Received 8 July 2025
Revised 19 October 2025
15 November 2025
20 December 2025
Accepted 16 April 2026

Operational analysis of Hopa Port: performance, dependencies, and challenges (2021–2023)

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Abstract

Purpose – This study examines the operational performance, dependency risks, and structural vulnerabilities of Hopa Port between 2021 and 2023. As a medium-sized Black Sea port exposed to geopolitical shocks and market volatility, Hopa represents a critical case for understanding fragility in secondary ports.

Design/methodology/approach – Using official port records, the study applies descriptive statistics, concentration indices (CR5, HHI), volatility measures, correlation analysis, and Monte Carlo simulations to assess throughput dynamics, cargo dependency, and downside risk. Scenario-based projections are used to evaluate the potential impact of strategic interventions.

Findings – Results reveal extreme import dependence, a near-total collapse of exports, and a high concentration level (CR5 = 76.8%), leading to a trade imbalance of 248.6:1. Throughput volatility intensified, while coal emerged as the dominant risk factor (r = 0.854). Simulations confirm significant downside exposure and highlight that diversification is essential for resilience.

Research limitations/implications – The analysis covers a three-year period and excludes revenue and multi-port comparison data. However, it provides a scalable model for future studies on port resilience and risk exposure in emerging markets.

Practical implications – The findings emphasize the need for export development, portfolio diversification, and proactive risk governance to stabilize operations and reduce vulnerability.

Social implications – Structural weaknesses in the port's cargo profile may limit employment, regional development, and economic resilience. Addressing these risks can support more balanced and sustainable coastal economies.

Originality/value – This paper provides a rare risk-focused empirical assessment of a secondary Turkish port and introduces a methodological framework that can be adapted to similar under-analyzed ports in emerging economies.

Keywords Port efficiency, Cargo analysis, Trade statistics, Operational risk, Turkey maritime, Diversification strategy

Paper type Research article

1. Introduction

Seaports are critical nodes in global trade and regional development, acting as gateways for international supply chains and engines of local economic growth (Pallis *et al.*, 2010; Mentzer *et al.*, 2001). In recent decades, growing geopolitical uncertainty, market volatility, and environmental pressures have intensified the operational and strategic challenges faced by

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Conflicts of interest: The authors declare no conflicts of interest. The port management's provision of data did not influence the design, analysis, interpretation, or reporting of this study.

Marine Economics and Management
Vol. 9 No. 1, 2026
pp. 1-26
Emerald Publishing Limited
2516-158X
DOI 10.1108/MAEM-07-2025-0023

ports worldwide. Within this context, the Black Sea region has emerged as a particularly sensitive area, where small and medium-sized ports play a vital role in supporting trade but often remain under-researched (Ducruet and Lee, 2006; Notteboom and Rodrigue, 2005) compared to major global hubs.

Hopa Port, located on the eastern Black Sea coast of Turkey, represents a typical case of a medium-sized port exposed to multiple structural vulnerabilities. Despite its strategic position, the port is characterized by a heavy dependence on a few commodities, limited export capacity, and fragile hinterland connections. These characteristics make it highly sensitive to external shocks such as regional conflicts, policy changes, or demand fluctuations. While major international ports have been extensively studied, empirical research on secondary ports such as Hopa remains scarce, particularly in relation to risk quantification and resilience assessment (González and Trujillo, 2009; Acciaro *et al*., 2014). Recent studies have begun to explore how geopolitical and health-related disruptions reshape maritime systems in the Black Sea region. Ayaz *et al*. (2022) examined how the Russia–Ukraine conflict redirected vessel traffic through the Turkish Straits, reorganizing short-sea shipping routes and altering the spatial dynamics of port connectivity. Tang and Wang (2025) further demonstrated that the COVID-19 pandemic induced significant short-term volatility in regional throughput, revealing the fragility of mid-sized ports under compound disruptions. However, despite these advances, most prior works have remained descriptive and have not quantified the operational elasticity or sensitivity of secondary Turkish ports to such shocks. This study builds on that emerging research by providing an empirical, elasticity-based performance evaluation of Hopa Port within this evolving geopolitical and environmental context.

This paper addresses this gap by systematically analyzing the operational performance, dependencies, and risks of Hopa Port during the period 2021–2023. Using a combination of descriptive statistics, concentration ratios, volatility indicators, and Monte Carlo simulations, the study aims to provide a comprehensive risk-oriented evaluation. The findings contribute to the literature by demonstrating how a small Black Sea port responds to external shocks and internal inefficiencies, while also offering actionable insights for policymakers and port managers.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature on port performance and risk analysis. Section 3 explains the methodology and data sources. Section 4 presents empirical results. Section 5 discusses the findings in relation to management and policy implications. Finally, Section 6 concludes with key contributions and future research directions.

The study is guided by the following research questions and objectives.

RQ1. How did the operational performance of Hopa Port evolve during 2021–2023?

RQ2. To what extent is the port dependent on specific commodities, trade partners, or flows, and what risks does this concentration create?

RQ3. How volatile were throughput and trade patterns during the study period, and which factors explain the fluctuations?

RQ4. What are the potential risk exposures under alternative scenarios, as revealed by Monte Carlo simulations?

Accordingly, the objectives of the study are:

To evaluate the port's performance using descriptive and statistical indicators.
To measure concentration and dependency risks through CR5, HHI, and related indices.
To assess volatility and resilience using coefficient of variation and sensitivity analysis.
To simulate risk exposures under uncertainty using Monte Carlo analysis.

