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An Assessment of Container Seaport Efficiency Determinants

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Abstract: Maritime transport plays a pivotal role in the global economy, facilitating the majority of international trade and serving as a cornerstone for efficient and expansive logistics networks. The proliferation of economic globalisation has resulted in a significant upsurge in intercontinental transactions, thereby fostering the utilisation of ports and shipping enterprises as cost-effective and expeditious means of accessing a wide range of destinations in Europe, Asia, Africa, and North America. The objective of this study is to evaluate the significance of five exogenous variables, namely, GDP per capita, water depth, commodity-type diversification, management model, and European directional division, in relation to the performance of seaports. Measuring the impact of exogenous variables in seaport performance is crucial for understanding how external factors influence efficiency, enabling informed decision-making, and facilitating the development of targeted policies for sustainable and effective port operations. This assessment will be conducted using robust benchmarking analysis methods, specifically the nonparametric order-α model. Several findings suggest that there is a negative relationship between GDP per capita and the performance of seaports when GDP per capita reaches very high levels. However, seaports located in regions with lower GDP per capita tend to exhibit superior performance. The inefficiency of southern seaports is evident, whereas seaports located in Central/Eastern Europe exhibit superior performance, irrespective of their model orientation. These findings underscore the importance of considering economic context and regional factors in understanding seaport performance and highlight potential areas for improvement in southern seaports.

Keywords: data envelopment analysis; containers; seaports; logistics

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1. Introduction

The maritime industry is a crucial component of the modern global economy, with the European Union being the leading commercial bloc. Over 80% of its member states rely on shipping for imports and exports, emphasizing the need for well-established networks for smooth cargo transportation [1]. Seaports and carriers play a fundamental role in the global supply chain, with their operational specifications and functions influenced by the diverse commodities they transport. The transformation of containerisation has transformed logistics and transportation, but factors such as product type, quantity, volume, vessel capacity, and available infrastructure still play a significant role. The trend towards globalisation has increased the importance of logistics and administration within ports, optimizing production processes and distribution. Economic globalisation has increased cross-continental trade, making ports and shipping companies a cost-effective and efficient means of accessing Europe, Asia, Africa, or the Americas. However, seaports are exclusively accessible to nations with maritime borders [2,3].

As stated in the "Europe's Seaports 2030: Challenges Ahead" memo on behalf of the European Commission in 2013, Europe, with a coastline of 70,000 km and a population of 746 million people, has over 1200 commercial ports, which account for 74% of the European Union's international trade in goods. These ports facilitate intra-European trade and are critical gateways for the continent. However, the performance levels of these ports vary significantly. Antwerp, Hamburg, and Rotterdam are the three most prominent ports, handling a fifth of all goods arriving in Europe via maritime routes. This imbalance within the European port network hampers Europe's competitiveness and leads to significant inefficiencies, resulting in extended shipping routes, traffic diversions, and longer overland and sea journeys, increasing emissions, congestion, and financial burdens for organisations [4].

The assessment of port performance is a multifaceted undertaking, owing to the wide range of factors and activities linked to a port, as well as the diversity of ports operating on an international and European scale [5]. An extensive body of literature exists regarding the efficiency of seaports. It is evident that nonparametric benchmarking methods are predominantly employed to assess the performance of seaports worldwide. The utilisation of such methodologies is rationalised by their absence of fundamental assumptions, particularly in contrast to parametric approaches. It is likely that this is the reason that the authors could only find three studies that employed stochastic frontier analysis (SFA), although there are possibly others. Despite this, only a small number of studies have assessed the influence of nondiscretionary variables on the performance of seaports, and this represents a significant lacuna in the literature. Indeed, as stated by Tongzon and Heng [6], the competitiveness and intrinsic performance of seaports are influenced by a multitude of factors, some of which are not under the jurisdiction of management or authorities.

Evaluating the influence of the surrounding environment on the technical efficiency of entities from any industry is nonetheless essential for several reasons, namely, effective resource allocation and management, cost reduction, competitive advantage, environmental sustainability, capacity planning, performance and benchmarking, risk mitigation, regulatory compliance, customer satisfaction, and economic impact. Identifying key determinants affecting seaport efficiency is crucial for port authorities and operators to allocate limited resources effectively, and as such to ensure the seaports' sustainability. By focusing on these determinants, these entities can prioritize investments, infrastructure development, and operational improvements that significantly impact efficiency. By addressing specific factors that impede efficiency, such as fuel consumption, labour, and maintenance expenses, ports can reduce operational costs and gain a competitive advantage. Efficient ports can attract more shipping lines, cargo, and customers, leading to increased revenue and economic growth. By implementing eco-friendly practices, ports can reduce emissions and minimize their environmental footprint. Accurate assessment of operational determinants informs better capacity planning, allowing ports to anticipate future demand and make necessary infrastructure investments. Understanding these determinants helps ports mitigate risks, align their operations with regulations, and enhance customer satisfaction. Efficient and sustainable ports contribute significantly to the economic development of the regions they serve, creating jobs and fostering local economic growth.

In essence, the evaluation of operational environment determinants pertaining to seaport efficiency holds significance as it facilitates enhanced resource allocation, improved decision-making, cost reduction, and overall performance enhancement. Seaports are able to maintain their competitiveness, environmental responsibility, and resilience with the added benefit of bolstering the economic prosperity of the regions they cater to. The purpose of this study is thus to evaluate the significance of exogenous variables for port performance by employing robust analysis techniques, specifically the nonparametric order-α model. To the best of our understanding, no prior investigation has conducted an analysis as exhaustive as the current one, which utilises various model orientations to bolster the findings and conclusions and examines the five exogenous variables deemed most pertinent based on an exhaustive review of the literature. For instance, Chang and Tovar [7] conducted an exhaustive literature review of studies attempting to explain the inefficiency of port terminals caused by external drivers. Environmental variables such as ownership, port size, localisation, capital intensity, type of organisation, regulation status and changes, private sector participation, containerisation rate, oil refinery presence, demand variability, bulk rate, and occupancy rate are readily apparent upon cursory examination of such a survey.

Regrettably, parametric models are employed in all examined studies to account for those variables. These models heavily depend on the functional form of the frontier, such as translog and Cobb–Douglas, as well as the distributions of (in)efficiency. Strong assumptions often incorporate substantial bias into results due to the fact that they are not invariably corroborated by empirical evidence. Furthermore, parametric methods solely reveal whether an environmental variable has an effect on the efficiency distribution, while neglecting to consider its influence on the efficiency boundary. Lastly, to the best of our knowledge, no other study has utilised robust empirically based benchmarking methods to examine the effect of the regional gross domestic product (GDP), the commodity type, the water depth, the management model, or the European directional division on the technical efficiency of European seaports. The research (null) hypothesis is that any of these five variables impact seaport technical efficiency. Following any statistical analysis, we will confront this hypothesis against the empirical data and evidence in order to reject it or not, and as such, to draw managerial implications. Particularly, we are interested in testing whether these exogenous factors influence both the efficiency boundary and/or efficiency distribution. The impact on the frontier (but not on the distribution shape) implies that the variable influences the behaviour of the benchmarks and may somehow justify their good performance, whereas the influence over the distribution (rather than the frontier) may help in justifying the poor performance of the inefficient seaports.

Therefore, this study adds to the current body of literature concerning the evaluation of environmental variables' ability to account for the shape of efficient frontier and efficiency distributions, considering those five aforementioned variables as potential explanations of seaport efficiency levels. It does so by employing a rigorous nonparametric approach known as order-α, which was introduced by Aragon et al. [8]. This method addresses several limitations identified in previous research. Order-α models provide benefits compared to parametric benchmarking approaches such as stochastic frontier analysis (SFA) for assessing the influence of exogenous or non-discretionary factors on seaport efficiency. Order-α models differ from SFA in that they do not make assumptions about a certain functional form or include distributional assumptions. Instead, they are nonparametric and do not depend on predetermined mathematical structures. Order-α models have the ability to capture intricate and nonlinear connections, making them highly suitable for situations where the exact shape of the production frontier is unclear. Furthermore, SFA often necessitates strict assumptions on the distribution of inefficiency. On the other hand, order-α models provide efficiency ratings that are independent of any particular distribution, therefore eliminating the possible bias that may arise from inaccurately specifying the distribution. The order-α approach's capacity to adjust to various patterns in the data improves its resilience in the face of external variables, providing a more versatile and dependable framework for evaluating and understanding the influence of outside factors on seaport efficiency.

Following this introductory section, the paper is structured as follows. The literature review is presented in Section 2. The methodology to be employed is described in Section 3, the case study is presented in Section 4, the results are presented and discussed in Section 5, and the main conclusions and suggestions for future research are outlined in Section 6.

2. Literature Review

Ports are essential for the global economy, since they act as crucial points in the transportation network that enables international commerce, connectivity, and economic growth. Ports serve as crucial linkages between land and marine transportation, playing a pivotal role in the supply chain by facilitating the flow of commodities and stimulating worldwide economic expansion.

International trade facilitation is mostly carried out via ports, which work as the main entry points for the bulk of global commodities. They enable the transportation of products across borders, enabling countries to participate in international commerce. Optimal port operations are crucial for minimising transit durations, decreasing expenses, and bolstering the competitiveness of nations in the international market. Ports function as central nodes for several types of transportation, such as vessels, vehicles, and railways, facilitating the smooth flow of commodities between diverse areas.

In terms of transportation and logistics, ports serve as vital links in these networks. Maritime routes are connected to land-based transportation networks, aiding as a vital connection point for transferring goods between ships and other transportation modes. Effective intermodal connection is crucial for optimising the whole supply chain, minimising transit times, and improving the dependability of goods transportation. Ports are essential for facilitating the efficient and coordinated movement of commodities from producers to consumers.

Ports have a crucial role in creating jobs and promoting economic growth in the surrounding area. They include a variety of operations, including the processing and storage of goods, provision of transportation services, and administration of logistics, being significant economic centres fostering employment opportunities not just inside the port facilities themselves but also in related businesses and services. The economic activities centred on ports attract investments, stimulate the development of industrial clusters, and significantly contribute to the general prosperity of the areas they serve.

Additionally, the establishment and upkeep of port infrastructure are vital for facilitating global commerce and economic endeavours. Ports need comprehensive infrastructure, including quays, berths, container terminals, storage facilities, and transit connections. Investing in contemporary, effective, and environmentally friendly port infrastructure improves a nation’s ability to compete, enticing shipping companies, logistics providers, and enterprises to make use of these facilities. Enhancing the infrastructure in and around ports also plays a role in enhancing connection and efficiency in transportation.

Finally, seaports possess strategic significance in terms of geopolitics and national security. These nodes are critical in the worldwide transportation network, and their efficient operation is vital for the security of nations and regions such that governments often allocate funds towards the development and fortification of ports to guarantee the unhindered transportation of vital commodities, energy resources, and crucial materials. The geographic positioning of ports may have a significant impact on trade routes and geopolitical dynamics, rendering them essential to global geopolitics.

The operational success of seaports is influenced by a multitude of linked elements that together affect their efficiency. Central to this is cutting-edge infrastructure and technology, including deep docks, effective cargo-handling machinery, and sophisticated digital systems that optimise operations. The effectiveness of seaports is greatly impacted by their integration with interior transportation networks, enabling smooth intermodal movement of commodities via roads and trains. The strategic positioning of ports along important shipping routes and the increased trade volumes in economic centres are crucial factors that contribute to economies of scale. Efficient governance, managerial strategies, and regulatory structures are crucial for assuring transparent decision-making, efficient allocation of resources, and cooperation between public and private players. Another crucial element is labour productivity, which is influenced by highly trained and motivated staff. Ports that adopt environmental sustainability policies and comply with security measures demonstrate improved efficiency, while investments in innovation facilitate adaptability to industry developments. The dimensions and magnitude of ports, in addition to their ability to adapt to market requirements and competition, also impact operational effectiveness. The primary factors that contribute to the efficiency of seaports are a holistic combination of infrastructure, connectivity, governance, labour, sustainability, security, size, innovation, and market dynamics. The complex interaction of these elements influences a seaport's capacity to effectively manage and transport products, eventually establishing its competitiveness in the global arena.

Table 1 presents and summarises some of the most important studies about the determinants of seaport efficiency. The table identifies the authors, the sample, the adopted methodology/methodologies, the variables (inputs and outputs), and finally the main conclusions drawn by them. International seaports, particularly the European ones, have faced severe inefficiency levels motivated by scale diseconomies (although this impact may vary significantly across the world), low containerisation, low occupancy rates, low bulk rates, and low trans-shipment. In opposition, the administrative structure of ports (corporate-owned/private vs. public-owned), the hinterland size and the operation of both types of cargoes seem to be determinants of (in)efficiency. Research on seaport efficiency has shown significant gaps, notably in the examination of essential external factors that may greatly influence performance. Previous research has often disregarded the impact of regional gross domestic product (GDP), a crucial economic factor that may determine the operational environment of seaports. Furthermore, the significance of the commodity type, a crucial determinant in port operations, has not been well investigated in terms of efficiency. Prior study attempts have not adequately included the crucial factor of water depth at ports, which significantly impacts vessel accessibility and cargo capacity. In addition, the selection of the management model, whether it is public or private, has not been given sufficient consideration, despite its ability to impact efficiency results. The European cardinal divide, a crucial geographic component, has also been disregarded, limiting understanding of efficiency disparities across various areas. It is essential to address these gaps in order to have a complete understanding of the dynamics of seaport efficiency. These variables are important in shaping the performance landscape and can offer valuable insights for policymakers, port authorities, and industry stakeholders who want to improve operational effectiveness and sustainability.

Table 1. Literature review on seaport efficiency. Note: DEA—data envelopment analysis; FDH—free disposal hull; BCC—Banker, Charnes, and Cooper; CCR—Charnes, Cooper, and Rhodes; RA—regression analysis; SFA—stochastic frontier analysis.

Authors	Sample	Methodology	Variables *Input*/*Output*	Main Conclusions
Simões and Marques [5]	41 seaports in 11 European countries	DEA FDH Order-m	*Input*: total expenses *Output*: container, dry bulk cargo, liquid bulk cargo and passengers	Considerable levels of inefficiency were found in the European seaports sector. A significant portion of inefficiency is caused by scale diseconomies. This means that European seaports could save on average 22.2% of the inputs consumed if they operated at an optimal scale.
Chang and Tovar [7]	14 terminals in Peru and Chile (2004–2010)	SFA	*Input*: capital, labour, bulk rate, containerisation rate, occupancy rate *Output*: containers, general and rolling freight, bulk	Chilean terminals were more efficient than the Peruvian ones, mainly due to greater agility in the implementation of the reform process. Furthermore, the higher the containerisation index, the greater the occupancy rate and the bigger the bulk rate, then the lower the inefficiency in terminals is. Also, the inefficiency is lower when the terminal is under private administration.
Wang, Song and Cullinane [9]	57 international ports/terminals (2001)	DEA_{BCC}, DEA_{CCR} and FDH	*Input*: quay length, terminal area, quayside gantry, yard gantry, straddle carrier *Output*: container throughput	The results found that some renowned container terminals, such as MTL in Hong Kong, are currently suffering from inefficient production. On the basis of using cross-sectional data, however, this inefficiency could very likely be caused by a recent investment in future production.
Cullinane, Wang, Song and Ji [10]	57 international ports/terminals (2001) (2001)	DEA and SFA	*Input*: quay length, terminal area, quayside gantry, yard gantry, straddle carrier *Output*: container throughput	High levels of technical efficiency are associated with scale, greater private-sector participation and with trans-shipment as opposed to gateway ports. In analysing the implications of the results for management and policymakers, a number of shortcomings of applying a cross-sectional approach to an industry characterised by significant, lumpy and risky investments are identified and the potential benefits of a dynamic analysis, based on panel data, are enumerated.
Munisamy and Singh [11]	69 container ports (17 Asian countries) (2007)	DEA_{BCC} and DEA_{CCR}	*Input*: berth length; terminal area; total refer points; total quayside cranes; total yard equipment *Output*: total throughput	The results indicate that the average technical efficiency of the Asian container ports is 48.4%. The overall technical inefficiency in Asian container ports is due to pure technical inefficiency rather than scale inefficiency.
Lu and Wang [12]	31 major container terminals (China and South Korea) (2008)	DEA_{BCC}, DEA_{CCR} and DEA (*super-efficiency*)	*Input*: yard area per berth, the quantities of quay crane, yard crane, yard tractor per berth, water depth and berth length *Output*: throughput per berth	According to efficiency analysis of container terminals, empirical results reveal that substantial waste exists in the production process of the container terminals in the sample.
Merk and Dang [13]	63 container ports around the world (Asia, Europe and America)	DEA	*Input*: quay length, surface terminal, reefer points, quay cranes, yard cranes *Output*: volume in deadweight tons, number of TEUs	The size of ports matters for port efficiency. When comparing the level of efficiency achieved by ports across commodities, technical gaps were more marked for container and oil terminals.
Lu and Park [14]	28 major East Asian container terminals	DEA_{CCR} and RA	*Input*: length of berth, number of quay cranes, size of yard area, number of yard cranes, and number of yard tractors per berth *Output*: throughput per berth	The results provided useful information indicating how relatively inefficient container terminals can improve their efficiency.
Mokhtar and Shah [15]	6 container terminals in Peninsular Malaysia (2003–2010)	DEA_{BCC} and DEA_{CCR}	*Input*: total terminal area, maximum draft in meter, berth length in meter, quay crane index, yard stacking index, vehicles, number of gate lanes *Output*: throughput	Result of the analysis shows no significant relationship between container terminal size and efficiency. Thus, efficiency is determined from allocation of resources efficiently by terminal operators and not by size of terminals.
Tongzon [16]	16 ports (4 Australian and 12 international) (1996)	DEA-Additive and DEA_{CCR}	*Input*: number of port authority employees, terminal area, delay time, number of cranes, number of berths, number of tugs *Output*: cargo throughput, ship working rate	The ports of Melbourne, Rotterdam, Yokohama, and Osaka are found to be the most inefficient ports in the sample, based on constant and variable returns to scale assumptions, mainly due to the enormous slack in their container berths, terminal area and labour inputs.

