

TECHNICAL EFFICIENCY OF ROMANIAN DANUBE PORTS. A STOCHASTIC FRONTIER ANALYSIS

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Abstract

This paper evaluates the technical efficiency of Romanian inland ports along the Danube River over the period 2020–2024 using a Stochastic Frontier Analysis (SFA) framework. A panel data model with time-invariant inefficiency is estimated based on a Cobb–Douglas production function, where total cargo throughput is the output and quay length, number of quay cranes, and storage area are specified as inputs. The analysis covers 16 ports administered under the Upper and Lower Danube authorities. Results indicate a low average technical efficiency and substantial heterogeneity across ports. Lower Danube ports generally outperform Upper Danube ports, although the difference is not statistically significant. The estimated production elasticities reveal decreasing returns to scale, suggesting that most ports operate beyond their optimal size. Cargo diversification shows no statistically significant association with technical efficiency. The findings challenge the assumption that larger or more diversified ports are inherently more efficient and support a shift toward efficiency-oriented port development policies. The results should be interpreted considering the relatively short five-year available panel, which captures recent operational conditions, including the market disruptions associated with the Russian invasion of Ukraine.

Keywords: inland waterways transport, inland port, stochastic frontier analysis, technical efficiency, entropy, Danube

1. INTRODUCTION

The shift of Europe’s inland waterway transport (IWT) into a key sustainable logistics solution underscores the durability of its physical networks and the strategic evolution of its guiding policies [1]. A central policy instrument of this strategy is the third iteration of the NAIADES Action Plans [2]. The core objectives—modal shift to waterways, reduction of the sector’s environmental footprint, and enhanced competitiveness through innovation—aim to reconcile

sustainability goals with economic efficiency. Even with dedicated EU support since the early 2000s, inland waterway transport (IWT) has achieved only limited market penetration, maintaining a stable but marginal share of 1.6%–1.8% [3]. Within the European Union, Romania ranks fifth in inland waterway transport (IWT) freight volume, but leads in IWT modal share, with 18.9% of its national freight transport market—significantly ahead of the Netherlands (11.7%) and Bulgaria (8.7%). Recent literature points to a dual reality: enduring structural challenges now coexist with new potential in digitalization, resilience, and integrated supply chains [4,5].

The barriers to IWT progress are evident in the inefficient operation of inland waterway ports, which serve as critical nodes for sustainable freight transport and regional economic development. In recent decades, economists and transport researchers have increasingly employed Stochastic Frontier Analysis (SFA) to evaluate port efficiency, owing to its ability to separate random noise from technical inefficiency in production or cost functions [6]. SFA has been particularly influential in the context of inland ports, where operational performance is subject to environmental variability, fluctuating demand, regional economy, and institutional constraints [7,8]. The efficiency of inland waterway ports has received less scholarly attention than that of maritime ports, yet relevant parallels are evident. While Cullinane et al. [9] identified terminal size as a key determinant of efficiency, this factor is less assured for inland waterway terminals; their growth potential is inherently constrained by smaller customer bases, making significant scale expansion far less certain. Other key determinants of maritime port efficiency include container mix, work practices, crane efficiency, vessel size, and cargo exchange [10]. However, when applied to the IWT context, most of these factors – with the notable exception of crane efficiency – play a significantly diminished role. This places the IWT at a disadvantage as these terminals often operate on not optimally configured terminal areas [11]. Beyond technical port variables (e.g., quay length, storage area, water depth, quay cranes, and yard handling equipment), Krljan et al. [12] argued that macro-level factors – including GDP, trade volume, and ownership structure – are critical determinants of efficiency, particularly in small economies in Adriatic Sea, characterized by a high concentration of economic activity in a single port. Lin and Tseng [13] also examined the correlations between operating efficiencies and three factors, that is, 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). Nonetheless, the results showed that the operating efficiencies are not significantly different with both location of port and administrative structure of port. On contrary, Liu [14]

found that port localization is significant. The results of Wiegmans and Witte [11] for inland container ports confirmed that yard and crane factors are significant, corroborating maritime terminal studies [15,16].

This study aims to address several key gaps in this literature by applying a longitudinal SFA framework to the understudied Romanian Danube port system. Specifically, it contributes by:

- employing a panel data SFA model to capture temporal dynamics in both the production frontier and inefficiency;
- integrating geographical localization as a key contextual to analyze variations in port technical efficiency;
- providing a focused analysis of a strategically vital yet underrepresented European waterway corridor.