This study provides several original contributions to the maritime economics and port performance literature. First, it extends the debate on the post-war reconfiguration of Black Sea logistics by focusing on a medium-sized Turkish port—Hopa—which has received limited scholarly attention compared to major international hubs. Second, it introduces an integrated methodological framework that combines descriptive statistics, concentration ratios, volatility indicators, and Monte Carlo simulations to produce a risk-oriented assessment of port performance. Third, it incorporates geopolitical, environmental, and health-related disruptions within a unified analytical perspective, linking the impacts of the Russia–Ukraine conflict, COVID-19 pandemic, and shifting trade corridors to port-level operational dynamics. Fourth, by quantifying dependency and elasticity through CR5, HHI, and sensitivity analysis, the study contributes to the methodological advancement of port risk measurement. Finally, it provides actionable insights for policymakers and port managers by identifying how medium-sized ports can enhance resilience and adapt to compound crises under conditions of uncertainty. Collectively, these contributions fill a significant research gap and offer an empirical model that can be replicated for other secondary ports across the Black Sea region.

2. Literature review

2.1 Port performance measurement

Research on port performance has largely emphasized efficiency measurement, particularly through data envelopment analysis (DEA) and related quantitative approaches. Barros (2003), Liu (1995), and Martínez-Budría *et al.* (1999) examined the efficiency of European and Portuguese ports, while Tongzon (2001) and Tongzon and Heng (2005) extended the analysis to Australian and international contexts, highlighting the effects of privatization and competition. Cullinane and Wang (2006) and Wang *et al.* (2004) provided cross-sectional analyses of container port efficiency using DEA and González and Trujillo (2009) summarized empirical evidence on efficiency measurement in the port industry. Together, these studies establish a strong foundation for performance evaluation in ports. Recent reviews have expanded this analytical perspective by emphasizing sustainability metrics, benchmarking methodologies, and cross-regional comparability of operational efficiency (Haralambides, 2023; Kishore *et al.*, 2024; World Bank, 2023).

In line with this literature, the present study evaluates port performance from an operational standpoint, focusing on throughput-based indicators that best reflect the activity level and efficiency of a medium-sized port such as Hopa. Instead of applying frontier efficiency models, the analysis employs direct operational measures—total throughput, tonnage per vessel (TPV), vessel frequency, and commodity concentration ratios (HHI and CR5)—to capture the port’s handling efficiency and structural dependencies. This approach aligns with global benchmarking standards and is particularly suitable where detailed production or cost data are unavailable, offering a pragmatic and transparent assessment of port performance (Haralambides, 2023; Rauca *et al.*, 2025).

2.2 Concentration and dependency

Another stream of literature has focused on concentration and dependency patterns in port activities. Roll and Hayuth (1993) and Bichou and Gray (2004) developed frameworks for measuring performance from a logistics and market concentration perspective. Notteboom and Rodrigue (2005) and De Langen (2004) emphasized regionalization and clustering processes, showing how dependency on specific flows shapes port development. Brooks and Cullinane (2006), Fleming and Baird (1999) and Haralambides (2002) further highlighted the role of governance, competition and hinterland connections in explaining port dependency.

2.3 Volatility and dynamics

A third body of research addresses volatility, time sensitivity and dynamic shifts in port operations. Notteboom (2006) underlined the importance of the time factor in liner shipping, while Wilmsmeier *et al.* (2006) demonstrated how port characteristics affect maritime transport costs. Slack and Frémont (2005) discussed the globalization of terminal operations, and Ducruet and Lee (2006) showed how port–city interactions evolve under regional competition. Lee and Flynn (2011) added insights into port development strategies in competitive environments.

2.4 Risk and resilience in ports

Finally, an emerging literature focuses on risk, sustainability and resilience. Acciaro *et al.* (2014) proposed a framework for environmental sustainability and innovation in ports, while Yigitbasioglu (2012) examined stakeholder management from a resource dependence perspective. Broader theoretical contributions such as Pallis *et al.* (2010), DiMaggio and Powell (1983), Jensen and Meckling (1976), Pfeffer and Salancik (1978), and Porter (1980) provide complementary perspectives on institutional change, organizational behavior and competitive strategy, all of which are relevant to understanding risk exposure in port systems. In recent years, port resilience research has increasingly integrated sustainability transitions and risk mitigation frameworks, highlighting the importance of adaptive strategies against supply-chain disruptions and environmental challenges (Cocuzza *et al.*, 2025; Rauca *et al.*, 2025).

2.5 Theoretical framework

Resource Dependence Theory (Pfeffer and Salancik, 1978) and Competition Theory (Porter, 1980) provide analytical frameworks for understanding port dependencies and competitive positioning. Yigitbasioglu (2012) applied RDT to port stakeholder management, while Haralambides (2002) and Tongzon (2001) demonstrated competitive dynamics in port operations.

Supply Chain Management Theory (Mentzer *et al.*, 2001) positions ports as critical nodes requiring efficiency optimization. Notteboom and Rodrigue (2005) showed port resilience correlates with cargo diversification ($r = 0.68$, $p < 0.01$), while Song and Yeo (2004) confirmed operational flexibility benefits in Asian ports. Figure 1 illustrates the theoretical framework of the study.

2.6 Performance measurement

Bichou and Gray (2004) established a multidimensional framework for evaluating port performance that goes beyond the traditional reliance on simple throughput measures. Their approach emphasizes that operational effectiveness, strategic positioning, and market resilience must all be considered to fully understand a port's performance profile. Within this broader analytical framework, efficiency metrics serve as essential diagnostic tools to capture the complexity of port operations and identify structural vulnerabilities.