Table 1. *Cont.*

Authors	Sample	Methodology	Variables *Input/Output*	Main Conclusions
Li and Tseng [17]	27 international container ports (1999–2002)	DEA$_{\text{BCC}}$, DEA$_{\text{CCR}}$, and SFA	*Input*: container gantry cranes, container quay length, stevedoring equipment, container yard *Output*: container throughput	Analysing the port performance between operating efficiencies and three factors: location of port (Asian vs. non-Asian), administrative structure of port (corporate-owned vs. public-owned), and national economic growth rate (above average vs. below average), the results show that the operating efficiencies are not significantly different from the location or administrative structure of ports. However, the DEA model shows significant difference with national economic growth rate.
Wang and Cullinane [18]	104 container ports (29 European countries) (2003)	DEA$_{\text{BCC}}$ and DEA$_{\text{CCR}}$	*Input*: quay length; terminal area; total cost of the equipment *Output*: throughput	Regarding the scale properties of container terminal production, it was found that while some container terminals are scale-efficient in general most of the container terminals under study exhibit increasing returns to scale. It was also found that the average efficiency of container terminals located in different regions differs, either to a large or to a small extent.
Al-Eraqi, Barros, Mustaffa and Khader [19]	22 Arabian and African seaports (2000–2005)	DEA$_{\text{BCC}}$ and DEA$_{\text{CCR}}$	Input: berth length; terminal area; distance from Hong Kong port of each port in the region *Output*: ships calling in; movement of general cargo (dry and liquid, containers)	In general, they concluded that the big length of the berth does not impact on ships' arrival, i.e., the increase in ships calling into these ports is possible without causing any congestion problem.
Munisamy and Jun [20]	30 Latin America seaports: Central America, Caribbean, and South America (2000–2008)	DEA$_{\text{BCC}}$ and DEA$_{\text{CCR}}$	*Input*: berth, terminal area, quay equipment, yard gantry, sophisticated yard equipment and general yard equipment *Output*: throughput	The results show that the pure efficiency of the Latin American seaports has improved over the period 2000 to 2008, with the Central American seaports showing the best performance in the region.
Shin and Jeong [21]	8 container terminals at Busan port and Kwangyang port (2007–2010)	DEA$_{\text{BCC}}$ and *Directional Distance Function Model*	*Input*: quay length, number of container cranes, and container yard area *Output*: container throughputs	Efficiency estimation results of each container terminal showed large differences depend on the terminal operators. Especially, the container terminal at Kwangyang port was concluded to be relatively less efficient than container terminal at Busan port.
Wanke and Barros [22]	27 Brazilian ports	Two-stage DEA	*Input*: quay length, maximal quay depth, number of berths, warehousing area, yard area, channel width, channel depth *Output*: solid bulk loading hours, container loading hours, solid bulk throughput, container throughput, solid bulk frequency, container frequency	Results indicate a strong positive impact of public–private partnerships on port scale efficiency, corroborating their impacts in relation to the most productive scale size.
Marques and Carvalho [23]	41 European ports of 11 countries (2005)	DEA$_{\text{BCC}}$ and DEA$_{\text{CCR}}$	*Input*: OPEX; CAPE x*Output*: solid bulk handling, liquid bulk, containers, fractional loading, Ro-Ro, passenger traffic	All the Portuguese ports had very low efficiency scores except Lisbon, which was deemed efficient due to a very high volume of passenger traffic. The possible cost reduction if the Portuguese seaports had performed efficiently was estimated at about EUR 64 million in 2005.
Barros [24]	24 Italian seaports (2002–2003)	DEA$_{\text{BCC}}$ and DEA$_{\text{CCR}}$	*Input*: workers; CAPEX; OPE x*Output*: solid/liquid bulk, total throughput, passengers, vessels, passengers, TEU containers, containers without TEU, sales	The general conclusion is that the Italians seaports examined display relatively high efficiency
Nigra [25]	57 ports of 5 continents (2008)	DEA$_{\text{BCC}}$ and DEA$_{\text{CCR}}$	Input: CAPEX; OPEX; workers Output: solid/liquid bulk, total throughput, passengers	Of the analysed ports in the study the ones that obtained the best results were those of Northern Europe

Table 1. *Cont.*

Authors	Sample	Methodology	Variables *Input/Output*	Main Conclusions
Pjevcevic, Radonjic, Hrle and Promet [26]	5 ports (Danube river in Serbia) (2001–2008)	DEA	*Input*: total area of warehouses, quay length, number of cranes per year *Output*: port throughput	There are two main sources of inefficiencies. First, the ports with low efficiencies are advised to attract more customers or to increase the amount of cargo that can be transferred. Second, the ports should rent their equipment to other companies in order to level the achieved output (throughput) with the use of inputs (total area of warehouses, quay length and number of cranes).
Wanke P. [27]	27 Brazilian ports	DEA	*Input*: number of berths, warehousing area, yard area *Output*: container throughput *Intermediate input/output*: solid bulk frequency, container frequency, solid bulk throughput	Results indicate that a private administration exerts a positive impact on physical infrastructure efficiency levels, while the hinterland size and the operation of both types of cargoes have a positive impact on shipment consolidation efficiency levels. Policy implications for the new regulatory framework on the Brazilian ports sector are also derived.
Wilmsmeier, Tovar, and Sanchez [28]	20 terminals in 10 countries in Latin America and the Caribbean and Spain (2005–2011).	DEA	*Input*: terminal area, ship-to-shore crane capacity equivalent, labour (number of workers) *Output*: TEU (throughput)	Infrastructure and/or superstructure expansion as single measures will not necessarily and directly increase technical productivity and efficiency of a terminal, but requires an integrated management and organisation of the different components to obtain the desired results. The increase in crane capacity has particular impact on the potential container handling capacity and productivity
Cullinane and Wang [29]	25 container ports	DEA panel data	*Input*: Total quay land, terminal area, gantry/yard gantry cranes, straddle carriers *Output*: Container throughput	Efficiency of different container ports can fluctuate over time to different extents. No direct relationship with efficiency.

3. Methodology

This study aims to determine the impact of explanatory environmental variables on the technical efficiency of seaports using an innovative nonparametric methodology (the order-α method). Exogenous variables can influence efficiency distribution and boundary shape of the attainable set. Various methodologies, including nonparametric and semiparametric approaches, have been employed in scholarly works to assess this effect, but the results obtained may be subject to bias, raising concerns about the validity of policy or managerial implications [30–32]. Efficiency scores are typically regressed against the explanatory variables in nonparametric methods, such as Tobit analysis. However, these methods exhibit serial correlation and depend on the separability condition, which states that explanatory variables influence the distribution of efficiency, but not the geometry of the efficient frontier. The double-bootstrap method, addressing the issue of serial correlation, continues to be dependent on the separability condition, resulting in potentially biased coefficients [33]. Utilising partial empirically based frontiers that are contingent on the external drivers (which are presumed to be explanatory) is a more robust alternative. These partial frontiers, such as order-α, are not dependent on the separability condition, and there is no serial correlation among the estimated efficiency scores [34], making them more useful and robust when dealing with the study of the impact made by the exogenous variables in the efficiency of seaports (or any other entities).

To determine whether an explanatory variable influences both the efficiency distribution and the shape of the efficient frontier, it is sufficient to limit the reference set utilised in the construction of the frontier, calculate the (conditional) efficiency scores, and compare them to the efficiency scores obtained using the unrestricted frontier. The explanatory variable being examined, a kernel function (functioning as a probability density function), and a bandwidth (functioning as a pruning parameter regulating the proximity of seaports with respect to the exogenous environment) are utilised in the process of restricting the reference set. The robustness of these partial frontiers and the results derived from them is attributed to the aforementioned factors [34]. As far as the authors are aware, no prior investigation has utilised such a resilient alternative method to assess the impact of environmental factors on the performance of seaports. The technique is detailed below.

3.1. The Basics of Order-α

The research paper uses the order-α method to analyse the impact of multiple exogenous variables on seaport performance. The order-α technique for efficiency estimate has both benefits and limitations in comparison to similar methodologies like data envelopment analysis (DEA), stochastic frontier analysis (SFA), order-m, free disposable hull (FDH), and others. An important benefit of the order-α technique is its nonparametric character, similar to DEA. This makes it appropriate for cases where the functional forms are unknown or there is uncertainty about the distribution of inefficiency. This adaptability is especially advantageous when handling intricate and nonlinear connections within the data. The order-α technique provides the flexibility to model the production process from many viewpoints, similar to DEA, by accommodating both input and output orientation. Nevertheless, this approach has its limitations. The "curse of dimensionality" may pose difficulties in high-dimension domains, resulting in sparse efficiency score distributions and less dependable estimations. The sensitivity to the selection of the order parameter (alpha) is a significant drawback, since an incorrect choice may lead to bias. Furthermore, the absence of uniformity, particularly when alpha is selected subjectively, sets order-α apart from consistent approaches such as DEA and SFA. Compared to DEA, which makes the assumption of a production frontier that is piecewise linear, the order-α technique is less affected by this assumption, but does not possess the same degree of consistency. Order-α offers efficiency ratings that are independent of distribution, unlike SFA. However, it does not include stochastic mistakes. Order-m techniques exhibit commonalities, but diverge in the finding of the frontier order, providing researchers with various options. The free disposable hull (FDH) method is nonparametric, meaning it does not make any assumptions about the underlying data distribution. However, it is important to note that FDH may be sensitive to outliers, which can have an influence on the accuracy of efficiency estimations. Ultimately, the decision between the order-α technique and other options depends on the distinct attributes of the dataset, the reasonable assumptions that may be made, and the research goals. Researchers must meticulously evaluate the benefits and drawbacks of each strategy in order to choose the most suitable approach for their specific circumstances.

The order-α quantile frontier method establishes the frontier by initializing the probability 1-α of observing points above the frontier at a value of alpha [32,34–36]. Note that since the order-α method is an upgrade of DEA, there is no need to specify the weights of indicators—instead, the model optimises them, given a set of constraints. That way, there is no need to obtain expert judgment, as the model is self-sufficient in estimating such weights for prioritizing indicators in efficiency measurement. The order-α may be specified as input-oriented (*IO*-α), output-oriented (*OO*-α), or directional (*D*-α). Robust partial frontier methods facilitate the straightforward incorporation of exogenous variables into the model, circumventing the two-stage approach's assumption of separability between internal and external environments and the one-stage approach's direct inclusion of variables as additional free-disposal inputs/outputs [34]. Conditional order-α efficiency measures use bandwidths (h) and kernel functions (K) to establish a probability distribution for each environmental variable, ensuring only units operating under comparable external conditions are compared to a given unit [30,32,33,37–40].

The conditional formulations of the three frameworks are presented below [32,36]. Let X, Y, and Z be the set of m inputs, s outputs, and q external variables, respectively, assessed for n decision-making units (DMUs), which are the seaports in the present context. Let ($x0$, $y0$, $z0$) be the DMU under evaluation, and d the directional vector to be used in the *D*-α model. Although no rule of thumb for selecting vector d exists, it is assumed to be d = ($-x0$, $y0$), in line with Chambers et al. [41]. If d = ($-x0$, 0), the model returns a linearly transformed Shephard's radial input distance function. The same if d = (0, $y0$), which returns a linearly transformed Shephard's radial output distance function. As per Färe et al. [42], Simar and Vanhems [43] and Daraio and Simar [36], the set (X, Y, Z) is transformed into ($\widetilde{X}$, $\widetilde{Y}$, Z) $\rightarrow$ ($X/x0$, $Y/y0$, Z). Then, the conditional estimator D-α efficiency of DMU ($x0$, $y0$, $z0$) is as follows [36,44,45]:

$$\beta_{\alpha,z} = log\left\{\left\{W^{xy}_{(k)}\ if\ l_k > 1-\alpha \geq l_{k+1}\ W^{xy}_{(n)}\ if\ l_n > 1-\alpha \geq 0\ \right\}\right. \\ \text{with} \\ l_{k+1} = \frac{\sum_{j=k+1}^{n} K\left(\left(Z^{xy}_{[j]} - z_0\right)/h\right)}{\sum_{i=1}^{n} K((Z_i - z_0)/h)} \tag{1}$$

In Equation (1), K is a kernel with a compact support, h a bandwidth, Z^{xy} the observation Z associated with the jth statistic of W^{xy}, such that $W_{(1)} \leq W_{(2)} \leq \ldots \leq W_{(n)}$, and:

$$W^{xy}\left(\widetilde{X},\widetilde{Y}\right) = \left\{\left\{\frac{\widetilde{x}_{0i}}{\widetilde{X}_i}\right\},\left\{\frac{\widetilde{Y}_r}{\widetilde{y}_{r0}}\right\}\right\} \tag{2}$$

Similarly, Daraio and Simar [32] define the *IO*- and the *OO*-α conditional efficiency scores, $\theta_{\alpha,z}$, as follows:

$$\begin{array}{cc}
\underline{\boldsymbol{IO\text{-}\alpha}} & \underline{\boldsymbol{OO\text{-}\alpha}} \\
l_{k+1} = \dfrac{\sum_{j=1}^{k+1} K\left(\dfrac{Z_{[j]}^{xy} - z_0}{h}\right)}{\sum_{i=1}^{n} I(Y_i \geq y_0) \times K\left(\dfrac{Z_i - z_0}{h}\right)} & l_{k+1} = \dfrac{\sum_{j=k+1}^{N_x} K\left(\dfrac{Z_{[j]}^{xy} - z_0}{h}\right)}{\sum_{i=1}^{n} I(X_i \leq x_0) \times K\left(\dfrac{Z_i - z_0}{h}\right)} \\
N_y = \sum_{i=1}^{n} I(Y_i \geq y_0) & N_x = \sum_{i=1}^{n} I(X_i \leq x_0) \\
W_j^x = \left\{\dfrac{X_{ji}}{x_{0i}}\right\},\ j = 1, \ldots, N_y & W_j^y = \left\{\dfrac{Y_{jr}}{y_{0r}}\right\},\ j = 1, \ldots, N_x \\
\theta_{\alpha,z} = \left\{W_{(k)}^x \ if\ l_{k+1} \geq 1 - \alpha \geq l_k \ W_{(1)}^x \ if\ l_1 \geq 1 - \alpha \geq 0 \ \ k = 1, \ldots, N_y - 1\right. & \theta_{\alpha,z} = \left\{W_{(k)}^y \ if\ l_{k+1} \leq 1 - \alpha \leq l_k \ W_{(N_x)}^y \ if\ l_{N_x} > 1 - \alpha \geq 0 \ \ k = 1, \ldots, N_x - 1\right.
\end{array} \tag{3}$$

3.2. The Impact of Environmental Factors on Efficiency

Should alpha approach 1, the partial and the full frontiers become overlapped. If Z has a meaningful effect on the efficiency boundaries, the full frontier-based estimates from Equations (1)–(3) with an endlessly large bandwidth, $\theta_{\alpha=1}$ (for the models *IO*- and *OO*-α) and $\beta_{\alpha=1}$ (for the model D-α), have no economic meaning. The frontier shift because of the environment correction is $Q = \theta_{\alpha=1,z}/\theta_{\alpha=1}$ and $\delta = \beta_{\alpha=1} - \beta_{\alpha=1,z}$, [30,36]. Since Q and δ do not depend on X and Y, they allow us to study the local effect of Z in the frontier. If Q is far from 1 or δ is far from 0, then there is no separability condition. Also, the evolution of Q and δ over Z allows us to study its impact in the full frontier, but they cannot disclose changes in inefficiency distributions because of the operational environment. For that, it is necessary to assume $\alpha = 0.5$ (the median frontier) and the parameters $Q_{\alpha=0.5} = \theta_{\alpha=0.5,z}/\theta_{\alpha=0.5}$ and $\delta_{\alpha=0.5} = \beta_{\alpha=0.5} - \beta_{\alpha=0.5,z}$.