2. MATERIALS AND METHODS

2.1. Study Area

The Danube River serves as a critical European transport artery and the principal waterway of the TEN-T Rhine–Danube Corridor. Stretching 2,400 km across ten countries, it connects Central Europe to the Black Sea, facilitating both regional and international trade. However, its freight volumes remain significantly below those of the Rhine, constrained by persistent structural, hydrological, regulatory, and institutional barriers, alongside deficits in multimodal integration, digitalization, and workforce capacity [17,18]. Within Romania, the Danube has been historically connected to industrial, agricultural, and energy sectors, offering a cost-efficient transport mode for bulk commodities, including grains, ores, coal, construction materials, and chemicals. Navigation on the Romanian Danube is governed by regional port administrations. This study selected 16 inland ports from two administrations, with documented activity between 2020 and 2024:

1. Upper Danube Administration: This sector extends from the Serbian border at Baziaș downstream to Cernavodă. Selected ports include Moldova Veche, Orsova, Drobeta-Turnu Severin, Calafat, Bechet, Corabia, Turnu Magurele, Giurgiu, Oltenita, Calarasi, and Cernavoda.
2. Lower Danube Administration: This sector is transitional, where riverine navigation rules gradually give way to maritime conventions. The ports of Galati and Braila are classified as “maritime-river ports,” requiring specialized regulatory frameworks for mixed traffic. Ports included in this sector are Braila, Galati, Tulcea, Macin, and Mahmudia.

2.2. Input/Output Variables

Estimating the technical efficiency of multi-cargo inland ports requires an output variable that universally reflects terminal throughput. The scholarly literature converges on the total gross weight of cargo handled (in tons or TEUs) as this standard metric [8,9,19,20]. This output aggregates all handling operations—import, export, and transshipment—and correlate directly with the scale of terminal infrastructure and services, making it essential for comparative analysis of capacity, investment, and operational performance [21,22,23,24,25].

Capital and labor are near-universal inputs in port efficiency studies, yet intermediate inputs (e.g., water, energy) are seldom incorporated. Furthermore, the operationalization of capital—spanning land, equipment, and infrastructure—lacks consistency across the literature. Labor input, conversely, is often measured simplistically due to persistent data limitations. Some studies omit labor as a distinct input [12,26], based on the rationale that capital—particularly the number of cranes—proxies for direct productive labor in container terminals, implying a fixed capital–labor relationship.

The model specification for this study balances theoretical relevance with empirical data constraints. The output variable is defined as the total gross weight of cargo handled. Inputs to the production frontier are quay length, number of quay cranes, and storage area.

The final balanced panel consists of 16 inland ports observed over five consecutive years (2020–2024), yielding 80 observations. Cargo throughput data were extracted from the Romanian National Institute of Statistics (INS TEMPO Online database), while infrastructure variables were collected from the annual reports and technical documentation of the Lower Danube River Administration (AFDJ Galati) and the Lower Danube Ports Administration (APDF Giurgiu).

2.3. The Stochastic Frontier Model

Stochastic Frontier Analysis (SFA) is an econometric methodology used to estimate the technical or cost efficiency of decision-making units. Formulated independently by Aigner et al. [6] and Meeusen and van den Broeck [27], its central premise is the estimation of a best-practice frontier while explicitly modeling deviations from this frontier as the sum of two distinct components: a symmetric random error (v), representing statistical noise and exogenous shocks, and a one-sided, non-negative inefficiency term (u), capturing the shortfall due to managerial or operational shortcomings. The model of Battese and Coelli [28]

stands as one of the most influential frameworks in SFA with time invariant efficiency and panel data, widely adopted for its practical and methodological advantages. Employing a Cobb–Douglas production function and the input variables defined in Section 2.2, the adapted SFA model for inland port efficiency estimation is specified as follows:

$$Y_{it} = \beta_0 QL_{it}^{\beta_1} QC_{it}^{\beta_2} SA_{it}^{\beta_3} e^{v_{it}-u_i} \quad (1)$$

or in logarithmic form:

$$\ln(Y_{it}) = \beta_0 + \beta_1 \ln(QL_{it}) + \beta_2 \ln(QC_{it}) + \beta_3 \ln(SA_{it}) + v_{it} - u_i \quad (2)$$

where: Y_{it} = total gross weight of cargo handled by port i ($i = 1, \dots, N$) in year t ($t = 1, \dots, T$);

QL_{it} = quay length in port i in time period t ;

QC_{it} = number of quay cranes in port i in time period t ;

SA_{it} = storage area in port i in time period t ;

v_{it} = random error term;

u_{it} = the technical inefficiency term;

β_j = frontier function parameters;