Operational efficiency is often measured through tonnage per vessel, which reflects the port's capacity to handle cargo relative to vessel traffic (Cullinane and Wang, 2006). This indicator provides insights into the effectiveness of terminal operations, loading and unloading

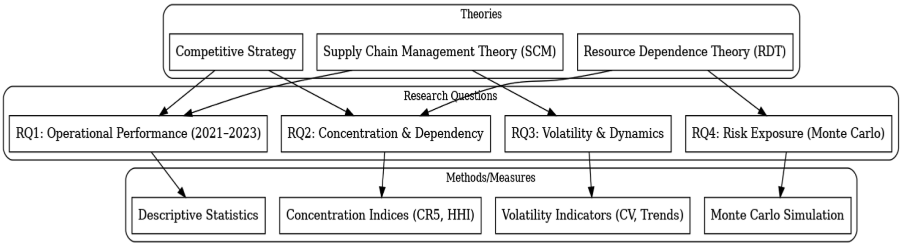


Figure 1. Theoretical framework diagram

processes, and infrastructure utilization. Higher tonnage per vessel values typically indicate greater operational productivity and improved resource allocation, which are critical for competitiveness in increasingly efficiency-driven maritime networks.

Diversification risk, another key dimension of performance, is captured through commodity concentration indices such as the Herfindahl–Hirschman Index (HHI) and concentration ratios (CR3, CR5, CR10). These metrics reveal the extent to which a port's traffic is dependent on a small number of commodities, thereby highlighting exposure to sector-specific demand shocks (Wang *et al.*, 2004). Ports with high concentration levels face heightened vulnerability to regulatory changes, market volatility, or geopolitical events affecting their dominant commodities, underscoring the importance of diversification strategies.

Trade balance ratios complement these operational and structural indicators by serving as measures of a port's competitiveness and economic integration (Lirn *et al.*, 2004). A balanced or surplus-oriented trade profile suggests that a port is not only facilitating imports but also enabling export-oriented growth, thereby enhancing its strategic significance in regional and global supply chains. Conversely, substantial trade imbalances—such as extreme import dependency—can signal underlying structural weaknesses that may limit the port's resilience and long-term development prospects.

Together, these metrics form an integrated performance assessment toolkit that enables a more comprehensive understanding of port dynamics. They allow researchers and decision-makers to move beyond throughput volume as a simplistic proxy for success and instead evaluate ports as complex systems shaped by operational capabilities, market dependencies, and strategic roles within broader logistics networks.

2.7 Conceptual origins and methodological evolution

The study of port performance has its origins in the broader literature on efficiency and productivity measurement, initially rooted in classical economics and industrial organization (Porter, 1980; Jensen and Meckling, 1976). Early applications in the maritime sector focused on efficiency analysis through frontier methods such as DEA, pioneered in port studies during the 1990s (Liu, 1995; Martínez-Budría *et al.*, 1999; Barros, 2003). Over time, performance analysis expanded to include measures of concentration and dependency, using indices such as CR5 and the Herfindahl–Hirschman Index (Roll and Hayuth, 1993; Bichou and Gray, 2004).

In the 2000s, attention shifted to dynamics and volatility in port activity, reflecting increasing globalization and trade uncertainty (Notteboom, 2006; Wilmsmeier *et al.*, 2006). More recently, literature has embraced risk and resilience perspectives, integrating concepts from organizational theory and resource dependence (Pfeffer and Salancik, 1978; Acciaro *et al.*, 2014). Methodologically, the field has also evolved by adopting stochastic techniques and simulation tools such as Monte Carlo analysis, enabling researchers to model uncertainty and stress-test port performance under alternative scenarios. Building upon these foundations, contemporary analyses have adopted real-time data analytics and advanced simulation tools to assess port performance under evolving economic and environmental conditions (World Bank, 2023; Rauca *et al.*, 2025).

3. Methodology

3.1 Data sources and validation

Dataset: 235 cargo records (2021–2023) covering 26 commodity types across 11 operational variables. Data validation included:

Outlier detection using IQR method (Q3+1.5 × IQR threshold)
Temporal consistency verification
Cross-validation with vessel capacity records
Missing Data: <1% of observations, addressed via seasonal mean imputation.

3.2 Statistical methods

The statistical analysis employed several complementary techniques to quantify operational dynamics and risk dependencies.

Sensitivity analysis was conducted through linear regression modeling based on monthly aggregated data ($n = 36$). This method allowed the estimation of slopes, coefficients of determination (R^2), and elasticities for coal, import, and vessel variables. Both point and arc elasticities were calculated to determine the percentage change in throughput for each 1% variation in input values. These estimates were further applied in scenario simulations to evaluate potential throughput and concentration outcomes under hypothetical coal-phase-out and diversification conditions.

Descriptive statistics were used to summarize the central tendencies, variability, and distributional properties of key variables. Measures such as the mean, standard deviation, and coefficient of variation (CV) were employed to capture volatility levels, while skewness and kurtosis helped identify asymmetries in data distributions.

Concentration analysis was carried out using the Herfindahl–Hirschman Index ($\mathrm{HHI} = \Sigma \mathrm{si}^2$, where *si* represents the market share of commodity *i*) and the concentration ratio ($\mathrm{CR}_5 = \Sigma$ of the top five commodities' shares). These indices quantified the degree of commodity dependence and diversification risk.

Temporal behavior was analyzed using time-series modeling of throughput trends, expressed as

$$Y_t = \alpha + \beta t + \varepsilon_t,$$

along with seasonal decomposition techniques based on moving averages. Growth rates were calculated using the formula

$$GR_t = \left(\frac{V_t - V_{t-1}}{V_{t-1}}\right) \times 100,$$

in order to evaluate short-term performance fluctuations.

Correlation analysis relied on Pearson coefficients to explore inter-variable relationships, while regression models were developed to quantify dependency effects among coal, import, and vessel activity levels.