We can use smoothing tools to regress those parameters on Z variables. For the present case, we consider the Nadaraya–Watson (NW) nonparametric regression, as follows.

1. If $\partial\delta/\partial Z > 0$ (resp. < 0), then Z has a negative (resp. positive) effect on the attainable set [36]; similarly, in an input-oriented (resp. output-oriented) framework, if $\partial Q/\partial Z > 0$, then Z is unfavourable (resp. favourable) to the production process, acting as an undesirable output (resp. freely available substitutive input) [32,34].
2. If $\Delta_{\alpha,z} = \delta - \delta_{\alpha=0.5} \neq 0$ (or $\nabla_{\alpha,z} = Q/Q_{\alpha=0.5} \neq 1$), then there is a shift in the median in the efficiency distribution in addition to the full frontier shift due to factor Z [34,36]. If $0 < \nabla_{\alpha,z} < 1$, then the shift between conditional frontiers is larger than that between the unconditional ones (or in turn, the gap among the conditional and the unconditional frontiers is larger for a smaller value of α, say equal to 0.5, than for the full frontier case, $\alpha \to 1$). The same can be said when $\Delta_{\alpha,z} > 0$. On the contrary, $\nabla_{\alpha,z} > 1$ and $\Delta_{\alpha,z} < 0$ suggest a higher efficiency spread among conditional measures [46].

In addition to the analysis of Q and δ, a second-stage regression between the efficiency scores and variable Z may be useful. Let $\theta_{\alpha,z} = \mu(Z) + \sigma(Z)\varepsilon$ designate such a regression, with $\mathbb{E}(\theta_{\alpha,z}) = \mu(Z)$, $\mathbb{V}(\theta_{\alpha,z}) = \sigma^2(Z)$, $\mathbb{E}(\varepsilon \mid Z = z_0) = 0$ and $\mathbb{V}(\varepsilon \mid Z = z_0) = 1$. In other words, the normalised residuals, $\varepsilon = (\theta_{\alpha,z} - \mu(Z))/\sigma(Z)$, are proxies for the managerial efficiency that does not depend on Z, i.e., they are the unexplained part of the conditional score [30]. Large (resp. small/negative) residual values indicate a poor (resp. good) managerial performance; then, ε can be used to rank units. As noted by Badin et al. [30] and Daraio and Simar [36], $\mu(Z)$ can be obtained using local constant or local exponential smoothing methods, while $\sigma^2(Z)$ is estimated by regressing $(\theta_{\alpha,z} - \mu(Z))^2$ on Z. Both $\mu(Z)$ and $\sigma(Z)$ allow inferring whether Z has an impact on the distribution of inefficiencies. As before, both regressions will follow the NW nonparametric estimator approach.

Regarding the multidirectional framework, instead of using $\beta_{\alpha,z}$ for regressions, which is a radial distance function, one uses the approach $\omega_{\alpha,z} = \left(\prod_{r=1}^{s} \frac{y_{r0} + \beta_{\alpha,z} d_Y}{y_{r0}}\right)^{s} \cdot \left(\prod_{i=1}^{m} \frac{x_{0i} - \beta_{\alpha,z} d_X}{x_{0i}}\right)^{-m}$, such that $\omega_{\alpha,z} \geq 1$ if $\alpha \to 1$. That is, a unit is technically and conditionally efficient if and only if $\omega_{\alpha\to1,z} = 1$. In this paper, with the purpose of regressing $\mu(Z)$ and $\sigma(Z)$ on Z, only the full frontier $\alpha = 0.9999$ is considered. In single-direction frameworks, the relationship between Q and the technical efficiency (in the full frontier) is $\theta_{\alpha \to 1} = \mu/Q \Longleftrightarrow \partial\theta_{\alpha \to 1} = (\partial\mu - (\mu/Q)\,\partial Q)/Q$, where ∂ labels the partial derivative and μ replaces $\theta_{\alpha \to 1,z}$ as its expected value. Accordingly, $\partial\theta_{\alpha \to 1}/\partial Z < 0 \Longleftrightarrow (\partial\mu/\partial Z)/\mu > (\partial Q/\partial Z)/Q$. Similarly, for the D-$\alpha$ model, $\partial\beta_{\alpha \to 1}/\partial Z < 0 \Longleftrightarrow -\,\partial\mu/\partial Z > \partial\delta/\partial Z$, where once again $\mu(Z) = \mathbb{E}(\omega_{\alpha,z})$. From the definition of $\omega_{\alpha,z}$, it is easy to conclude that the higher $\beta_{\alpha \to 1}$ is, the higher $\omega_{\alpha \to 1}$ is; therefore, a negative slope of $\beta_{\alpha \to 1}$ implies a negative slope of $\omega_{\alpha \to 1}$. This analysis is important when the separability condition holds, i.e., there is statistical evidence that $Q(Z) = 1 \wedge \partial Q/\partial Z = 0$, or $\delta(Z) = 0 \wedge \partial\delta/\partial Z = 0$.

4. Case Study

Examining the influence of many parameters, such as regional GDP, product type, water depth, management style, and European directional division, on the technical efficiency of European seaports is of utmost importance for multiple reasons. An analysis of the impact of regional GDP on seaport efficiency may provide valuable insights into the correlation between economic growth and port effectiveness. This information can assist policymakers in making efficient resource allocation decisions. Furthermore, various kinds of commodities may need specialised handling facilities and infrastructure, which might have varying effects on port efficiency. Examining this correlation might provide valuable insights for investment choices and operational strategies. The depth of water is a crucial factor in determining the capacity and variety of ships that a port can handle, thereby impacting its effectiveness in managing substantial amounts of cargo. The various management methods, whether public, private, or hybrid, have the potential to influence port governance, investment choices, and operating procedures, all of which may have an effect on efficiency. Finally, analysing the European directional divide may effectively highlight regional discrepancies in port effectiveness, facilitating the identification of regions requiring improvement and the formulation of focused strategies to bolster marine commerce throughout Europe.

4.1. Seaport Sector in Europe

Seaports are of utmost importance in the transportation industry, handling over 80% of global commerce. This may be attributed to their ability to transport heavy loads efficiently, affordably, and under favourable conditions. As stated by Simões and Marques [47], containerised transportation has experienced a significant surge. In Europe specifically, containers account for approximately 25% of the market share in seaports, which is equivalent to solid cargo. According to 2014 data, liquid bulk accounts for approximately 35% of the overall cargo transported in Europe. European seaports manage a staggering 3.85 billion tons of total throughput, placing them among the busiest port systems in the world [48].

There are four primary administration models for seaports in operation worldwide: private ports, tool ports, landlord ports, and public ports. The classification is based on the distinction between public and private infrastructures, superstructures, and activities; for further information, refer to Table 2. As an illustration, the proprietor model has emerged as the prevailing approach to managing seaports. The sample utilised in this research does not include any public seaports. Rather, it consists primarily of landlord ports, which have privately managed public infrastructures, supplemented by tool ports and private seaports, each of which represents less than 10% of the sample ex aequo (refer to Table 3).

Table 2. Seaport management model.

	Infrastructure	**Superstructure**	**Port Activity**	**Other Functions**
Public port	Public	Public	Public	Mostly public
Private port	Private	Private	Private	Mostly private
Tool port	Public	Public	Private	Public/private
Landlord port	Public	Private	Private	Public/private

Table 3. Distribution of seaports in Europe according to the management model, the commodity type, and geographic location.

Commodity Type		Management Model		Geographic Location	
Only containers	16 (18.82%)	Private port	5 (9.26%)	Central and Eastern Europe	6 (11.11%)
Diversified commodities	38 (81.18%)	Tool port	5 (9.26%)	Southern Europe	23 (42.59%)
-	-	Landlord port	44 (81.48%)	Western Europe	13 (24.07%)
-	-	Public port	0 (0%)	Northern Europe	12 (22.23%)
Total	54	-	54	-	54

4.2. Data and Variables

The sample for analysis and evaluation comprised 54 European seaports, as depicted in Figure 1. The document contained information pertaining to various management models (including landlords and others), diverse commodity categories (excluding containers and diversified commodities), and all European directional divisions (Western, Central, Eastern, Southern, and Northern) with respect to the year 2019.

Figure 1. Geographic location of seaports that are part of the sample.

Data utilised in the development of the database were collected from various sources, with the preponderance of information being extracted from reports and websites of the port authority or obtained directly from telephone conversations and correspondence with port authority representatives. The environmental non-discretionary variables (exogenous variables) were obtained from the Eurostat database and the websites of each port; when necessary, they were supplemented with data from national statistical offices. Since most of the data were retrieved from official data sources, about which we cannot claim any lack of confidence, we believe that the quality and reliability of the data are both safeguarded. These data can be delivered to the interested reader upon reasonable request.

The following variables were considered, based on data availability and the extensive literature review, as shown in Table 1.

Inputs:

Total quay cranes—The performance of cranes in container terminal operations is influenced by factors such as technology, size, capacity, depth range, and lifetime [9–15].

Terminal area—The operational efficiency of a container terminal is intrinsically linked to its extension, as more containers can be stored in a larger area, which prevents congestion and facilitates logistics, organisation, and optimisation within the terminal [9–13,15–20].

Quay length—The quay handles container handling, trans-shipment, storage, and park quays. As the length increases, so does the number of cranes, enabling more vessel mooring, potentially boosting seaport productivity by increasing the number of vessels moored [9–13,15,17–22].

Operational expenses (OPEX)—The financial logic suggests that limited operating funds can sometimes hinder a seaport's performance. The adjustment of OPEX is done using the same currency purchasing power parity index (PPP), as not all EU member states use the same currency and their weight varies by country. Some authors avoid monetary variables due to its complexity [23–25]. The OPEX variable, which includes personnel and outsourcing expenditures, is crucial in seaport manufacturing. Outsourcing expenses make up a significant proportion of operational expenditures. Neglecting this could result in overestimation of seaport efficacy and higher ranking for those that utilize outsourcing. It's impossible to separate the OPEX into its constituent elements.

Output:

Container throughput—This is the most crucial indicator, and it is widely accepted that output is the revenue generated by seaports [9–12,14–25,48,49]. It is worth noting that additional output variables, such as loiter time, delay surcharge, ignorance by larger ships resulting from inadequate infrastructure, passengers, and solid/liquid bulk, ought to be incorporated. In accordance with the Marine Department of Hong Kong (2006), these variables fall into four primary classifications: inland transportation, cargo management, warehousing, and ship operations. Regrettably, the absence of data for the majority of European seaports precluded the utilisation of these variables in the present study. Disregarding certain of these variables may introduce bias into the ultimate findings, a subject that will be elaborated upon subsequently. The container throughput variable, which is utilised by a number of the authors in Table 1, is deemed to be an adequate surrogate for the total production of seaports in this instance.

External/operational environment variables:

Although there seems to exist no consensus among researchers about what should be the most relevant variables [50], the following have been selected.

Z1—Regional GDP per capita—Global GDP growth is a key driver of growth in the shipping containers and freight industry. GDP is a comprehensive measure of an economy's total factor productivity, quantifying the market value of all final goods and services produced in a country [51]. This study aims thus to verify the relationship between GDP value and port efficiency in a given region, without focusing on foreign trade's influence on economic growth and GDP change.

Z2—Water depth—Caldeirinha et al. [52] suggest that increased water depth at ports allows larger vessels to berth, resulting in increased productivity and efficiency. This leads to increased traffic from direct liner services, boosting customer satisfaction.

Z3—Commodity-type diversification (binary variable: 0 for diversified commodities, 1 for only containers)—Levinson [53] asserts that the containerisation of products has been largely responsible for the decrease in transportation expenses, owing to the increased automation and efficiency of its handling. While prior research has employed a containerisation index (the proportion of total general cargo comprised of containerised merchandise as measured by weight)—e.g., Chang and Tovar [7] and Trujillo and Tovar [54]—the sample for this study was clustered into two groups: those that handled only containers (containerisation index = 100%) and those that handled a variety of commodities (containerisation index < 100%). This decision was based on the absence of data.

Z4—Management model (binary variable: 0 for landlords and 1 for the others)—Additionally, the management model is a significant and potentially influencing factor in port performance. Indeed, and as Chang and Tovar [7] assert, the majority of prior research has been devoted to determining whether or not ownership is correlated with efficiency; however, none of these studies have examined the management model. The prevailing management paradigm is landlord ports, which entails the leasing of infrastructure, specifically terminals, to private operating companies while the port authority maintains land ownership. In light of the landlord-based model's preponderance in Europe, it is necessary to determine whether or not this model has improved the technical efficacy of seaports.

Z5—Position in Europe (categorical variable: 1 for Western Europe, 2 for Central and Eastern Europe, 3 for Northern Europe, and 4 for Southern Europe). The geographic position can be regarded as a strategic entryway into various spheres of influence in Europe. Geographic location is a widely utilised exogenous variable [7].

Please be advised that there is a possibility that other environmental variables could be utilised in place of those previously mentioned. Illustrative instances may include trans-shipment operations, investments, trade restrictions, connectivity, population and industrial density (which reflect the economic and demographic characteristics of the seaport region), and connectivity [55]. To ensure fair comparisons are avoided, it is critical that these variables comprise both the internal and external environments in which seaports operate. Further research is required to utilise these variables, as the authors do not possess the requisite data.

Table 4 contains the average (and the standard deviation) of inputs and outputs for the whole sample and for the sample split by the binary/categorical external variables. Table 5 presents the correlation between inputs and outputs. All coefficients are statistically significant, i.e., those variables show a strong and positive correlation between them. In short, as expected, larger seaports tend to present a higher number of quay cranes (and longer quays), larger terminal areas, and more operational expenses and "produce" more container throughput. Comparing those two tables, it seems that those larger seaports are located in Western Europe, are mainly landlord seaports, and merely manage containers, which justifies the choice of external variables Z3 to Z5. The high correlation between the inputs and outputs is not a problem in nonparametric frameworks [56].

Table 4. Some basic input and output statistics (average (std)), by binary/categorical external variable.

		Total Quay Cranes	**Terminal Area (10^5 m^2)**	**Quay Length (10^3 m)**	**OPEX (Eur 10^6)**	**Container Throughput (10^4 TEU)**
	Total (whole sample)	15.52 (21.85)	9.70 (13.50)	2.18 (2.84)	26.97 (45.13)	161.45 (239.67)
Z5	Western Europe	32.69 (37.79)	21.73 (22.27)	4.54 (4.91)	65.02 (77.80)	352.45 (396.16)
	Central and Eastern Europe	9.33 (6.62)	6.96 (8.14)	1.04 (0.67)	10.13 (9.35)	87.57 (89.85)
	Northern Europe	5.75 (3.31)	4.76 (4.59)	1.10 (0.72)	13.01 (8.88)	32.35 (24.34)
	Southern Europe	12.52 (10.49)	6.19 (5.42)	1.70 (1.18)	17.14 (20.16)	140.13 (134.27)
Z4	Landlords	17.63 (23.69)	11.23 (14.51)	2.45 (3.07)	30.47 (49.14)	187.40 (258.48)
	Others	6.20 (3.58)	2.95 (2.25)	0.95 (0.56)	11.59 (11.69)	47.29 (35.73)
Z3	Diversified commodities	10.53 (19.77)	7.14 (11.54)	1.62 (2.66)	15.20 (20.84)	91.34 (190.56)
	Only containers	27.38 (22.60)	15.79 (16.12)	3.50 (2.90)	54.93 (70.30)	327.96 (267.13)

Table 5. Pearson's correlation coefficients between inputs and outputs. All coefficients are significant at 5%.