N = number of ports;

T = number of time periods (year).

v_{it} are assumed to be iid $\sim N(0, \sigma_v^2)$, whereas u_i are iid $\sim N^+(\mu, \sigma_u^2)$. The technical efficiency of port i is [28]:

$$TE_i = e^{-u_i}. \quad (3)$$

It quantifies the proximity of a port's observed output to its maximum feasible output (the stochastic frontier). The total error variance is $\sigma^2 = \sigma_v^2 + \sigma_u^2$. The key parameter $\gamma = \frac{\sigma_u^2}{\sigma^2}$ indicates the share of variance due to inefficiency. Values of γ near 1 signify that inefficiency explains most of the deviation from the frontier, whereas values near 0 imply that deviations are primarily random. The existence of technical inefficiency is formally tested using a Likelihood Ratio (LR) test. This test compares the unrestricted stochastic frontier model which includes a one-sided inefficiency component with a restricted model that assumes no inefficiency. Under the null hypothesis ($H_0: \gamma = 0$), all deviation from the frontier is attributed to random noise. The generalized LR test statistic is given by:

$$LR = -2[\ln L(H_0) - \ln L(H_1)] \quad (4)$$

where $L(H_0)$ and $L(H_1)$ denote the likelihood values of the restricted and unrestricted (SFA) models, respectively. The test statistic follows a mixed chi-square distribution with one degree of freedom, $\chi^2(1)$.

3. RESULTS

The ports' infrastructure characteristics are summarized in Table 1.

Table 1. Ports' infrastructure and localization *

Infrastructure element	Mean	Median	Standard Error	Min	Max
QL [km]	0.936	0.600	0.097	0.14	4.063
SA [ha]	4.619	2.600	0.876	0.3	24.6
QC [units]	4.196	3.000	0.600	2	26

Eleven ports are located in Upper Danube and five ports in Lower Danube sector. Figure 1 depicts the evolution of the total cargo weight handled by each port.

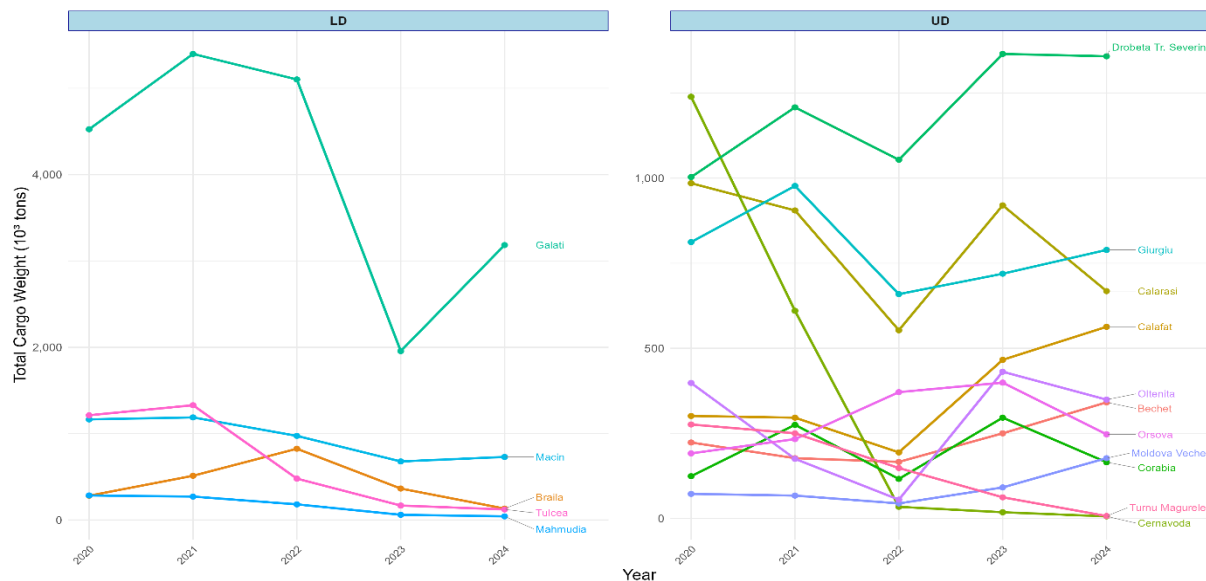


Figure 1. Total cargo weight handled by port

By ports' localization, the trend in cargo weight is shown in Figure 2.