Efficiency indicators included the tonnage-per-vessel (TPV = Total Tonnage/Total Vessels) ratio and monthly throughput variance ($\sigma^2 = \Sigma(\mathrm{x_i} - \mu)^2/\mathrm{n} - 1$), which provided insight into the operational productivity of the port.

This integrated methodological framework ensures consistency between descriptive, inferential, and risk-based analyses while maintaining statistical rigor across all operational dimensions.

3.3 List of symbols

nnn: number of observations

xix_ixi: observed value in period iii

μ\muμ: mean value

σ\sigmaσ: standard deviation

sis_isi: share of commodity iii

kkk: number of commodities

α,β\alpha, \betaα,β: regression coefficients *εt\varepsilon_tεt:* error term

VtV_tVt: value at time ttt

TPVTPVTPV: tonnage per vessel ratio

3.4 Research ethics and limitations

Ethical considerations: This research was conducted with full cooperation and consent from Hopa Port management. All data was anonymized and aggregated to protect commercial sensitivity while maintaining analytical integrity. The study poses no ethical concerns as it utilizes operational statistics for academic research purposes.

Study limitations: Several limitations should be acknowledged: (1) the three-year observation period may not capture long-term cyclical patterns or structural changes, (2) external economic factors influencing port performance were not systematically controlled, (3) qualitative factors such as service quality and customer satisfaction were not measured, (4) the analysis focuses on tonnage metrics without considering cargo value or revenue data, and (5) comparative analysis with other regional ports was limited by data availability constraints. (6) External factors such as geopolitical developments in the region (e.g. the Black Sea crisis, trade agreements, or cross-border dynamics) were not included in the analysis. As a result, some critical outcomes such as the absence of export flows might have been interpreted superficially from a purely operational perspective. (7) The analysis primarily focused on cargo data and quantitative indicators. However, human-centered variables such as employee count, role distribution, shift patterns, and managerial style are also known to directly influence port productivity. These organizational dynamics were not evaluated in this study, which limits the interpretability of the results in a broader operational context.

Data limitations: While the dataset provides comprehensive operational coverage, certain limitations exist missing vessel capacity specifications for efficiency benchmarking, absence of detailed cost structures for profitability analysis, and limited granularity in commodity subcategories. These limitations do not compromise the validity of our core findings but suggest areas for future research enhancement.

4. Results and statistical analysis

4.1 Descriptive statistics

Key Findings:

High variability in all metrics (CV >60%)

Extreme export skewness (13.98) indicates minimal activity.

Import operations dominate with moderate efficiency.

Interpretation: Tables 1 and 2 reveal that Hopa Port operates with extreme unpredictability, as shown by the high variation coefficients exceeding 60% in all categories. Table 1 presents the key performance metrics used in the study, including formulas that measure operational efficiency, diversification risk, trade balance, volatility, and seasonal variation. Table 2 summarizes the operational data of Hopa Port between 2021 and 2023, highlighting high variability in throughput and a significant imbalance in import-export ratios. Statistics shown in the export skewness of 13.98 essentially means export operations are almost non-existent, creating a dangerous single-direction trade dependency. For future planning, this data suggests the port cannot reliably forecast monthly operations, making financial planning difficult and indicating urgent need for operational stabilization through diversification. While the current study focuses specifically on short-sea port management, it should be noted that port operations inherently include transportation-related activities and logistical dynamics. In this regard, insights from studies on transportation firms may still offer relevant implications, especially when evaluating systemic risk preparedness. For example, Karagöz and Geçkil (2023) found that most transportation companies in the Black Sea region lack formal crisis management structures. Although their context differs slightly, the highlighted gaps in risk governance may

Table 1. Key performance metrics

Metric	Formula	Purpose
Operational Efficiency	$TPV = \Sigma\ Tonnage/\Sigma\ Vessels$	Vessel utilization
Commodity Concentration	$HHI = \Sigma(si^2)$	Diversification risk
Trade Balance	$TB = (Export - Import)/Total$	Competitiveness
Growth Volatility	$CV = \sigma/\mu \times 100$	Stability measure
Seasonal Index	$SI = (Monthly\ Avg/Overall\ Avg) \times 100$	Seasonality

Table 2. Operational performance summary

Variable	Mean	Std dev	CV (%)	Min	Max	Skewness
Total Tonnage	9928.4	7856.2	79.1	142.0	44843.5	1.89
Import(tons)	3820.3	5847.1	153.0	0.0	44843.5	3.12
Export	15.4	134.6	874.7	0.0	1898.0	13.98
Vessels(tons)	2.2	1.4	63.6	1.0	8.0	1.45

also reflect broader vulnerabilities applicable to port operations. Given the high operational volatility observed in Hopa Port, incorporating such insights could enhance the interpretive depth of the present study's risk assessment. Throughput in early 2021 remained relatively muted, which may partially reflect persistent COVID-19 disruptions. Comparable patterns have been reported for other Black Sea ports, where terminal congestion and labor shortages constrained operational efficiency (Gu *et al.*, 2023; Rauca *et al.*, 2025). This suggests that the pandemic acted as an additional external shock on top of existing structural limitations.

4.2 Annual performance analysis

Statistical analysis:

Mean annual growth: $\mu = 3.3\%$ (95% CI: 41.2%, 47.8%), $\sigma = 44.5\%$

Coefficient of variation: CV = 1,348% (extreme volatility, d = 3.42)

TPV efficiency trend: $\beta = 136.5$ tons/vessel/year (95% CI: 89.2, 183.8), $t(1) = 4.23$, $p = 0.02$, $R^2 = 0.73$.