	Total Quay Cranes	**Terminal Area**	**Quay Length**	**OPEX**	**Container Throughput**
Total Quay Cranes	1	0.9427	0.9690	0.7503	0.9573
Terminal Area		1	0.9517	0.7254	0.9114
Quay Length			1	0.7116	0.9198
OPEX				1	0.7968
Container throughput					1

Tables 6 and 7 show additional basic statistics of environmental variables as a function of the binary/categorical variables and the corresponding distribution of seaports. As one can observe:

(1) The sample is not uniformly distributed across those variables.

(2) Landlord seaports are by far the most frequent management model in the sample. (Ports in Southern Europe do not present any other type of management model, and they constitute about half of the present set.)
(3) About a third of this dataset is composed of seaports only for containers, mainly due to Southern Europe, where a quarter of them are located.
(4) Most of the seaports only for containers present a landlord management model, but the reciprocal is not true.
(5) Northern European countries present the highest average regional GDP.
(6) It seems that landlord seaports and ports for diversified commodities are associated with the highest average regional GDP.
(7) The water depth seems to be associated only with the commodity-type diversification. Greater water depths are associated with ports only for containers.

Table 6. Some (environmental) data statistics, by binary/categorical variable.

		Seaports	% Landlord Seaports	% Seaports Only for Containers	Average (Std) Regional GDP per Capita/EUR 1000	Average (Std) Water Depth/m
	Total (whole sample)	54	81.48	29.63	32.74 (22.66)	13.44 (2.72)
Z5	Western Europe	13	69.23	38.46	38.55 (9.88)	13.90 (3.41)
	Central and Eastern Europe	6	66.67	16.67	19.44 (17.30)	13.18 (1.18)
	Northern Europe	12	66.67	0	58.53 (31.06)	12.13 (1.38)
	Southern Europe	23	100	43.48	19.47 (6.42)	13.93 (2.99)
Z4	Landlords	44	100	34.09	33.79 (23.71)	13.67 (2.70)
	Others	10	0	10.00	28.12 (19.10)	12.40 (2.71)
Z3	Diversified commodities	38	76.32	0	35.32 (24.94)	12.95 (2.71)
	Only containers	16	93.75	100	26.60 (16.01)	14.60 (2.45)

Table 7. Pearson's correlation coefficients between environmental variables. * Significant at 10%; ** significant at 5%.

	Regional GDP per Capita	Water Depth	Commodity Type Diversification	Management Model	European Region
Regional GDP per capita	1	−0.2053	−0.1757	−0.0972	−0.2537 *
Water depth		1	0.2798 **	−0.1831	0.0045
Commodity-type diversification			1	−0.2049	0.0557
Management model				1	−0.3274 **
European region					1

5. Results

This section presents the case study's results and discusses them. In short, expected results are the NW regression estimates and their behaviour regarding the evolution of the explanatory variable, Z.

Figures 2 and 3 and Figures A1–A4 (Appendix A) condense the NW nonparametric regressions of δ and Q (as defined in Section 3) against each exogenous variable Z_ℓ ($\ell = 1, \ldots, 6$). Two different frontier approaches are adopted here: the median partial frontier with $\alpha = 0.5$ and the "full" frontier with $\alpha = 0.9999$ (~1). On the other hand, Figures A5–A8 (Appendix A) show those regressions, but for the direct conditional full frontier-based ($\alpha = 0.9999$) efficiency measures (instead of the gaps between the conditional and the unconditional frontiers) against the same external variables Z_ℓ. There, "NW expected" (resp. "NW std") represents the $\mu(Z)$ (resp. $\sigma(Z)$) from the approach $\theta_{\alpha,z} = \mu(Z) + \sigma(Z)\varepsilon$, while the "Residuals" term represents $\varepsilon = (\theta_{\alpha,z} - \mu(Z))/\sigma(Z)$, which is a measure of the managerial efficiency after removing the environmental effects. A large value of ε reveals poor managerial performance, which is not the focus of this paper.

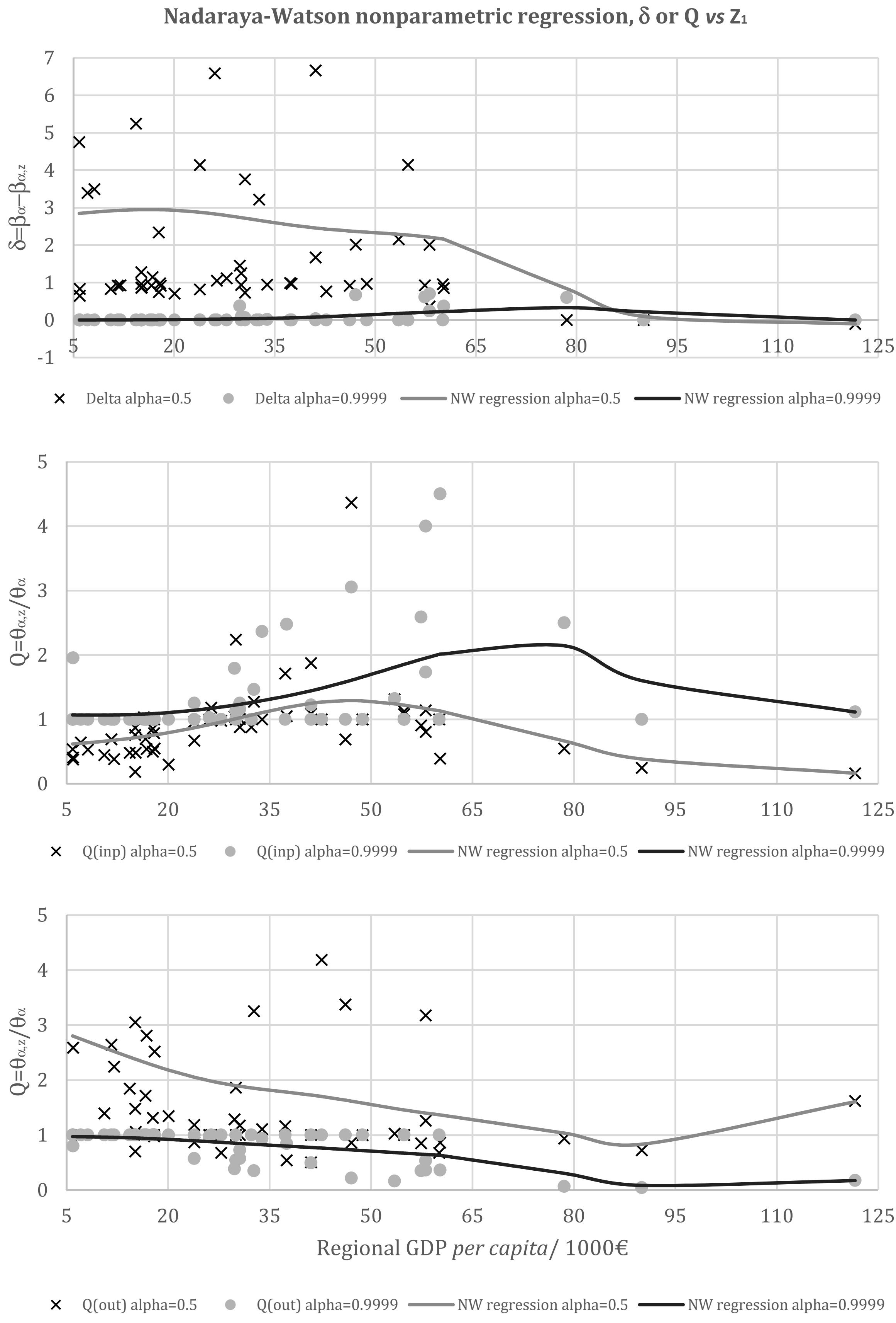

Figure 2. Nadaraya–Watson nonparametric regressions of conditional vs. unconditional relationships concerning the exogenous variable Z_1 (regional GDP per capita).

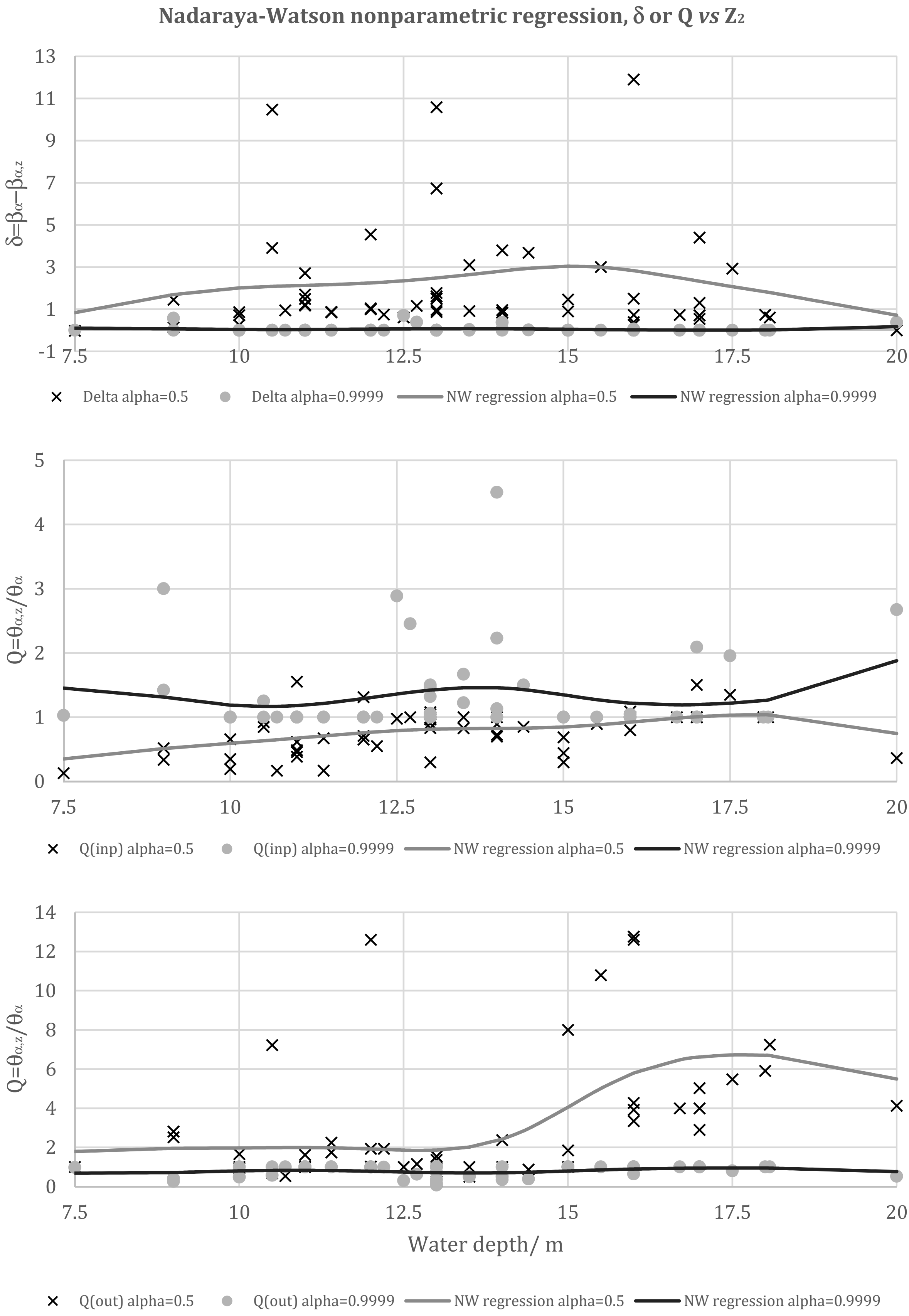

Figure 3. Nadaraya–Watson nonparametric regressions of conditional efficiency and management efficiency (residuals) concerning the exogenous variable Z_1 (regional GDP per capita).

Tables A1–A3 (Appendix A) provide the effect of the continuous environmental variables on the efficient frontiers, efficiency distributions and dispersion. The first column contains the independent variable (δ, Q, etc.), IV, for different values of α (second column) and model orientations (third column). Spearman's coefficient for each case is computed, and the behaviour of the function on Z (sgn $\partial/\partial Z$) is provided. While "↘' (resp. "↗") reveals a decreasing (resp. increasing) behaviour, symbol "≈" indicates that there is no statistical effect of Z on the independent variable. If sgn $\partial/\partial Z$ is represented by "≈" for $\alpha = 0.9999$, then one may assume that the separability condition holds, i.e., the impact of Z (if any) lies in the efficiency distribution, not in the frontier.

From these results and the analysis of Figures 2 and 3 and Figures A1–A8, some noteworthy conclusions are delivered. The significance of the correlation coefficients, $\rho_{\alpha,\ell,\varpi}$, for the NW-based estimations, $m_{\alpha,\varpi}(Z_\ell)$, is represented with asterisks at the 5% significance level, as follows (For this particular case study, Spearman's and Kendall's nonparametric coefficients provide similar results. To save space, only the Spearman's coefficients are displayed.). Allow the following:

$$H_0\text{: } \rho_{\alpha,\ell,\varpi} = \text{corr}(m_{\alpha,\varpi}(Z_\ell), Z_\ell) = 0;$$

$$H_1\text{: } \rho_{\alpha,\ell,\varpi} = \text{corr}(m_{\alpha,\varpi}(Z_\ell), Z_\ell) < 0;$$

$$H_2\text{: } \rho_{\alpha,\ell,\varpi} = \text{corr}(m_{\alpha,\varpi}(Z_\ell), Z_\ell) > 0,$$

s.t. $\ell = 1, 2, 6$; $\alpha \in [0, 1]$ and $\varpi = \{\text{IO} - \alpha, \text{OO} - \alpha, \text{D} - \alpha\}$, for the input-oriented, the output-oriented, and the multidirectional framework, respectively.

5.1. Regional GDP per Capita

Table A1 (Appendix A) gives an overview of the effect of the regional GDP per capita on seaport performance. In short, one can conclude that (1) this external variable has a negative impact as it grows to EUR 80,000, so DMUs with smaller values present higher average efficiency levels; (2) these results are consistent among different models; and (3) this analysis reveals the danger of investigating Z on performance solely in light of the evolution of $\theta_{\alpha=0.9999} = f(Z)$. In fact, such behaviour reveals only the impact of Z on the efficiency distribution (as measured by $\mu(Z)$, $\beta_{\alpha\to 1} = f_1(Z)$ and $\theta_{\alpha\to 1} = f_2(Z)$, see Table 4). Accordingly, and consistent with the model, one can say that for lower (resp. larger) values of Z_1, the seaports tend to be farther away from (resp. closer to) the efficient frontier, presenting a significant dispersion in that region of Z1.

At elevated levels, a detrimental correlation may arise between GDP per capita and seaport performance, owing to many causes. A crucial determinant is the decreasing marginal benefits of investing in maritime infrastructure. As the GDP per capita rises, the demand for products and services may see a slower growth rate in comparison to the exponential rise in infrastructure expenses. As a result, the additional advantages gained by investing more in seaports decrease, resulting in a levelling off or decrease in performance compared to GDP per capita. Moreover, when wealth levels increase, nations may shift their focus away from strong dependence on marine commerce, so diminishing the significance of seaport performance as a catalyst for economic development. Lastly, the effectiveness of port operations and overall economic performance may be hindered by congestion and environmental issues that arise from excessive port activity.

Meanwhile, seaports in areas with lower GDP per capita often demonstrate exceptional performance as a result of many variables. First and foremost, these areas may substantially depend on marine commerce as the main catalyst for economic activity, resulting in substantial expenditures in port infrastructure and steps to improve efficiency. Additionally, these locations often have lower labour expenses, which enables more efficient operations and cheaper pricing. Additionally, there might be a reduction in administrative obstacles and regulatory limitations, leading to more efficient port activities. Furthermore, the prospect of expansion in these areas has the ability to allure investments and encourage innovation, leading to ongoing enhancements in seaport efficiency. In locations with lower

GDP per capita, seaports outperform due to their strategic significance, advantageous cost structures, and potential for expansion.

In short, the null hypothesis that the regional GDP has no influence on either the efficiency distribution or the efficiency frontier is rejected in light of the statistical evidence. The results seem to be robust, as they do not depend on the model orientation, i.e., on managerial points of view.

5.2. Water Depth

Table A2 (Appendix A) details the effect of water depth on seaport performance. As is easy to conclude, the effects over the production process are visible only in the IO model (even so, the effect does depend on Z2 levels); otherwise, the effect reduces to the efficiency distribution. In the $IO - 0.9999$ model, the water depth seems to have a positive impact on the attainable set for $Z_2 \in \Omega+ = [7.5; 10) \cup (13; 17.5)$ m as Q decreases in that range. Outside $\Omega+$, that effect is negative, i.e., seaports with mid-depth or excessively deep water are in general in an unfavourable environment. Regarding the efficiency distribution, although the conditional efficiency distributions' behaviour as a function of $Z2$ is somewhat consistent among different models (deeper water generally indicates a lower efficiency spread near the frontier), the same cannot be said for unconditional measures of efficiency. In this case, the conclusion is the opposite (see Table 5): Deeper water generally indicates a larger efficiency spread near the frontier, which shows that the traditional two-stage of regressing the technical efficiency on Z variables should be avoided because it could provide inconsistent results. That is, the behaviour shown by conditional measures should be adopted instead.