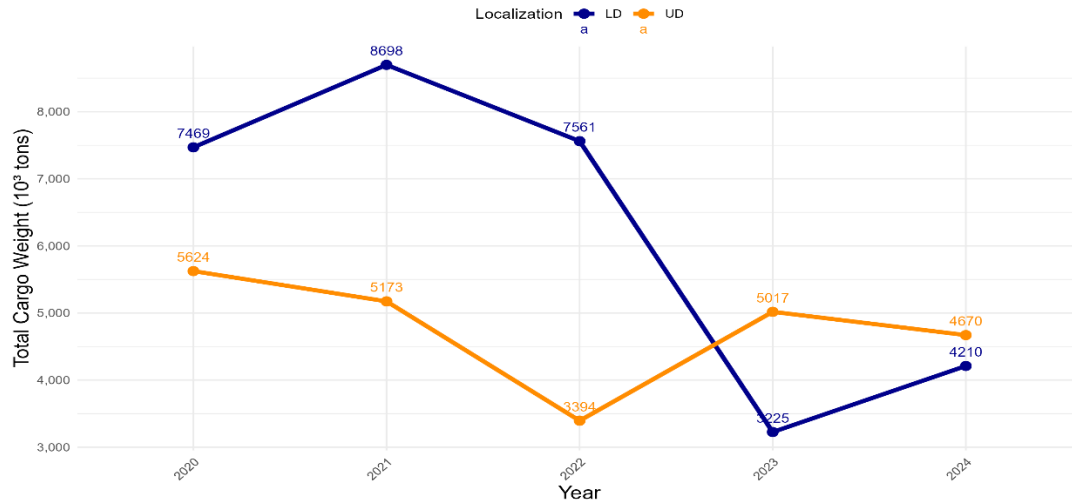


Figure 2. Total cargo weight handled by port administration

The conflict in Ukraine precipitated a fundamental realignment of cargo movements along the Romanian Danube from 2020 to 2022, catalyzing a substantial transshipment of Ukrainian grain through Romanian facilities as an economic help. This impact was most acute for the ports of the Lower Danube sector, mainly Galati and Braila. On the contrary, freight trajectories on the Upper Danube remained largely decoupled from the geopolitical disturbance, mirroring instead the evolution of regional economic conditions. Within this segment, the ports of Drobeta-Turnu Severin, Giurgiu, and Calarasi registered the most elevated, though notably unstable, operational volumes.

For the study period 2020-2024, the time-invariant model of inefficiency provides the results depicted in Table 2.

Table 2. SFA parameters

β_0 (Intercept)	6.940***
β_1 (QL)	0.032
β_2 (QC)	0.167*
β_3 (SA)	0.382**
σ^2	3.485***
γ	0.99***
μ	0.252

*** p < 0.001, ** p < 0.01, * p < 0.05

Therefore, the analysis shows that 99% of total variance is due to inefficiency (u), and only 1% is due to random noise (v). The LR test provides LR

= 19.633, so the null hypothesis ($H_0: \gamma = 0$) is rejected and inefficiency is statistically significant. The number of quay cranes and the storage area are significant parameters compared to the quay length. The mean technical efficiency of the ports ranges from 0.046 to 0.961, with a mean of 0.389 and a median of 0.238. The ports efficiency is depicted in Figure 3.