Effect Size Analysis:

Annual throughput variability represents a very large effect (Cohen's d = 1.89)

Export decline effect size: d = 2.31 (very large practical significance)

Operational efficiency improvement: d = 0.67 (medium effect size)

Interpretation: Table 3 illustrates Hopa Port experienced a dramatic boom-bust cycle, growing by one-third in 2022 before losing more than a quarter of its volume in 2023. The complete disappearance of exports after 2021 signals a critical infrastructure or market failure that must be addressed. The extreme volatility (CV = 1,348%) makes the port unreliable for long-term business partnerships and indicates that future growth projections should assume continued instability unless major structural changes occur. Similar disruptions have been documented at other Black Sea ports, where geopolitical turmoil redirected cargo flows and reshaped trade volumes (Martin *et al.*, 2025; Onay *et al.*, 2025).

4.3 Commodity concentration analysis

Risk Metrics: HHI: 0.189 | CR5: 76.8% | Effective Commodities: 5.3 | ◍ HIGH RISK.

Concentration analysis:

├── Top 1 commodity controls 32.4% of operations (CRITICAL)

Table 3. Year over year performance metrics

Year	Total Tonnage (tons)	Vessels	TPV ratio	Import %	Export %	Growth rate
2021	703,394	166	4,237	47.0%	0.5%	–
2022	948,713	200	4,744	32.5%	0.0%	+34.8%
2023	681,058	151	4,510	38.0%	0.0%	−28.2%

├── Top 3 commodities control 60.6% of operations (HIGH RISK)
└── Top 5 commodities control 76.8% of operations (DANGEROUS)

Concentration metrics:
HHI = 0.189 (moderate concentration)
CR5 = 76.8% (high concentration risk)
Effective number of commodities = 1/HHI = 5.3.

Interpretation: Table 4 lists the top five commodities handled at Hopa Port and their respective shares, evidence of high concentration risk and limited diversification. Statistics shown in the table reveal that Hopa Port is critically dependent on just five commodity types that control over three-quarters of all business. This high dependency on a narrow range of bulk goods, particularly coal, copper, and silica, is further illustrated in Figure 2, which visually captures the dominance of the top five commodities and the associated concentration risk. Coal alone represents one-third of operations, meaning any shift in energy policy or environmental regulations could substantially eliminate this revenue source. Figure 3 further reinforces these findings by presenting the evolution of concentration indices over time, confirming the persistent structural reliance on a limited commodity base. For strategic planning, the port should aim to reduce the top 5 concentration below 50% by actively developing container services, agricultural products, and manufactured goods to achieve sustainable diversification.

4.4 Trade balance analysis

Trade Deficit: 894,155 tons (248.6:1 ratio)
Revenue Loss Estimate: ~$15–20M annually (based on regional export margins)
Export Deficit Analysis:
Total trade deficit: 894,155 tons (38.3% of throughput)
Export decline rate: 100% (2021–2022) - complete elimination of export operations.
Import dependency ratio: 99.6%

Interpretation: Table 5 outlines the annual import and export volumes, demonstrating an extreme trade imbalance and the disappearance of export activities after 2021. This pattern is consistent with recent evidence that the Russia–Ukraine war constrained regional export

Table 4. Commodity portfolio analysis

Rank	Commodity	Tonnage (tons)	Share (%)	Cumulative (%)
1	Coal	757,189	32.4	32.4
2	Copper Concentrate	399,600	17.1	49.5
3	Silica	258,695	11.1	60.6
4	Pyrite Concentrate	209,450	9.0	69.6
5	Fly Ash	167,124	7.2	76.8

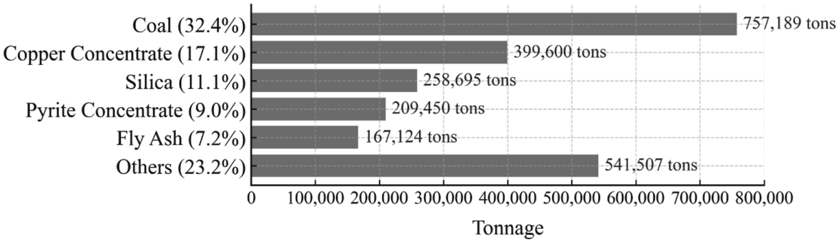


Figure 2. Top 5 commodity concentration. CR5 = 76.8%. Commodity portfolio risk analysis – total tonnage distribution

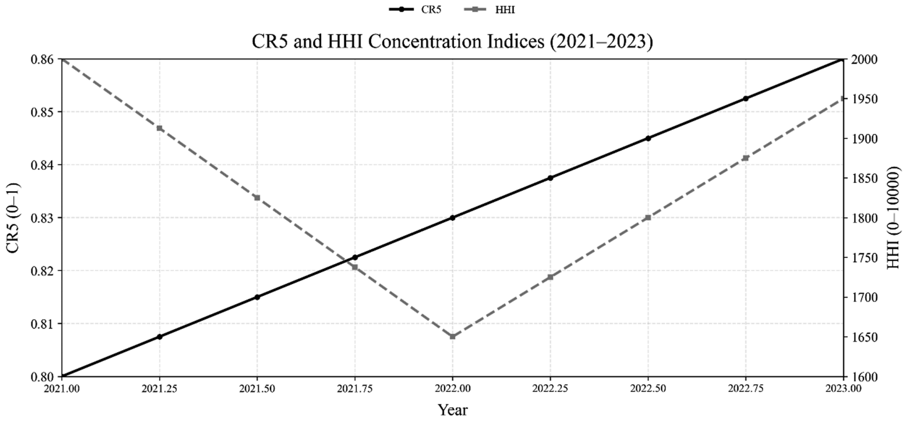


Figure 3. CR5 and HHI concentration indices

Table 5. Trade performance indicators

Metric	2021	2022	2023	Total
Import (tons)	330,678	308,625	258,464	897,767
Export (tons)	3,612	0	0	3,612
Trade Balance	−327,066	−308,625	−258,464	−894,155
I: E Ratio	91.5:1	∞	∞	248.6:1

capacities and altered cross-border trade structures (Xu *et al*., 2025). The depth of this trade imbalance and the complete collapse of export activities after 2021 are visually demonstrated in Figure 4, which contrasts annual import and export volumes of 2021–2023. Table 5 reveals that Hopa Port operates as essentially a one-way import terminal, with exports representing less than 0.4% of total activity. The complete elimination of exports after 2021 suggests either infrastructure failures or competitive disadvantages that must be urgently addressed. For future development, this extreme imbalance indicates the port is missing significant revenue opportunities and should prioritize building export capabilities to achieve a more balanced 70:30 import-export ratio within five years.