In short, the null hypothesis that the water depth has no influence on the efficiency distribution is rejected in light of the statistical evidence. However, the results seem to depend on the model orientation. Furthermore, the variable does not help explaining why the benchmarks are more efficient than the other seaports in the sample.

5.3. Commodity-Type Diversification

For the case of binary and categorical external variables ($\ell = 3, 4, 5$), the between-group conditional efficiency distributions ($\omega_{\alpha,z}$ and $\theta_{\alpha,z}$) and the conditional-to-unconditional efficiency gap distributions (δ and Q) are compared using a bootstrap-based test proposed by Oliveira et al. [57], which is an improvement on the statistical test introduced by Simar and Zelenyuk [58]. In short, this test compares efficiency distributions, so the null hypothesis is H_0:

H_0. *The two samples are drawn from the same distribution.*

Clearly, for $\ell = 5$, the analysis is performed by pairs. For this approach, $B = 1500$ bootstrap iterations are utilised.

Concerning external variable Z3, it becomes evident that the separability condition holds for the full frontier as the statistical test returns the following p-values: $p(D - 0.9999) = 0.4813$, $p(IO - 0.9999) = 0.4427$ and $p(OO - 0.9999) = 0.7900$. That is, there is no statistical evidence (at 1% significance) to reject the null hypothesis. Therefore, one can assume that the two groups of seaports share the same distribution features (average, median, *inter alia*) regarding the full frontier; that is, $Z3$ has no effect on the AS (full frontier). Furthermore, for $D - 0.5$ and $IO - 0.5$, one has $p(D - 0.5) = 0.6840$, $p(D, \Delta) = 0.7620$, $p(IO - 0.5) = 0.0773$, and $p(IO, \nabla) = 0.0253$, which means that there is no difference in the median efficiency distributions due to Z3. The same cannot be said regarding model $OO - 0.5$, which presents $p(OO - 0.5) = p(OO, \nabla) = 0$. Looking at Figure A2, one would conclude that conditional efficiencies are deeply affected by Z3, but this is true for only the $OO - 0.9999$ model, at 1% significance, as $p(D - 0.9999) = 0.0213$, $p(IO - 0.9999) = 0.0119$ and $p(OO - 0.9999) = 0.0047$ (<0.01). While seaports handling diversified commodities will increase their production on average to approximately 46% (resources held), this level reduces to 17% for seaports only for containers with respect to a meta-frontier.

In short, the null hypothesis that commodity-type diversification has no influence either on the efficiency distribution or the efficiency frontier is rejected in light of the statistical evidence. The results, however, seem to be depend on the model orientation.

5.4. Management Model

When the management model is analysed, different conclusions are drawn depending on the model orientation. If the model is bi-oriented, there are no meaningful differences in efficiency distributions at 1% significance, and thus the separability condition holds as well. On average, $\omega_{\alpha=0.9999,z=0}$ = 1.5877 and $\omega_{\alpha=0.9999,z=1}$ = 1.2963; therefore, landlords seem to be less efficient than the remainder, but the differences are not statistically significant. When the model is single-oriented, statistically significant differences arise: the non-landlord seaports are those with higher average efficiency, but also present a larger efficiency spread. That is, landlords will reduce their consumed resources to approximately 32% (outputs held) or increase their production to 45% (inputs held); those values reduce to approximately 4% for non-landlord seaports.

In short, the null hypothesis that the seaport's management model has no influence on either the efficiency distribution or the efficiency frontier cannot be rejected in light of the statistical evidence. The results, however, seem to be depend on the model orientation.

5.5. European Region

Table A3 (Appendix A) contains the *p*-values of the statistical tests applied in the case of European regions and the average (geometric mean) efficiency (for α = 0.9999) for each reference group and model orientation. To compute the *p*-values, a group of references is compared against the others (as a new group excluding the former). It becomes clear that the Southern European seaports are the most inefficient ones, regardless of the model orientation. In the input-oriented model, efficiency distribution differences are significant: the Central/Eastern European seaports are the most efficient ones, followed by those in Western Europe and then by those in Northern Europe. In this model, $Z4$ seems to have no effect on the frontier. On the contrary, it influences the frontier shape in the output-oriented model. Under this model orientation, the Central/Eastern and Western European seaports are the most efficient, ex aequo. On the other hand, in the bi-oriented model (D-α), the external factor has no expressive impact on the production process in the first three groups of reference, as $\delta(Z) \approx 0$, but the Western and Southern Europe seaports present the larger efficiency spread, the latter group having the worst levels of efficiency. Accordingly, excluding that group, there are no marked differences in efficiency levels or efficiency distributions in the remaining groups.

Southern seaports often encounter inefficiencies resulting from factors such as insufficient infrastructure, bureaucratic regulations, and labour disputes. Inadequacies in infrastructure, such as obsolete facilities and restricted capacity, may result in congestion and delays in the processing of goods. Operational efficiency is hindered by bureaucratic inefficiencies, including intricate rules and customs processes, which result in delays and higher expenses. Moreover, labour conflicts and inefficiency have the potential to interrupt port activity. Seaports in Central/Eastern Europe are advantaged by their strategic positions, updated infrastructure, efficient regulatory frameworks, and highly qualified workforce. These ports have used their strategic geographic location to become crucial centres for commerce between Europe and Asia. Furthermore, the allocation of resources towards technology and automation has bolstered productivity, resulting in decreased processing durations and increased customer demand. Collectively, these characteristics contribute to the exceptional performance of seaports in Central/Eastern Europe in comparison to their counterparts in the south.

6. Discussion

This study complements the literature regarding the analysis of the impact of exogenous variables on seaports' performance using a recent and rarely used but very robust methodology. Unlikely previous studies, the method can be classified as *data-driven* rather than *strong unreliable assumptions-based*. Indeed, it constructs empirical frontiers that can either be conditioned to any exogenous variable or not. The gap between the conditional and the unconditional version of the method discloses potential effects of environment on efficiency boundaries and on efficiency distributions with clear policy and managerial implications, as policymakers and managers should know how the system will likely behave when nondiscretionary variables change.

The first conclusion drawn by this work is that the traditional analysis of the full frontier-based efficiency vs. environmental variables may jeopardize the study conclusions, as it relies on the separability condition. Then, no changes on the frontier as the result of such variables are accounted for. Unfortunately, most of the literature is full of this type of analysis, regardless of the type of model employed. An alternative is then to utilize the robust nonparametric partial median and full frontiers to check whether the exogenous variables tend to affect the frontier shape and whether the aforementioned condition holds. If this is the case, the exogenous variable changes only the efficiency distributions, not the frontier shape.

In that light, several important conclusions about the effect of such exogenous variables on performance can be drawn. First and foremost, because the models are consistent among themselves, one may conclude that the regional GDP per capita tends to have a negative impact on seaports for very large values. On the contrary, seaports farther away from that value (poorer regions) usually perform better. This finding can be explained considering commercial exchanges, as well as considering the involvement of activities at the higher-order capability development level in intermodal transport operations that include (a) dealing with cargo claims, (b) sharing profit with business partners, (c) handling multimodal transport, (d) forming alliances with business partners, (e) developing agency networks, and (f) integrating the operational system [59]. Hence, if GDP per capita is low, it increases the effort in improving the performance of all the entities involved. Seaports operating in richer regions (Northern Europe) are likely more inefficient and should make a benchmarking effort to search for best practices that, as discussed later, are in Central/Eastern Europe. According to our previous findings, this region is close to Southern Europe in terms of GDP per capita, both being the poorest regions in Europe. However, seaports located in Southern Europe are, on average, less efficient than the ones in Central/Eastern Europe, which means that there are other factors that may affect performance rather than GDP.

Southern seaports are clearly the most inefficient ones, while seaports in Central/Eastern Europe take the podium, regardless of the model orientation. The positions of other regions may switch within the ranking, depending on the model. Even so, this variable seems to have no meaningful impact on the attainable set, thus the separability condition holds. These results reinforce the conclusions drawn by Niavis and Tsekeris [60], who attribute the low efficiency of Southern seaports to both a lack of managerial skills and scale effects. In general, seaports in Northern Europe have a larger output volume than those in Southern Europe, which can be due to the combination of economic and geographic factors.

In the water depth case, the results strictly depend on the model orientation. If one takes the input-oriented model, it seems that seaports with mid-depth (say [10; 13] m) and very deep (>17.5 m) water face an unfavourable environment, but in general, seaports with deeper water tend to be closer to the efficient frontier. This result is expected and in line with the literature, as the water depth tends to limit the ships' dimensions and then their transported cargo. In fact, improved water depth allows a concentration of larger vessels at the port, which, taking advantage of economies of scale and cargo density, achieve higher productivity and efficiency levels; this, in turn, attracts more traffic from direct liner services, thus satisfying customers [52].

Although there is no statistical evidence that the commodity-type diversification has any effect on the possible production set, under the output orientation, seaports only for containers (container terminals) seem to present higher average technical efficiency, which is in line with the conclusions of Liu [51]. For instance, countries in Northern Europe are in general richer than the remaining parts of the continent (the former exhibit larger GDP per capita levels), and simultaneously, their seaports all handle diversified commodities, which may link it to the findings regarding efficiency vs. GDP. Moreover, these results seem to be in line with Chang and Tovar [7] and Trujillo and Tovar [54], who used a containerisation index and concluded that the higher this rate, the lower the inefficiency of terminals. This can be justified by the higher degrees of mechanisation allowed by this kind of cargo.

The management model appears to have no meaningful impact on seaport performance when the multidirectional framework is adopted; otherwise, differences can be found, the landlords being those with lower levels of efficiency, but a narrower efficiency spread. This result is unexpected as landlords are commonly associated with better performance, and managers and authorities should be aware of this result given the fact that landlords have been continuously applied in Europe as the preferred management model for seaports. Nonetheless, it could be a biased result because most of the sample is composed of landlords. Therefore, this analysis should be left for further research with a broader sample, homogeneously distributed among those different groups.

Although seaport size was not considered here as an environmental variable, the results seem to suggest that size is not a good driver of efficiency or at least should be cautiously used for managerial and policy purposes. One would be tempted to claim that smaller seaports are in general more efficient than the larger ones, see e.g., Coto-Millán et al. [61]. However, if containerisation and terminal area are two good proxies for seaport size, then Western European seaports would likely be the most inefficient ones. This is not the case, as their performance is close to Central/Eastern Europe-located entities. Likewise, Northern European seaports would be the most efficient in our sample, because they are the smallest units on average, but they were classified as less efficient than Western European seaports.

Some limitations of our results can be pointed out to be improved in further research. The major shortcoming is the choice of variables. Although limited by data availability and selecting variables according to a comprehensive literature review, the results may not totally explain the seaports' overall production. Indeed, all relevant production variables should be used and disregarding important data will likely lead to unfair comparisons. This study uses containers throughput as the only output, despite nearly two-thirds of the sample being seaports providing other kinds of services. Such a fact may have introduced some bias in the results, which should be explored in the future.

Regarding inputs, although operational expenses (OPEX) have been included in the model and this variable considers expenses with labour and outsourcing, in the future, one should disaggregate (if possible) OPEX into its main components and test whether the final results are influenced by the number and choice of input variables.

Exogenous variables assumed a prominent role in this research. The more data we include, the more conclusions and managerial implications we can draw from results. This study has considered five exogenous variables that, despite their importance, have been mostly disregarded from previous studies. As mentioned earlier, other variables can be assumed in further research, including those related with connectivity, industrial and population density, trans-shipment activity, investments, and trade restrictions.

Although this study used only a single year's data, the analysis can be extended to other periods of time and to enjoy some dynamic effects on results. Some hints for future research are as follows. One needs to estimate a multidimensional kernel-based probability density function that simultaneously accounts for a variable *year* and the exogenous variables that are being analysed. For instance, one may use the approach suggested by Daraio and Simar [32] (pp. 110–112), and used by Ferreira and Marques [62–64], which uses a covariance matrix to consider potential relationships between the exogenous variables composing the multidimensional framework. Then, one should estimate efficiency scores (un)conditional to the exogenous variable, and relate them just like we did in this research. The difference is that time (and its effects on environment) is accounted for and results may have a dependence on it. However, one may assume that the environment is mostly stable and variables have little dependence on time, which means that no significant changes are expected [65,66].

Another problem that can be identified is related to the perfect knowledge about data that somehow can jeopardize the quality and validity of the results. Although most of the data used in this research come from official sources, measuring errors always exist [34,67], requiring the use of sophisticated techniques to surpass this issue. A newly developed alternative is the so-called hit and run, which is based on stochastic multicriteria acceptability analysis. This technique was recently integrated with DEA and models alike and would be an interesting topic for further research [46,68].

7. Conclusions

Evaluating efficiency disregarding the exogenous environment surrounding operators is a misleading exercise that results in unfair comparisons [69,70]. This paper highlights that assessing seaport efficiency solely based on internal factors can lead to misleading and unfair comparisons. It stresses that seaport operators, managers, and authorities should be acutely aware of the external environment's influence on their operations and overall efficiency. This awareness is crucial for devising strategies aimed at enhancing competitiveness and performance.

So far, studies have been focused on outdated methods whose outcomes are expectedly biased. This study has proposed to use a robust, novel and promising approach that solves the main shortcomings found in the literature, is easy to compute, and disentangles the effect of environment on efficiency distributions from its impact on the efficient frontier's shape [34].

Findings were usually dependent on the model orientation, and some bias could arise from this issue. For that reason, in the future one should test whether these results remain when a non-oriented and non-radial model is used. Nevertheless, some insights can be drawn. First, poorer regions (in terms of the regional GDP per capita) possess the most efficient seaports. This result seems to justify why Central/Eastern European entities are more efficient, but it is not sufficient to justify why Southern European seaports are the worst performers. That is, the GDP per capita is not the only driver of efficiency, but helps to understand the behaviour of operational efficiency. Second, deeper water is associated with better performance, an expected outcome, as seaports can receive larger ships and handle more cargo transported by the latter. Third, the commodity-type diversification is a driver of efficiency, as seaports that handle only containers are expectedly more efficient. This suggests that diversification can enhance seaport efficiency by spreading risk and increasing the potential for revenue generation. Last but not least, the management model concludes that landlords are perhaps the most inefficient, casting doubts regarding the advantages of its application to other seaports in the future. This insight prompts a reconsideration of management strategies and their impact on seaport efficiency.

The research presents a rigorous technique, different from prior methods, for evaluating the influence of external factors on the operation of seaports. By using a data-driven approach instead of making assumptions, this strategy creates empirical boundaries based on external factors, providing a detailed comprehension of their impacts. The findings have important implications for policy and management. Regional GDP per capita has a detrimental effect on big seaports, highlighting the need for developing specific policies that take into account the economic conditions. Southern European seaports are recognised as being less efficient, which indicates places where improvements may be made. Additionally, an unexpected finding shows that landlord management methods have worse efficiency. The research questions conventional studies, emphasising the need to be cautious when assessing efficiency merely based on environmental factors and pushing for a more sophisticated understanding of seaport performance. To expand the study's depth and relevance in directing effective policies and management practices for seaports internationally, future research could investigate more factors, break down inputs into smaller components, and take into account dynamic impacts over time. In summary, this paper underscores the significance of considering the external environment's influence on seaport efficiency. It introduces a novel methodology to address this issue and provides valuable insights into the complex determinants of seaport performance. The findings challenge conventional wisdom, such as the sole reliance on GDP per capita as a determinant, and offer new perspectives on the influence of water depth, commodity diversification, and management models on seaport efficiency. These insights have implications for seaport operators and policymakers aiming to enhance competitiveness and operational performance.

The study's findings and approach provide useful insights that may be used in regions with seaports, serving as a basis for comprehending and improving port efficiency. The methodology's suitability for different locations depends on the careful examination of various geographic situations. Researchers seeking to modify this approach should thoroughly evaluate local variations, including economic frameworks, infrastructural advancements, and governmental environments. The process of selecting variables becomes vital, as it involves identifying the external elements that are most relevant to the distinctive features of each place. The availability and quality of data may differ, requiring modifications and the inclusion of alternate sources or factors. Incorporating a dynamic analysis that considers temporal changes and emerging situations improves the flexibility of the process. It is crucial to actively include stakeholders such as local lawmakers and industry experts in order to address the particular issues and possibilities unique to each location. Although the comprehensive framework serves as a basis, researchers must be cautious when drawing comparisons across different regions, since standards and factors affecting efficiency may vary. In order to apply this technique to other geographic situations, a careful and context-specific approach is necessary. This will enable its wider use in seaports across the world.