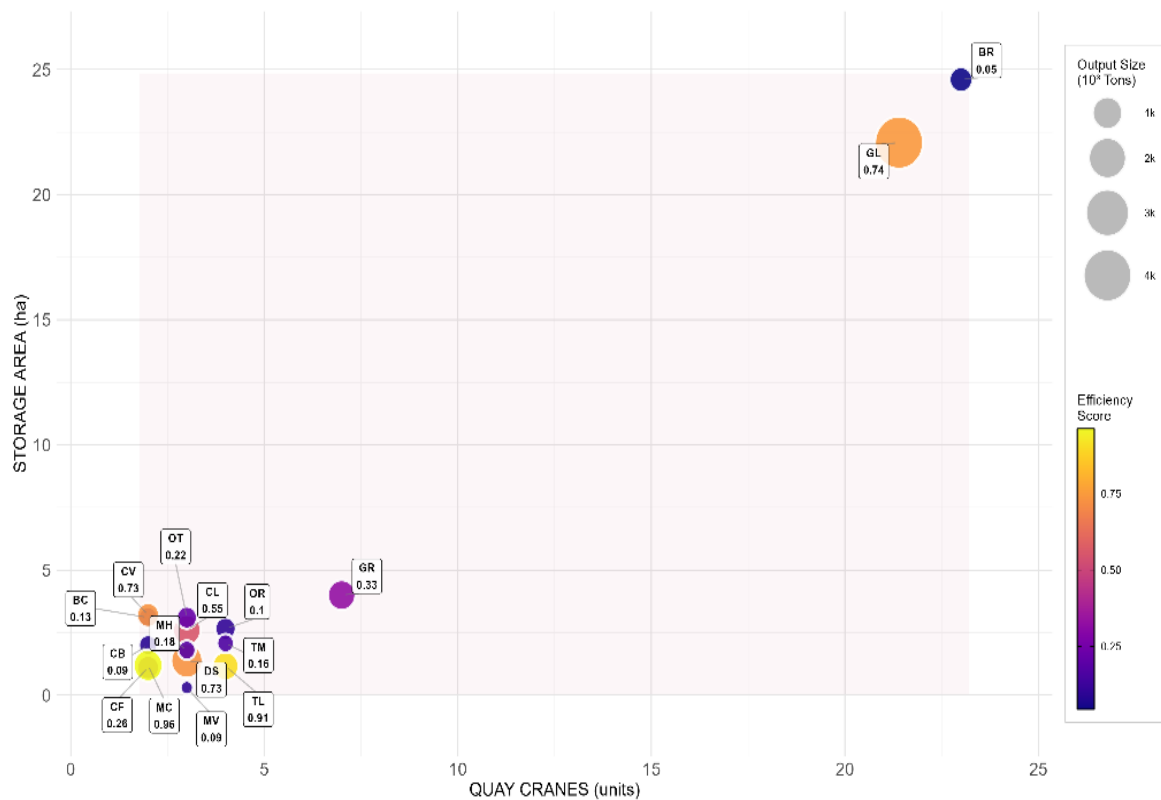


Figure 3. Technical efficiency of the ports

The highest technical efficiency is exhibited by Macin (0.961), Tulcea (0.905), and Galati (0.744). The lowest efficiency is recorded at Moldova Veche (0.094), Corabia (0.085), and Braila (0.046). The most efficient ports are predominantly located along the Lower Danube, whereas many of the less efficient ones are situated on the Upper Danube. A notable exception is the port of Braila (LD). Despite its substantial infrastructure – including extensive storage areas, a large number of quay cranes, and long quays – it exhibits very low-capacity utilization. This result indicates substantial underutilization of existing capacity rather than insufficient infrastructure. During the study period, cargo flows were strongly influenced by the reorganization of regional logistics following the Russian invasion of Ukraine. While Braila experienced temporary increases in Ukrainian grain transit, these flows were highly volatile and did not

generate sustained utilization of its infrastructure. Also, following the transition to the market economy, Braila's hinterland industry (chemical, manufacturing) experienced a great decay, thus the port infrastructure designed to support the flows is now underutilized. As shown in Figure 4, the average efficiency score for the Lower Danube region is 0.568, compared to 0.307 for the Upper Danube region.

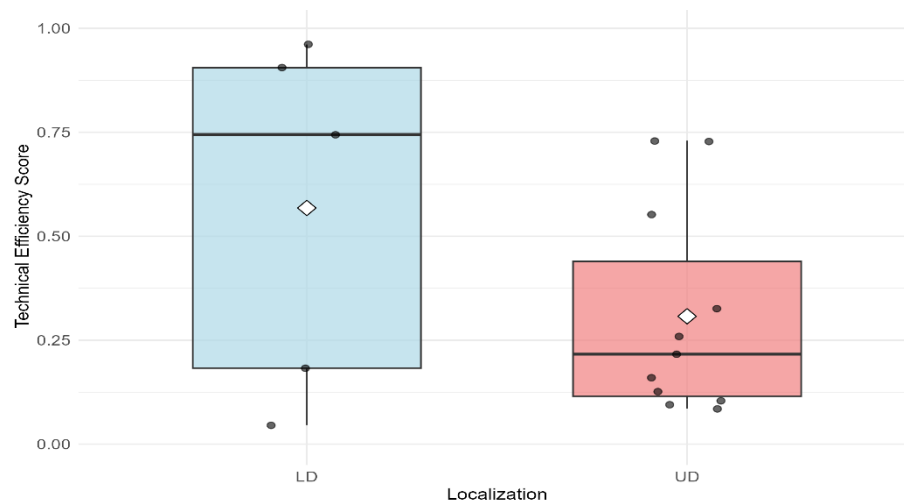


Figure 4. Technical efficiency by port administration

The Wilcoxon rank-sum test yields no significant efficiency difference between LD and UD ports ($W = 38$, $p = 0.267$), indicating that geographical location does not determine technical performance in the port system.