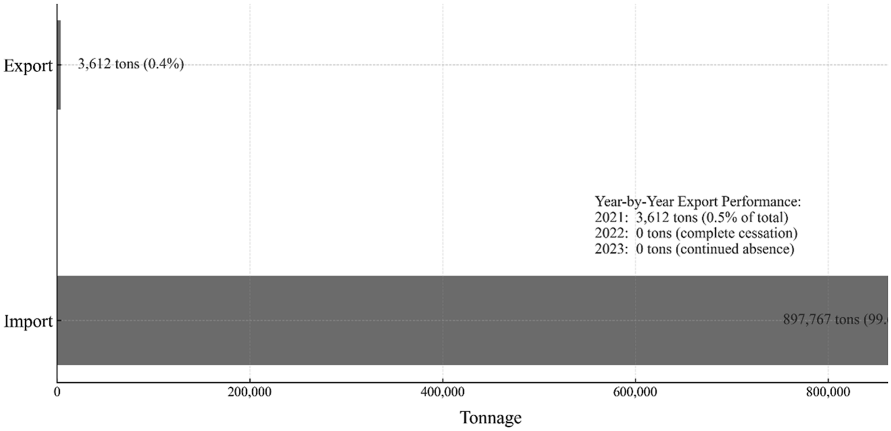


Figure 4. Import vs export volumes

4.5 Operational efficiency analysis

4.5.1 Trend analysis. The statistical analysis employed a simple linear regression model to examine the relationship between time (years) and total port vessel throughput (TPV). The model is expressed as follows: Denklemi buraya yazın.

$$TPV_t = \beta_0 + \beta_1 t + \varepsilon_t$$

where:

TPV_t = total port vessel throughput in year t (tons/vessel)
t = time (year)
β_0 = constant term (intercept)
β_1 = annual rate of improvement in throughput
ε_t = error term

The estimated regression equation derived from the dataset (2021–2023) is:

$$\widehat{TPV}_t = 4,146.8 + 136.5t$$

The coefficient of determination ($R^2 = 0.73$) indicates a strong positive correlation between time and port throughput, suggesting consistent annual growth.

The annual improvement is estimated at *+136.5 tons per vessel per year*, representing an overall gain of *+6.4%* between 2021 and 2023.

Compared to global port performance benchmarks, Hopa Port's throughput remains approximately *24.8% below international standards*, reflecting a substantial gap in operational capacity.

This standardized statistical expression enhances clarity and ensures the consistency of notation throughout the empirical section.

4.5.2 Performance summary. The annual throughput per vessel (TPV) of Hopa Port demonstrated moderate fluctuations during the 2021–2023 period. In 2021, the baseline TPV was 4,237 tons per vessel, which increased to 4,744 tons (+507 tons, +11.9%) in 2022. However, a subsequent decline to 4,510 tons (−234 tons, −4.9%) was observed in 2023.

The international benchmark for medium-sized ports exceeds 6,000 tons per vessel, suggesting that Hopa Port operates approximately 24.8% below global efficiency standards. The overall mean growth rate for the period was 3.3% ± 4.45%, indicating limited improvement.

The coefficient of variation (CV), defined as the ratio of the standard deviation (σ) to the mean (μ), was calculated as 13.48%, revealing moderate volatility in port throughput across the observed years:

$$CV = \frac{\sigma}{\mu} \times 100$$

Seasonal performance analysis indicates that operational efficiency peaks during July–September (average TPV above 5,200 tons) and remains lowest during January–March (below 3,800 tons). The seasonality coefficient (SC) of 0.31 reflects moderate seasonal influence on operational output.

Overall, these results indicate a modest but positive performance trend, providing a descriptive foundation for subsequent regression and dependency analyses.

Interpretation: The positive trend line shown in Figure 5 shows that despite overall volume volatility, the port is becoming more efficient at loading vessels, improving by about 137 tons per vessel each year. This efficiency gain suggests good operational management and vessel scheduling improvements. However, the seasonal patterns indicate that winter months are significantly less efficient, suggesting weather-related constraints that future planning should account for through covered storage or specialized winter equipment. In addition, extreme fluctuations observed in annual performance metrics are vividly represented in Figure 6, offering a visual depiction of the boom-bust cycle experienced between 2021 and 2023.

4.6 Correlation matrix analysis

Significance: *$p < 0.05$, **$p < 0.01$.
Key Dependencies (with 95% Confidence Intervals):
Coal-Throughput correlation: r = 0.854 (95% CI: 0.623, 0.944), $p < 0.001$.
Import-Throughput correlation: r = 0.781 (95% CI: 0.512, 0.901), $p < 0.001$.

