0,04971	0,04333	0,04806
Dakar	0,41001	0,41001	0,37669	0,39715	0,43747	0,43747	0,40296	0,42076	0,41419	0,41419	0,38352	0,39074	0,54196	0,54196	0,52791	0,53304	0,45090	0,51310	0,43173	0,50314
Douala	0,52028	0,52028	0,44421	0,49106	0,80982	0,80982	0,70235	0,76228	0,73924	0,73924	0,63580	0,68447	0,64588	0,64588	0,53165	0,59262	1,00000	1,00000	0,70678	0,80605
Durban	1,00000	1,00000	0,73657	0,84706	1,00000	1,00000	0,75300	0,84519	1,00000	1,00000	0,76307	0,82162	1,00000	1,00000	0,74881	0,82467	1,00000	1,00000	0,77652	0,81841
East London	1,00000	1,00000	0,73305	0,84577	1,00000	1,00000	0,74158	0,83758	1,00000	1,00000	0,74899	0,81216	1,00000	1,00000	0,72870	0,81983	1,00000	1,00000	0,69738	0,81115
Port Elizabeth	0,14956	1,00000	0,12318	0,84393	0,15927	1,00000	0,13379	0,83860	0,16301	0,16301	0,13699	0,14869	0,12222	1,00000	0,09977	0,82580	0,09472	1,00000	0,07672	0,80696
Tanger Med	1,00000	1,00000	0,75818	0,84342	1,00000	1,00000	0,76551	0,84514	1,00000	1,00000	0,75987	0,83165	1,00000	1,00000	0,74497	0,82683	1,00000	1,00000	0,75194	0,82823
Tema	0,59624	0,59624	0,50688	0,55595	0,63762	0,63762	0,55414	0,59955	0,74259	0,76970	0,65554	0,71199	0,56499	0,56499	0,51583	0,54092	0,43336	0,48569	0,37777	0,45639
Walvis Bay	0,32973	1,00000	0,30490	0,84220	0,25062	1,00000	0,23414	0,84163	0,25545	1,00000	0,23575	0,81583	0,17663	1,00000	0,15784	0,83098	0,11745	1,00000	0,10584	0,80895
Cotonou	0,45334	0,45334	0,42328	0,43356	0,45156	0,45156	0,41292	0,43119	0,41697	0,41697	0,37292	0,39242	0,52324	0,52324	0,47588	0,50157	0,51958	0,51958	0,48418	0,49951
Luanda	0,81810	0,81810	0,70464	0,76304	0,44840	0,44840	0,38833	0,41809	0,64491	0,64491	0,56610	0,60439	0,39332	0,39332	0,33234	0,36193	0,35546	0,35546	0,30301	0,33093
Onne	1,00000	1,00000	0,73431	0,84250	1,00000	1,00000	0,75093	0,83655	1,00000	1,00000	0,74454	0,81515	1,00000	1,00000	0,72214	0,82834	1,00000	1,00000	0,69776	0,81219
Las Palmas	0,40882	1,00000	0,36464	0,83843	0,53199	1,00000	0,47652	0,83681	0,50629	1,00000	0,44983	0,82328	0,44024	1,00000	0,40762	0,82176	0,40840	1,00000	0,38754	0,81836
St C. Tenerife	0,60251	1,00000	0,54646	0,84161	0,78276	1,00000	0,71296	0,84229	0,56993	1,00000	0,52362	0,82246	0,65782	1,00000	0,63055	0,82295	0,52802	1,00000	0,49853	0,80839

Source: Own Elaboration.