The sum of production elasticities provides the returns to scale measure $RTS = \beta_1 + \beta_2 + \beta_3 = 0.581$. This value indicates decreasing returns to scale, meaning a 1% increase in all inputs yields only a 0.581% increase in output. The estimated RTS suggests Danube ports are operating in the diseconomies of scale region. This finding contradicts the conventional wisdom in port development that "bigger is more performant" and aligns with emerging literature on optimal port size [9,22]. The current situation reveals that ports are operating beyond their best size and additional expansion will reduce efficiency. The distance to optimal frontier is depicted in Figure 5. The curved surface shows maximum possible output for given QC and SA. The average inefficiency gap is 1.43×10^6 tons, and the maximum inefficient gap is 5.69×10^6 tons (Braila, LD).

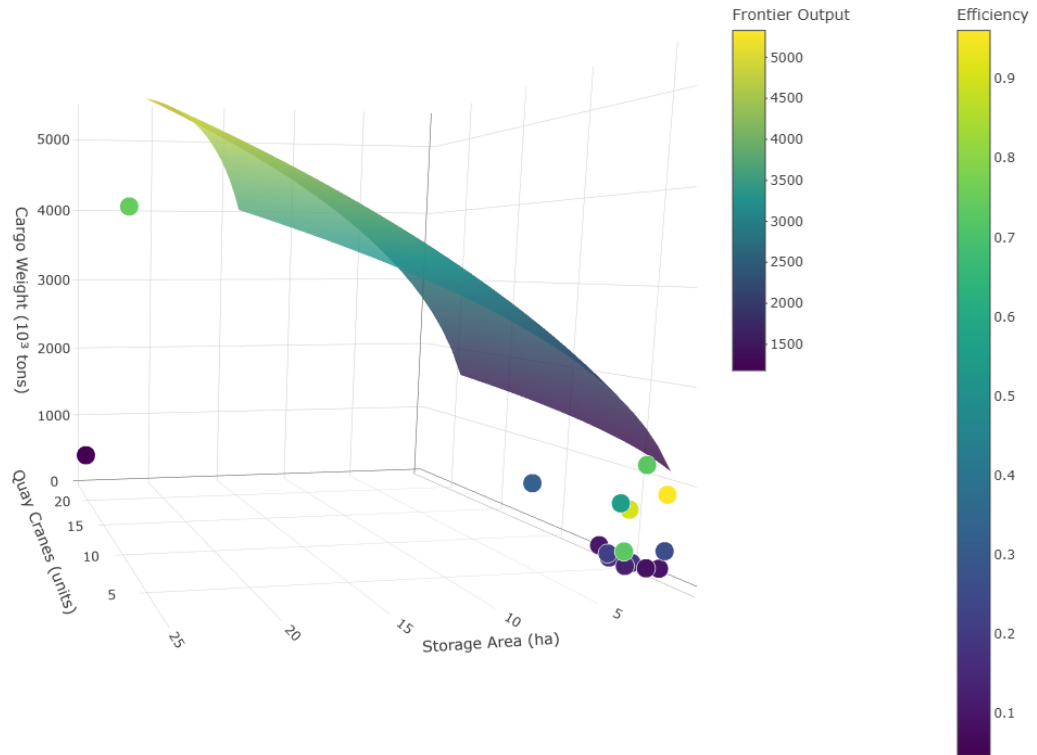


Figure 5. Frontier output for Danube ports

The problem of inefficiency is not lack of resources – it is how existing resources are used. The strategic planning actions should be oriented towards:

- Capacity Planning: Future capacity requirements should be met through efficiency improvements rather than physical expansion where possible;
- Competitive Positioning: Danube ports should compete on service quality and reliability rather than scale advantages;
- Integration with Hinterland: Improved hinterland connectivity may offer greater efficiency gains than port expansion.

Ports exhibit varying degrees of cargo diversity. A commonly employed metric for quantifying this diversity is the normalized Shannon-Weaver Index (entropy). For port i , the index is computed as:

$$H_i = \frac{-\sum_{k=1}^n p_{ik} \log(p_{ik})}{\log(n)} \quad (5)$$

where: H_i = normalized Shannon-Weaver diversity index (entropy) for port i ;

p_{ik} = proportion of cargo k in the total cargo volume in port i ;

n = total number of cargo types considered.

In the Danube port context, $n=5$ cargo categories are analyzed: agricultural/food, chemicals, fuel/coal, ore/minerals, and general cargo. The normalized index ranges from 0 (complete specialization in one cargo type) to 1 (perfect diversification across all cargo types).