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Appendix A

Table A1. Effect of Z_1 (regional GDP per capita) on efficiency frontier, distribution, and scattering. At 5% significance, * H_0 is not rejected, ** H_1 is not rejected, and *** H_2 is not rejected.

IV	α	ϖ	$\rho_{\alpha,l,\varpi}$	$sgn \frac{\partial}{\partial Z}$	**Notes/Conclusions**
δ	0.5	*D*-α	−0.8773 **	↘	Z_1 seems to have a little (meaningless) negative effect on the attainable set (AS) for seaports with $Z_1 \approx$ 80,000 €. For smaller and larger values of Z_1, technical efficiency is higher. However, this external variable presents a strong negative effect on efficiency distribution, since as Z_1 decreases, $\delta_{0.5}$ increases. That is, smaller values of Z_1 show lower values of Δ.
	0.9999	*D*-α	0.8902 ***	≈	

Table A1. *Cont.*

IV	α	ϖ	$\rho_{\alpha,I,\varpi}$	$sgn\frac{\partial}{\partial Z}$	Notes/Conclusions
Q	0.5	*IO*-α	0.6652 ***	↗	Z_1 has a negative impact on the AS for values close to 80,000 €. When Z_1 goes beyond (or retrograde from) that value, the technical efficiency is higher. The efficiency spread (as measured by the gap between the partial- and the full-frontier related efficiencies) is smaller for lower levels of Z_1, as ∇ increases with Z_1.
	0.9999	*IO*-α	0.9521 ***	↗	
	0.5	*OO*-α	−0.9950 **	↘	Z_1 has a negative impact on the AS for values close to 80,000 €. When Z_1 goes beyond (or retrograde from) that value, the technical efficiency is higher. The efficiency spread is higher for lower levels of Z_1, as ∇ decreases with Z_1, in line with the behavior of Δ.
	0.9999	*OO*-α	−0.9999 **	↘	
Δ	N.A.	*D*-α	0.9353 ***	↗	Δ is a monotone increasing function on Z_1; $\Delta > 0$ for $Z_1 > 78{,}540$ €.
∇	N.A.	*IO*-α	0.6564 ***	↗	∇ is an increasing function on Z_1, and $\nabla > 1$ for all values of Z_1.
		OO-α	−0.3102 **	↘	∇ is a decreasing function on Z_1, and $\nabla < 1$ for all values of Z_1.
μ	0.9999	*D*-α	−0.9949 **	↘	Units under larger Z_1 levels are closer to the efficient frontier.
	0.9999	*IO*-α	0.8660 ***	↘	
	0.9999	*OO*-α	−0.9770 **	↘	
σ	0.9999	*D*-α	−0.9757 **	↘	The higher Z_1, the lower the technical efficiency dispersion (heteroscedasticity).
	0.9999	*IO*-α	−0.7279 **	↘	
	0.9999	*OO*-α	−0.9963 **	↘	
β_α	0.9999	*D*-α	N.A.	N.A.	$Z_1 < 80,000: \left\{-\frac{\partial\beta_z}{\partial Z} > 0\ \frac{\partial\delta}{\partial Z} \gtrsim 0 \wedge \frac{\partial\delta}{\partial Z} < -\frac{\partial\beta_z}{\partial Z} \Longrightarrow \frac{\partial\omega}{\partial Z} < 0\right.$ (positive effect as Z increases) $Z_1 > 80,000: \left\{-\frac{\partial\beta_z}{\partial Z} \lesssim 0\ \frac{\partial\delta}{\partial Z} \lesssim 0 \wedge \frac{\partial\delta}{\partial Z} \gtrsim -\frac{\partial\beta_z}{\partial Z} \Longrightarrow \frac{\partial\omega}{\partial Z} \gtrsim 0\right.$ (negative effect, meaningless though, as Z increases)
θ_α	0.9999	*IO*-α	N.A.	N.A.	$Z_1 < 80,000: \left\{\frac{\partial Q/\partial Z}{Q} > 0\ \frac{\partial\theta_{\alpha\to 1,z}/\partial Z}{\theta_{\alpha\to 1,z}} > 0 \wedge \frac{\frac{\partial Q}{\partial Z}}{Q} > \frac{\frac{\partial\theta_{\alpha\to 1,z}}{\partial Z}}{\theta_{\alpha\to 1,z}} \Longrightarrow \frac{\partial\theta}{\partial Z} > 0\right.$ (positive effect as Z increases) $Z_1 > 80,000: \left\{\frac{\partial Q/\partial Z}{Q} < 0\ \frac{\partial\theta_{\alpha\to 1,z}/\partial Z}{\theta_{\alpha\to 1,z}} \gtrsim 0 \wedge \frac{\frac{\partial Q}{\partial Z}}{Q} \lesssim \frac{\frac{\partial\theta_{\alpha\to 1,z}}{\partial Z}}{\theta_{\alpha\to 1,z}} \Longrightarrow \frac{\partial\theta}{\partial Z} \lesssim 0\right.$ (negative effect, meaningless though, as Z increases)
	0.9999	*OO*-α	N.A.	N.A.	$Z_1 < 80,000: \left\{\frac{\partial Q/\partial Z}{Q} < 0\ \frac{\partial\theta_{\alpha\to 1,z}/\partial Z}{\theta_{\alpha\to 1,z}} < 0 \wedge \frac{\frac{\partial Q}{\partial Z}}{Q} < \frac{\frac{\partial\theta_{\alpha\to 1,z}}{\partial Z}}{\theta_{\alpha\to 1,z}} \Longrightarrow \frac{\partial\theta}{\partial Z} < 0\right.$ (positive effect as Z increases) $Z_1 > 80,000: \left\{\frac{\partial Q/\partial Z}{Q} > 0\ \frac{\partial\theta_{\alpha\to 1,z}/\partial Z}{\theta_{\alpha\to 1,z}} \cong 0 \wedge \frac{\frac{\partial Q}{\partial Z}}{Q} > \frac{\frac{\partial\theta_{\alpha\to 1,z}}{\partial Z}}{\theta_{\alpha\to 1,z}} \Longrightarrow \frac{\partial\theta}{\partial Z} > 0\right.$ (negative effect as Z increases)

Table A2. Effect of Z_2 (water depth) on efficiency frontier, distribution, and scattering. At 5% significance, * H_0 is not rejected, ** H_1 is not rejected, and *** H_2 is not rejected.

IV	α	ϖ	$\rho_{\alpha,I,\varpi}$	$sgn\frac{\partial}{\partial Z}$	Notes/Conclusions
δ	0.5	*D*-α	0.4906 ***	↗	Z_2 has no meaningful effect on the AS. However, it seems to negatively affect the efficiency distribution since $\delta_{0.5}$ increases until Z_2 = 16 m.
	0.9999	*D*-α	−0.3326 **	≈	
Q	0.5	*IO*-α	0.9461 ***	↗	The effect of Z_2 in AS depends on the water depth level. For $Z_2 \in [7.5;10] \cup [14;18]$, Q decreases, which means that Z_2 acts as a substitutive input, being conductive to efficiency; outside those ranges, its behavior seems to be the opposite. Narrower efficiency gaps occur for Z_2 levels close to 10 m and 17.5 m.
	0.9999	*IO*-α	0.2479 *	↗↘	
	0.5	*OO*-α	0.7590 ***	↗	Z_2 has no meaningful effect on the AS. However, it seems to negatively affect the efficiency distribution since $\delta_{0.5}$ increases until Z_2 = 17.5 m. Seaports with water depth between 7.5 and 13 m present lower levels of efficiency spread.
	0.9999	*OO*-α	0.3754 ***	≈	
Δ	N.A.	*D*-α	−0.2970 **	↘	Δ is a decreasing function until $Z_2 = 16$ and increasing after that value; $\Delta < 0$ for all values of Z_2.
∇	N.A.	*IO*-α	−0.6452 **	↘	∇ is a decreasing function on Z_2, and $0 < \nabla < 1$ for all values of Z_2.
		OO-α	−0.8967 **	↘	
μ	0.9999	*D*-α	−0.9503 **	↘	Units under larger Z_2 levels are closer to the efficient frontier.
	0.9999	*IO*-α	0.5203 ***	↘	
	0.9999	*OO*-α	−0.9069 **	↘	
σ	0.9999	*D*-α	−0.8930 **	↘	The higher Z_2, the lower the technical efficiency dispersion (heteroscedasticity).
	0.9999	*IO*-α	−0.4911 **	↘	
	0.9999	*OO*-α	−0.9400 **	↘	

Table A2. *Cont.*

IV	α	ϖ	$\rho_{\alpha,l,\varpi}$	$sgn\frac{\partial}{\partial Z}$	Notes/Conclusions
β_α	0.9999	*D*-α	N.A.	N.A.	$Z_2 \leq 9: \left\{-\frac{\partial\beta_z}{\partial Z} < 0 \ \frac{\partial\delta}{\partial Z} \approx 0 \wedge \frac{\partial\delta}{\partial Z} > -\frac{\partial\beta_z}{\partial Z} \Longrightarrow \frac{\partial\omega}{\partial Z} > 0\right.$ (negative effect as Z increases) $16 \geq Z_2 > 9: \left\{-\frac{\partial\beta_z}{\partial Z} > 0 \ \frac{\partial\delta}{\partial Z} \approx 0 \wedge \frac{\partial\delta}{\partial Z} < -\frac{\partial\beta_z}{\partial Z} \Longrightarrow \frac{\partial\omega}{\partial Z} < 0\right.$ (positive effect as Z increases) $Z_2 > 16: \left\{-\frac{\partial\beta_z}{\partial Z} \lesssim 0 \ \frac{\partial\delta}{\partial Z} \approx 0 \wedge \frac{\partial\delta}{\partial Z} \gtrsim -\frac{\partial\beta_z}{\partial Z} \Longrightarrow \frac{\partial\omega}{\partial Z} > 0\right.$ (negative effect as Z increases)
θ_α	0.9999	*IO*-α	N.A.	N.A.	$Z_2 \leq 10: \left\{\frac{\frac{\partial Q}{\partial Z}}{Q} < 0 \ \frac{\frac{\partial\theta_{\alpha\to1,z}}{\partial Z}}{\theta_{\alpha\to1,z}} < 0 \wedge \frac{\frac{\partial Q}{\partial Z}}{Q} > \frac{\frac{\partial\theta_{\alpha\to1,z}}{\partial Z}}{\theta_{\alpha\to1,z}} \Longrightarrow \frac{\partial\theta}{\partial Z} > 0\right.$ (positive effect as Z increases) $14 \geq Z_2 > 10 \ or \ Z > 16.7: \left\{\frac{\frac{\partial Q}{\partial Z}}{Q} > 0 \ \frac{\frac{\partial\theta_{\alpha\to1,z}}{\partial Z}}{\theta_{\alpha\to1,z}} > 0 \wedge \frac{\frac{\partial Q}{\partial Z}}{Q} > \frac{\frac{\partial\theta_{\alpha\to1,z}}{\partial Z}}{\theta_{\alpha\to1,z}} \Longrightarrow \frac{\partial\theta}{\partial Z} > 0\right.$ (positive effect as Z increases) $14 < Z_2 \leq 16.7: \left\{\frac{\frac{\partial Q}{\partial Z}}{Q} < 0 \ \frac{\frac{\partial\theta_{\alpha\to1,z}}{\partial Z}}{\theta_{\alpha\to1,z}} < 0 \wedge \frac{\frac{\partial Q}{\partial Z}}{Q} < \frac{\frac{\partial\theta_{\alpha\to1,z}}{\partial Z}}{\theta_{\alpha\to1,z}} \Longrightarrow \frac{\partial\theta}{\partial Z} < 0\right.$ (negative effect as Z increases)
	0.9999	*OO*-α	N.A.	N.A.	$Z_2 \leq 10: \left\{\frac{\partial Q/\partial Z}{Q} \approx 0 \ \frac{\partial\theta_{\alpha\to1,z}/\partial Z}{\theta_{\alpha\to1,z}} > 0 \wedge \frac{\frac{\partial Q}{\partial Z}}{Q} < \frac{\frac{\partial\theta_{\alpha\to1,z}}{\partial Z}}{\theta_{\alpha\to1,z}} \Longrightarrow \frac{\partial\theta}{\partial Z} < 0\right.$ (positive effect as Z increases) $15 \geq Z_1 > 10: \left\{\frac{\partial Q/\partial Z}{Q} \approx 0 \ \frac{\partial\theta_{\alpha\to1,z}/\partial Z}{\theta_{\alpha\to1,z}} < 0 \wedge \frac{\frac{\partial Q}{\partial Z}}{Q} > \frac{\frac{\partial\theta_{\alpha\to1,z}}{\partial Z}}{\theta_{\alpha\to1,z}} \Longrightarrow \frac{\partial\theta}{\partial Z} > 0\right.$ (negative effect as Z increases) $Z_1 > 15: \left\{\frac{\partial Q/\partial Z}{Q} \approx 0 \ \frac{\partial\theta_{\alpha\to1,z}/\partial Z}{\theta_{\alpha\to1,z}} \lesssim 0 \wedge \frac{\frac{\partial Q}{\partial Z}}{Q} > \frac{\frac{\partial\theta_{\alpha\to1,z}}{\partial Z}}{\theta_{\alpha\to1,z}} \Longrightarrow \frac{\partial\theta}{\partial Z} > 0\right.$ (negative effect, meaningless though, as Z increases)

Table A3. Comparison of efficiencies across Europe.

Reference Group	D-α	IO-α	OO-α
1—Western Europe	$p^{\delta}_{D-0.9999} = 0.5247$ $p^{\delta}_{D-0.5} = 0.4613$ $p^{\Delta}_{D} = 0.4693$ $p^{\omega_{\alpha=0.9999,z=1}}_{D-0.9999} = 0.2940$ $\omega_{\alpha=0.9999,z=1} = 1.1276$	$p^{Q}_{IO-0.9999} = 0.1853$ $p^{Q}_{IO-0.5} = 0$ $p^{\nabla}_{IO} = 0.0020$ $p^{\theta_{\alpha=0.9999,z=1}}_{IO-0.9999} = 0$ $\theta^{IO-0.9999}_{\alpha=0.9999,z=1} = 0.9803$	$p^{Q}_{OO-0.9999} = 0$ $p^{Q}_{OO-0.5} = 0.0800$ $p^{\nabla}_{OO} = 0.7613$ $p^{\theta_{\alpha=0.9999,z=1}}_{OO-0.9999} = 0.0093$ $\theta^{OO-0.9999}_{\alpha=0.9999,z=1} = 1.0092$
2—Central and Eastern Europe	$p^{\delta}_{D-0.9999} = 0.5427$ $p^{\delta}_{D-0.5} = 0.7193$ $p^{\Delta}_{D} = 0.7480$ $p^{\omega_{\alpha=0.9999,z=2}}_{D-0.9999} = 0.7973$ $\omega_{\alpha=0.9999,z=2} = 1.2970$	$p^{Q}_{IO-0.9999} = 0.5767$ $p^{Q}_{IO-0.5} = 0.0253$ $p^{\nabla}_{IO} = 0.2153$ $p^{\theta_{\alpha=0.9999,z=2}}_{IO-0.9999} = 0$ $\theta^{IO-0.9999}_{\alpha=0.9999,z=2} = 1$	$p^{Q}_{OO-0.9999} = 0$ $p^{Q}_{OO-0.5} = 0.3027$ $p^{\nabla}_{OO} = 0.7007$ $p^{\theta_{\alpha=0.9999,z=2}}_{OO-0.9999} = 0$ $\theta^{OO-0.9999}_{\alpha=0.9999,z=2} = 1$
3—Northern Europe	$p^{\delta}_{D-0.9999} = 0.0373$ $p^{\delta}_{D-0.5} = 0.2500$ $p^{\Delta}_{D} = 0.1167$ $p^{\omega_{\alpha=0.9999,z=3}}_{D-0.9999} = 0.2540$ $\omega_{\alpha=0.9999,z=3} = 1.1641$	$p^{Q}_{IO-0.9999} = 0.1340$ $p^{Q}_{IO-0.5} = 0.0100$ $p^{\nabla}_{IO} = 0.2707$ $p^{\theta_{\alpha=0.9999,z=3}}_{IO-0.9999} = 0$ $\theta^{IO-0.9999}_{\alpha=0.9999,z=3} = 0.9635$	$p^{Q}_{OO-0.9999} = 0$ $p^{Q}_{OO-0.5} = 0.4687$ $p^{\nabla}_{OO} = 0.0420$ $p^{\theta_{\alpha=0.9999,z=3}}_{OO-0.9999} = 0.5053$ $\theta^{OO-0.9999}_{\alpha=0.9999,z=3} = 1.2387$
4—Southern Europe	$p^{\delta}_{D-0.9999} = 0$ $p^{\delta}_{D-0.5} = 0.7493$ $p^{\Delta}_{D} = 0.8373$ $p^{\omega_{\alpha=0.9999,z=4}}_{D-0.9999} = 0.0807$ $\omega_{\alpha=0.9999,z=4} = 1.5051$	$p^{Q}_{IO-0.9999} = 0$ $p^{Q}_{IO-0.5} = 0.0020$ $p^{\nabla}_{IO} = 0.1733$ $p^{\theta_{\alpha=0.9999,z=4}}_{IO-0.9999} = 0$ $\theta^{IO-0.9999}_{\alpha=0.9999,z=4} = 0.7443$	$p^{Q}_{OO-0.9999} = 0$ $p^{Q}_{OO-0.5} = 0.5260$ $p^{\nabla}_{OO} = 0.0593$ $p^{\theta_{\alpha=0.9999,z=4}}_{OO-0.9999} = 0.0113$ $\theta^{OO-0.9999}_{\alpha=0.9999,z=4} = 1.5784$