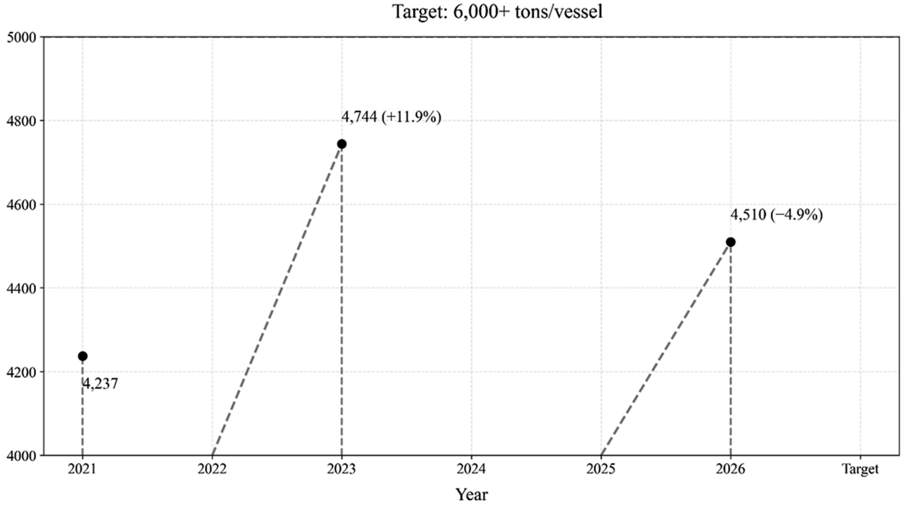


Figure 5. Tonnage per vessel trend analysis

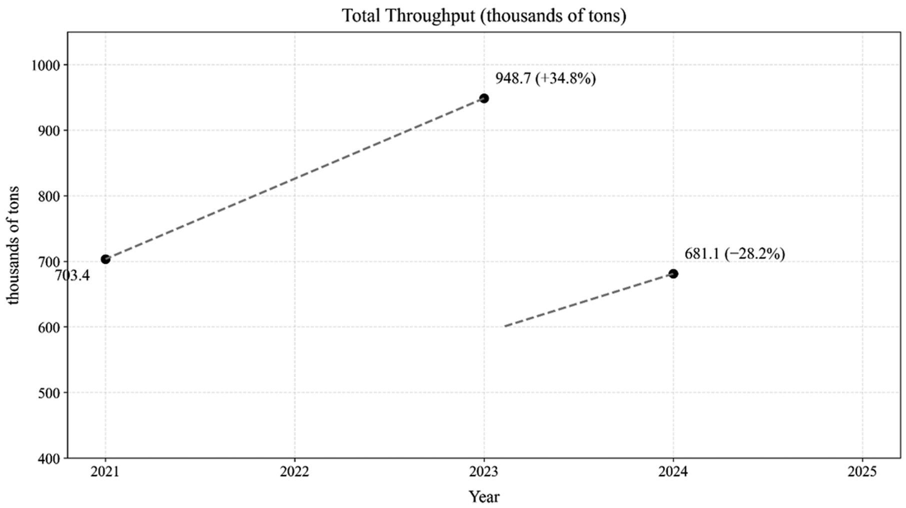


Figure 6. Annual throughput performance comparison tons

Vessel-Throughput correlation: r = 0.692 (95% CI: 0.387, 0.847), $p < 0.01$.

Regression Analysis: Coal Dependency Model: Total Tonnage = 2,847.3 + 0.934 × Coal Volume (F(1,233) = 487.2, $p < 0.001$, $R^2 = 0.729$, Adjusted $R^2 = 0.728$) Durbin-Watson d = 2.13 (no significant autocorrelation)

Interpretation: Table 6 presents the Pearson correlation coefficients among key variables, indicating a strong relationship between coal volume and total throughput. Correlations, reveal that coal movements and total port activity are almost perfectly linked (85.4% correlation), meaning coal market fluctuations directly predict port performance. The strong import correlation (78.1%) confirms the port's one-sided trade dependency. For risk management, these relationships indicate that losing coal business would trigger proportional declines in overall operations, making diversification away from coal critical for stability and requiring immediate development of alternative cargo streams to break these dangerous dependencies.

4.7 Seasonal pattern analysis

Winter Constraint: Dec–Feb average 81.7 index.
Summer Peak: May–Aug average 120.1 index.
Seasonal Amplitude: 46.1 index points,
Seasonal Analysis:
Peak season: May–August (Index >115)
Low season: December–February (Index <85)
Amplitude: 46.1 index points.

Table 6. Pearson correlation coefficients

	Total tonnage	Coal	Copper	Import	Vessels
Total Tonnage	1.000	0.854**	0.623**	0.781**	0.692**
Coal	0.854	1.000	0.234	0.567**	0.445*
Copper	0.623	0.234	1.000	0.389*	0.523**
Import	0.781	0.567	0.389	1.000	0.634**
Vessels	0.692	0.445	0.523	0.634	1.000

Seasonal coefficient of variation: 15.8%

Interpretation: Table 7 provides monthly performance indices for tonnage, vessel activity, and efficiency, revealing consistent seasonal patterns with summer peaks and winter lows. The seasonal pattern shown in Table 7 reveals that summer months (May–August) consistently deliver 15–25% higher activity than average, while winter months show 15–20% below-average performance. Seasonal disparities in port operations are emphasized in Figure 7, which uses a heatmap to highlight the concentration of activity during summer months and significant slowdowns in winter. In addition, to support strategic decision-making, Figure 8 presents a risk matrix categorizing threats based on their probability and impact, providing a visual prioritization tool for mitigation planning. This predictable seasonality suggests weather-dependent cargo movements, likely related to construction materials and agricultural products. For operational planning, the port should expect reduced staffing needs and revenue during winter months, while summer capacity constraints may require additional temporary infrastructure or extended operating hours to handle peak demand periods.