Table 3. Ports cargo diversification

Port ID	Port Name	Normalized Entropy	Dominant Cargo Type	Port Category*
BC	Bechet	0.34	Agricultural/Food	Moderately Specialized
BR	Braila	0.60	Agricultural/Food	Moderately Diversified
CB	Corabia	0.05	Agricultural/Food	Highly Specialized
CF	Calafat	0.35	Agricultural/Food	Moderately Specialized
CL	Calarasi	0.49	Ore/Minerals	Moderately Specialized
CV	Cernavoda	0.16	Ore/Minerals	Highly Specialized
DS	Drobeta-Turnu Severin	0.92	Fuel/Coal	Highly Diversified
GL	Galati	0.78	Ore/Minerals	Moderately Diversified
GR	Giurgiu	0.95	Fuel/Coal	Highly Diversified
MC	Macin	0.24	Ore/Minerals	Highly Specialized
MH	Mahmudia	0	Ore/Minerals	Highly Specialized
MV	Moldova Veche	0.41	Agricultural/Food	Moderately Specialized
OR	Orsova	0.92	Fuel/Coal	Highly Diversified
OT	Oltenita	0.61	Agricultural/Food	Moderately Diversified
TL	Tulcea	0.03	Ore/Minerals	Highly Specialized
TM	Turnu Magurele	0.37	Agricultural/Food	Moderately Specialized

* Highly Specialized ($H < 0.3$), Moderately Specialized ($0.3 \leq H < 0.6$), Moderately Diversified ($0.6 \leq H < 0.8$), and Highly Diversified ($H \geq 0.8$)

Agricultural/Food predominates in ports along the Upper Danube (Bechet, Calafat, Moldova Veche, Turnu Magurele, Oltenita), while Ore/Minerals are concentrated in Lower Danube ports (Tulcea, Cernavoda, Macin, Mahmudia, Galati), reflecting the historical development patterns and the hinterland activities.

Cargo diversity versus technical efficiency is depicted in Figure 6.