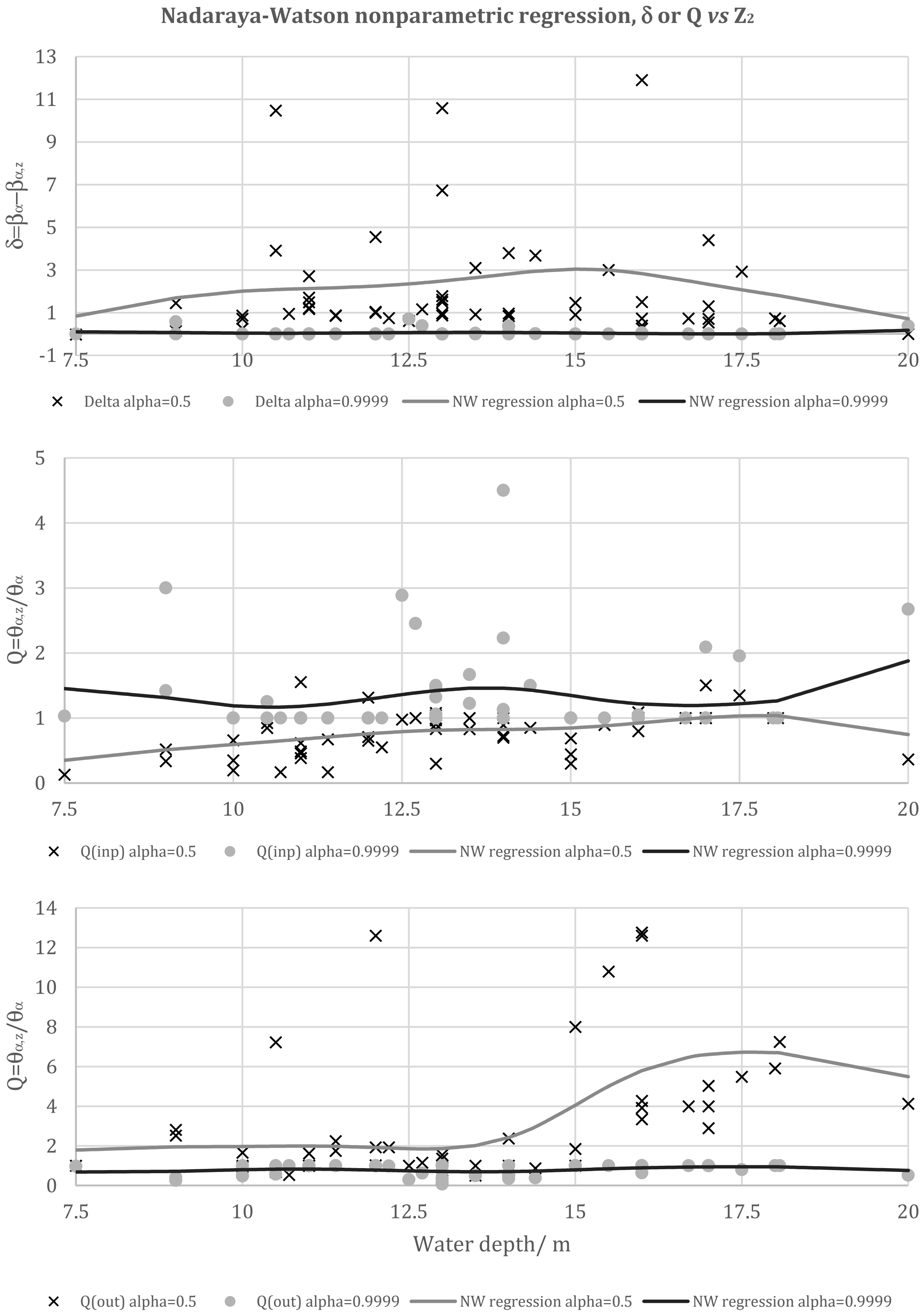

Figure A1. Nadaraya–Watson nonparametric regressions of conditional vs. unconditional relationships concerning the exogenous variable Z_2 (water depth).

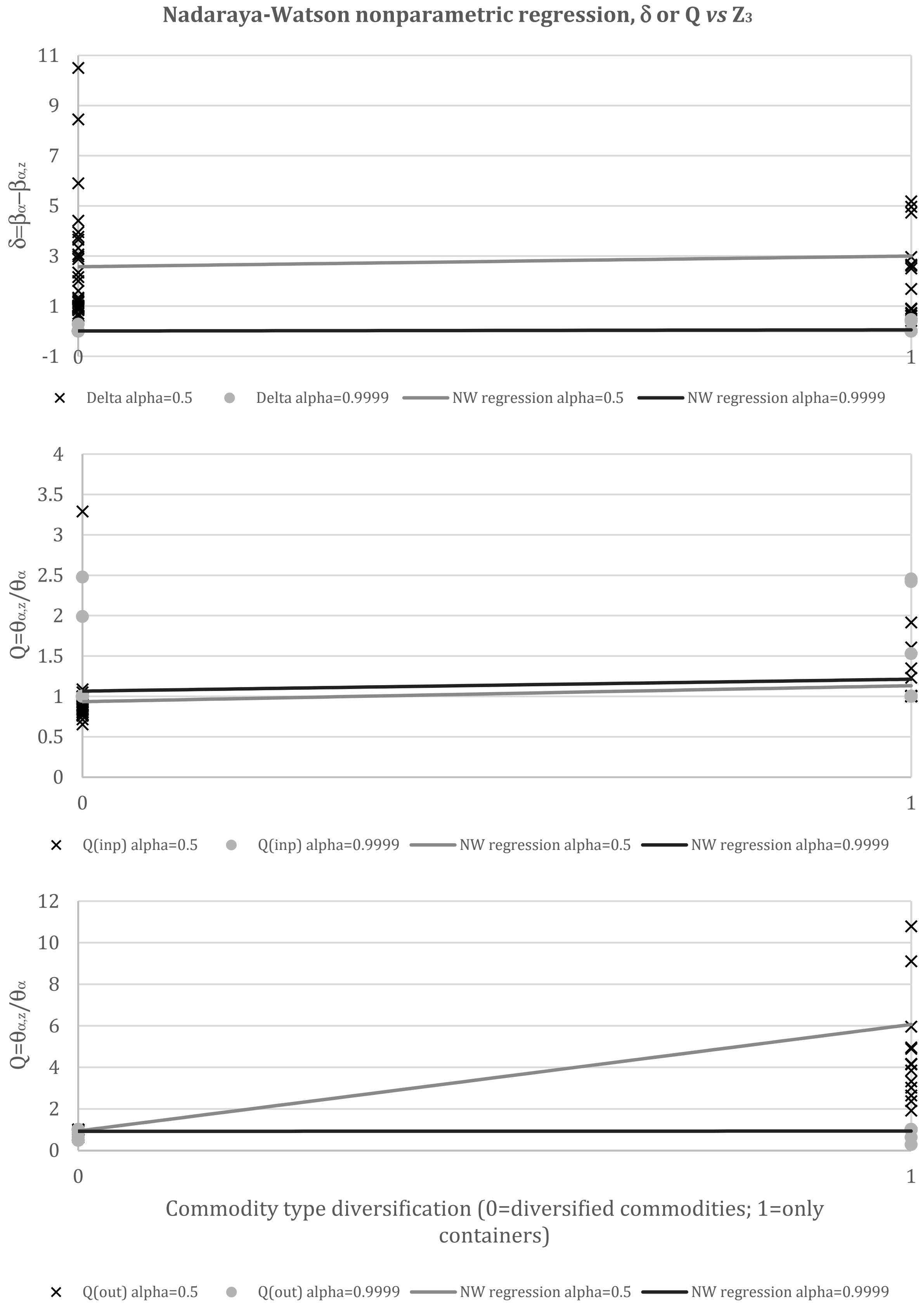

Figure A2. Nadaraya–Watson nonparametric regressions of conditional vs. unconditional relationships concerning the exogenous variable Z_3 (commodity-type diversification).

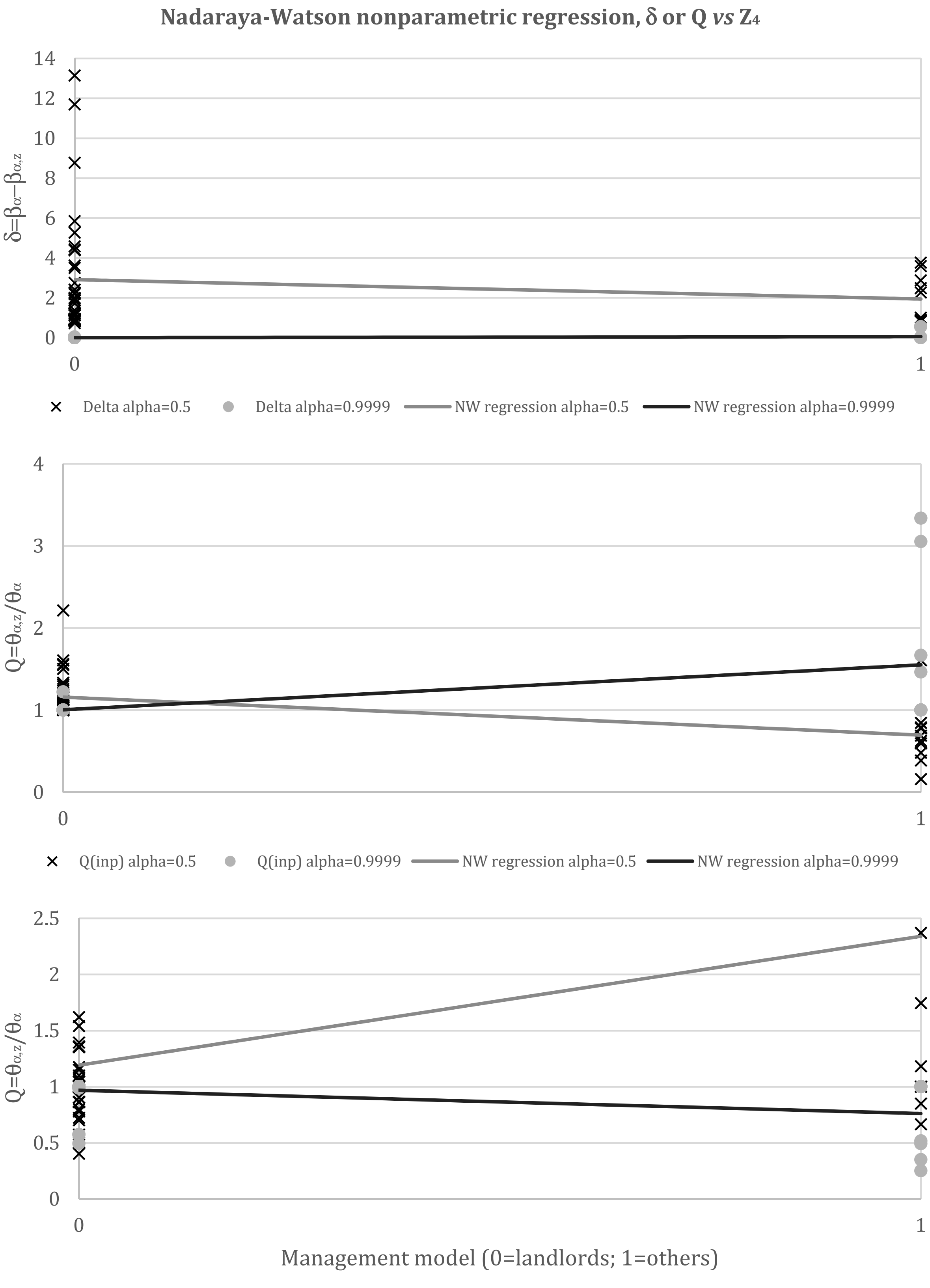

Figure A3. Nadaraya–Watson nonparametric regressions of conditional vs. unconditional relationships concerning the exogenous variable Z_4 (management model).

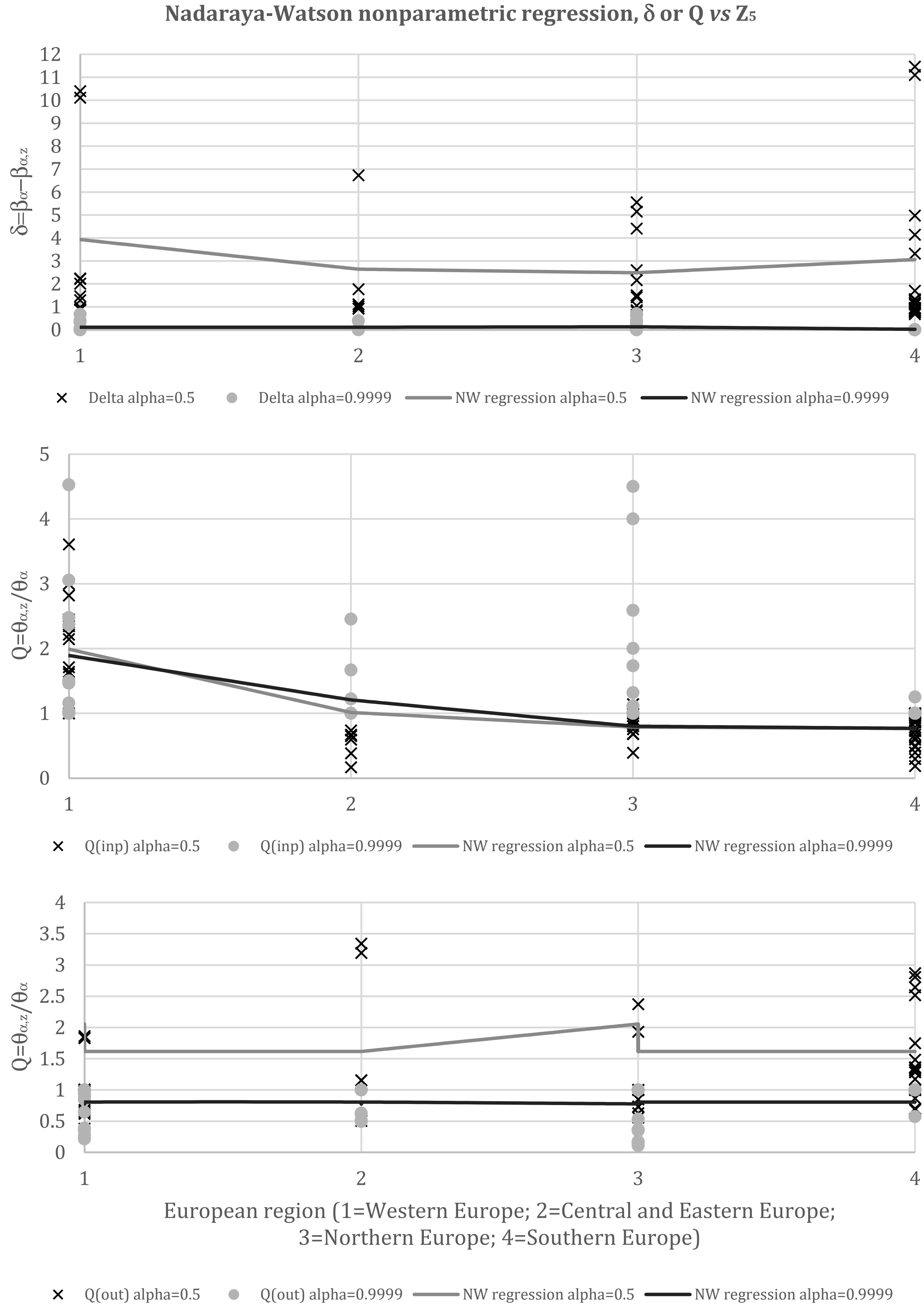

Figure A4. Nadaraya–Watson nonparametric regressions of conditional vs. unconditional relationships concerning the exogenous variable Z_5 (European region).