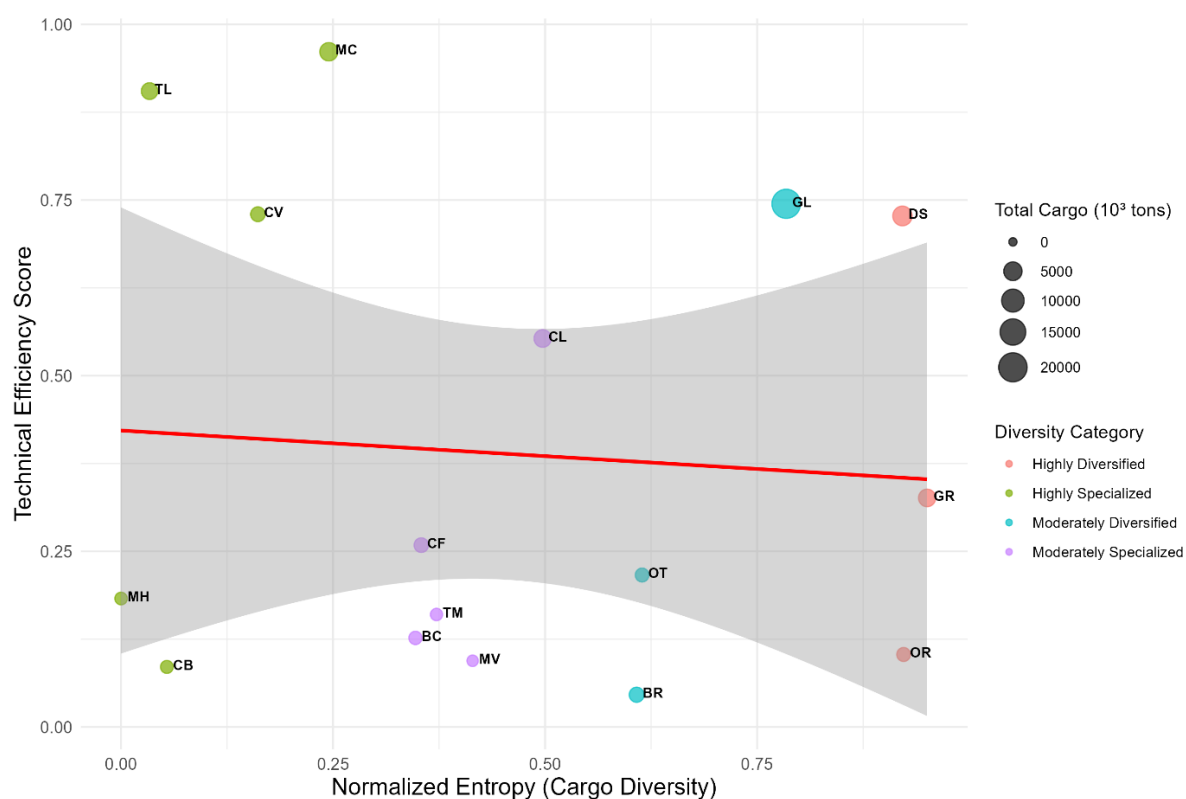


Figure 6. Ports technical efficiency vs. cargo diversity

Statistical analysis using Spearman's rank correlation coefficient demonstrates no significant relationship between technical efficiency and cargo diversity across Danube ports ($\rho = -0.072$, $p > 0.05$). This finding suggests that operational factors rather than cargo composition drive ports' technical performance.

4. CONCLUSIONS

This paper investigated the technical efficiency of Romanian inland ports along the Danube River using a panel-data Stochastic Frontier Analysis for the period 2020–2024. By estimating a Cobb–Douglas production frontier with key infrastructure inputs – quay length, number of quay cranes, and storage area – the study provides a systematic assessment of port performance within a strategically important but empirically underexplored European inland waterway corridor. The results reveal substantial inefficiencies across the Romanian Danube port system. Average technical efficiency is low (0.389), with pronounced heterogeneity among ports. Lower Danube ports generally outperform those located upstream, although the difference between the two administrative sectors is not statistically significant. The case of Braila stands out as particularly illustrative: despite

possessing extensive infrastructure, it exhibits one of the lowest efficiency scores, indicating severe underutilization of existing capacity. These findings underscore that infrastructure endowment alone does not guarantee efficient port performance.

The estimated production elasticities indicate decreasing returns to scale, suggesting that most Danube ports are operating beyond their optimal size. This result challenges the traditional assumption that capacity expansion is a reliable pathway to improved port performance. Instead, it aligns with recent literature emphasizing the risks of overinvestment and the importance of operational optimization. For Romanian inland ports, inefficiency appears to stem less from resource scarcity and more from how existing assets are deployed and integrated into broader logistics chains.

Cargo diversification, measured through the normalized Shannon–Weaver index, varies widely across ports and reflects historical specialization patterns and hinterland characteristics. However, the empirical analysis finds no statistically significant association between cargo diversity and technical efficiency, as evidenced by Spearman’s rank correlation. This suggests that, in the Romanian Danube context, efficiency is driven primarily by operational and managerial factors rather than by the composition of cargo flows. Diversification alone does not automatically translate into superior technical performance.

From a policy perspective, these findings carry clear implications. Romanian Danube port development strategies should move away from a paradigm of growth through physical expansion and toward one focused on efficiency gains through better capacity utilization, improved operational practices, and stronger integration with hinterland transport networks. Investments in digitalization, service reliability, and coordination with rail and road systems may yield higher efficiency returns than additional infrastructure. More broadly, enhancing the competitiveness of inland waterway transport requires not larger ports, but smarter, better-managed ones. Such measures would contribute to increasing the competitiveness of the Rhine–Danube Corridor while supporting the European Green Deal objective of shifting freight from road to more sustainable transport modes. These findings are directly aligned with the objectives of the European Union's Trans-European Transport Network (TEN-T) policy and the NAIADES III Action Program. Both initiatives emphasize improving the efficiency, resilience, smart inland waterway transport, and multimodal integration of inland waterway transport rather than merely expanding physical infrastructure.

This study makes several contributions to the literature on inland port performance evaluation. First, it provides one of the first applications of panel-

data Stochastic Frontier Analysis (SFA) to assess the technical efficiency of Romanian Danube inland ports, thereby extending the limited empirical evidence available for inland waterway transport systems in Central and Eastern Europe. Second, by combining infrastructure-based efficiency estimation with an analysis of cargo diversification, the study demonstrates that greater cargo diversity does not necessarily translate into higher technical efficiency. Third, the research offers empirical evidence that larger infrastructure endowments do not automatically result in superior performance, highlighting the importance of capacity utilization and operational efficiency. Finally, the findings contribute to current discussions on sustainable inland waterway development by providing evidence that supports efficiency-oriented investment strategies consistent with the objectives of the Trans-European Transport Network (TEN-T) and the NAIADES III Action Program.

Future research could extend this analysis by incorporating time-varying inefficiency models, explicitly modeling institutional and governance factors. Such extensions would further refine the understanding of performance drivers in inland port systems and support more targeted policy interventions.

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