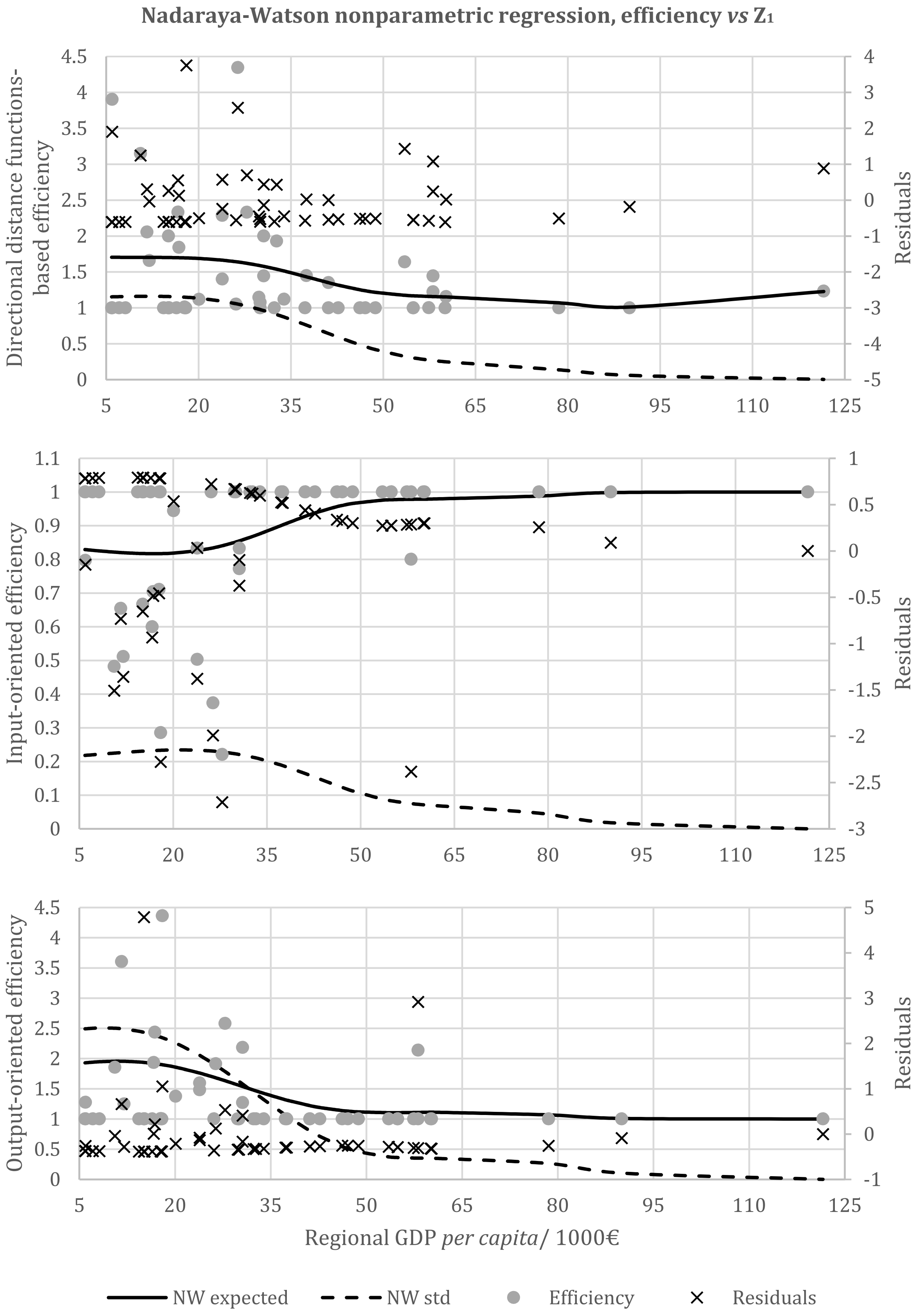

Figure A5. Nadaraya–Watson nonparametric regressions of conditional efficiency and management efficiency (residuals) concerning the exogenous variable Z_2 (water depth).

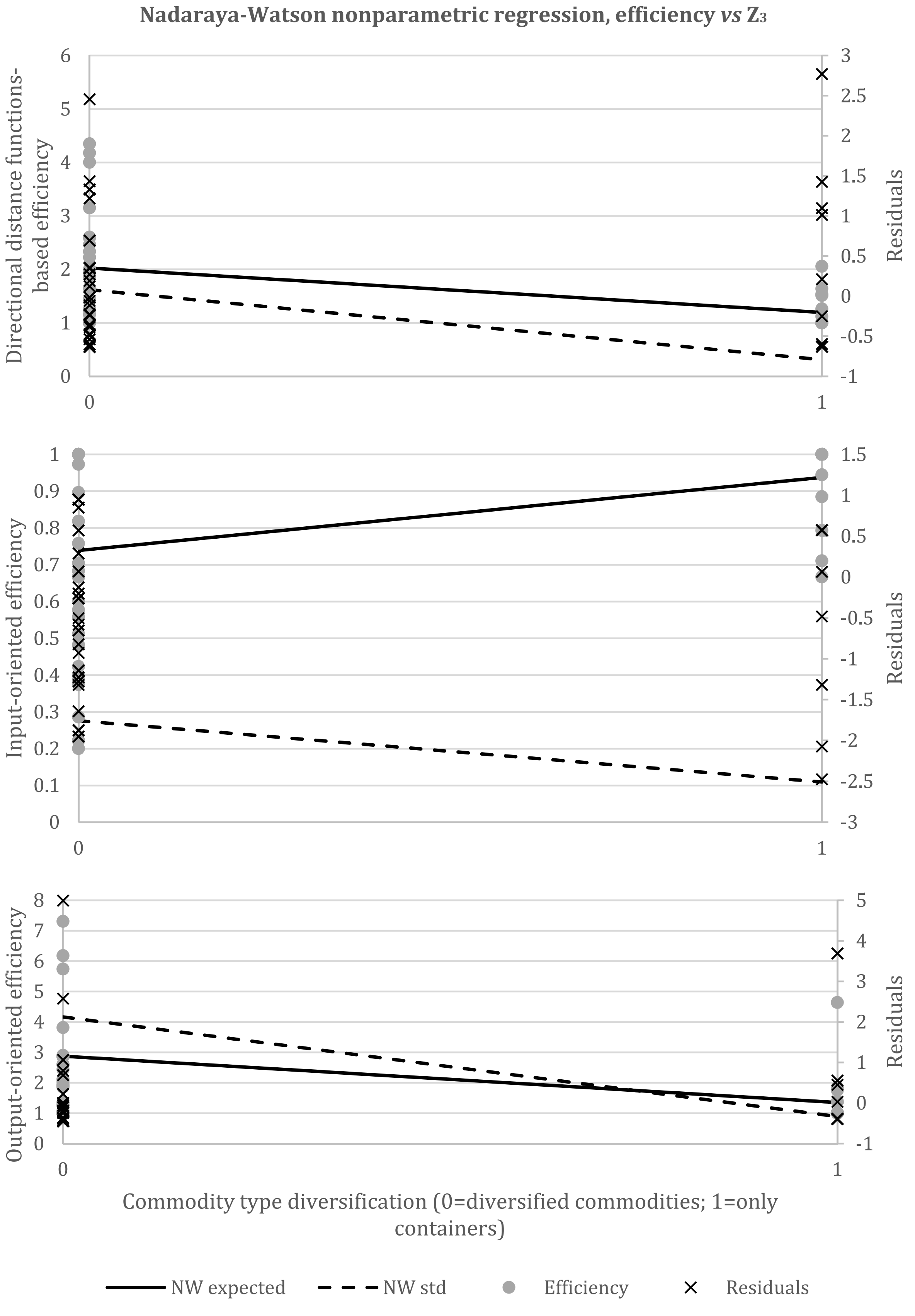

Figure A6. Nadaraya–Watson nonparametric regressions of conditional efficiency and management efficiency (residuals) concerning the exogenous variable Z_3 (commodity-type diversification).

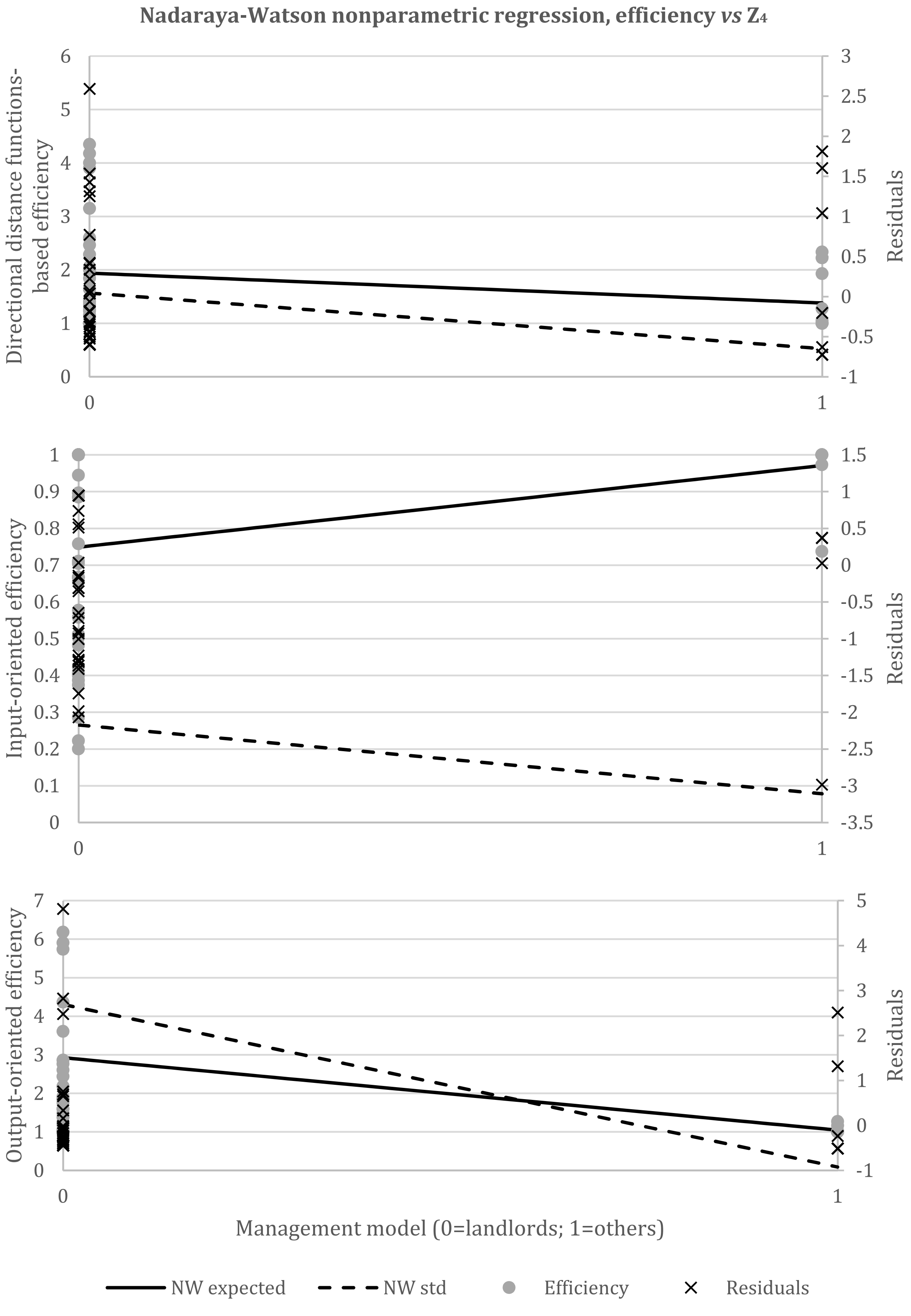

Figure A7. Nadaraya–Watson nonparametric regressions of conditional efficiency and management efficiency (residuals) concerning the exogenous variable Z_4 (management model).

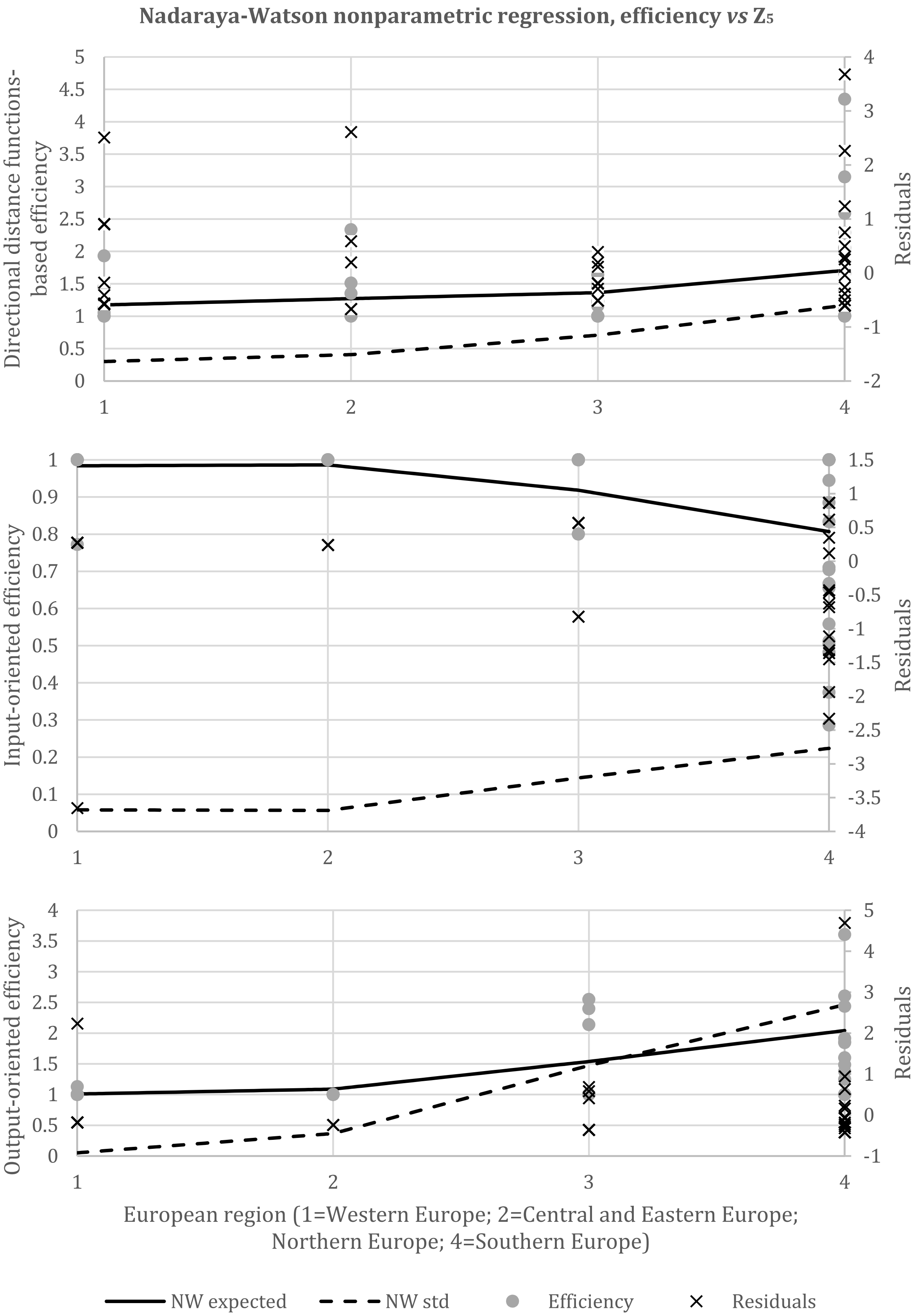

Figure A8. Nadaraya–Watson nonparametric regressions of conditional efficiency and management efficiency (residuals) concerning the exogenous variable $Z5$ (European region).

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