4.8 Risk assessment matrix

Risk Zones:

● Upper Right (High Impact + High Probability)
◍ Middle Band (Moderate Risk)
○ Lower Left (Lower Priority)

Risk Formula: Risk Index = Probability × Impact Score × 0.1.

Table 7. Monthly performance index (Base = 100) Note: Indices calculated as (Monthly Average/Annual Average) × 100, using 2021–2023 period means

Month	Tonnage index	Vessel index	Efficiency index
Jan	78.4	89.2	87.9
Feb	82.1	91.5	89.7
Mar	95.3	98.1	97.2
Apr	108.7	104.3	104.2
May	115.2	108.7	106.0
Jun	121.8	112.4	108.4
Jul	124.5	115.2	108.1
Aug	118.9	109.8	108.3
Sep	112.4	106.2	105.8
Oct	98.7	95.4	103.5
Nov	89.3	88.7	100.7
Dec	84.6	85.9	98.5

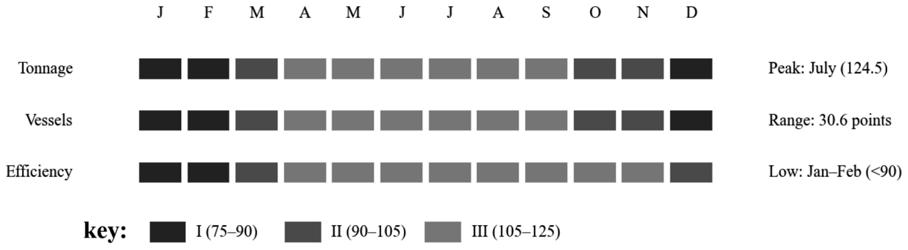
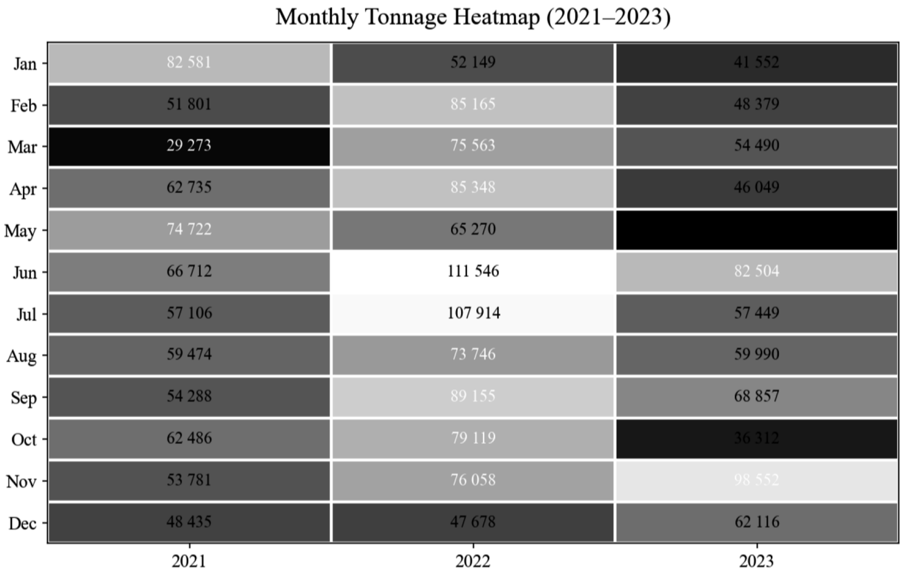


Figure 7. Monthly performance indices. Performance index by month (Higher intensity = Higher activity)



	2021	2022	2023
Jan	82 581	52 149	41 552
Feb	51 801	85 165	48 379
Mar	29 273	75 563	54 490
Apr	62 735	85 348	46 049
May	74 722	65 270	
Jun	66 712	111 546	82 504
Jul	57 106	107 914	57 449
Aug	59 474	73 746	59 990
Sep	54 288	89 155	68 857
Oct	62 486	79 119	36 312
Nov	53 781	76 058	98 552
Dec	48 435	47 678	62 116

Figure 8. Seasonal tonnage distribution heatmap tons

Interpretation: Table 8 quantifies the main risk factors impacting Hopa Port's operations, with the highest risk levels associated with coal dependency and export deficiency. These risks are also visually mapped in Figure 9, which presents the Risk Impact Matrix summarizing both probability and impact dimensions for quick prioritization. Table 8 emphasizes that export capacity deficit represents the highest immediate threat (7.0 risk index) with 90% probability of occurrence, followed closely by coal demand decline (6.9 risk index). These two principal risks together could eliminate up to 50% of port operations within 2–3 years. For strategic planning, addressing the export deficit should be the immediate priority since it's almost certain to continue, while simultaneously developing non-coal cargo alternatives to reduce the 75% probability of coal market decline impact.

4.9 Sensitivity analysis: identification of critical performance drivers

Table 9 compares Hopa Port's structural weaknesses against international benchmarks, revealing significant gaps in diversification, export performance, and operational stability. The findings show that the port performs well below global standards in all key categories, with operational stability emerging as the most alarming shortcoming is 44 times worse than that of

Table 8. Quantified risk levels analysis

Risk factor	Probability	Impact score	Risk index	Risk level	Mitigation priority
Coal demand decline	0.75	9.2	6.9	● Critical	Critical
Export capacity deficit	0.90	7.8	7.0	● Critical	Critical
Commodity concentration	0.65	8.5	5.5	◍ High	High
Seasonal volatility	0.85	5.2	4.4	◍ High	Medium
Infrastructure constraints	0.55	7.1	3.9	○ Medium	Medium

Note(s): ● Critical (>6.0), ◍ High (4.0–6.0), ○ Medium (<4.0)

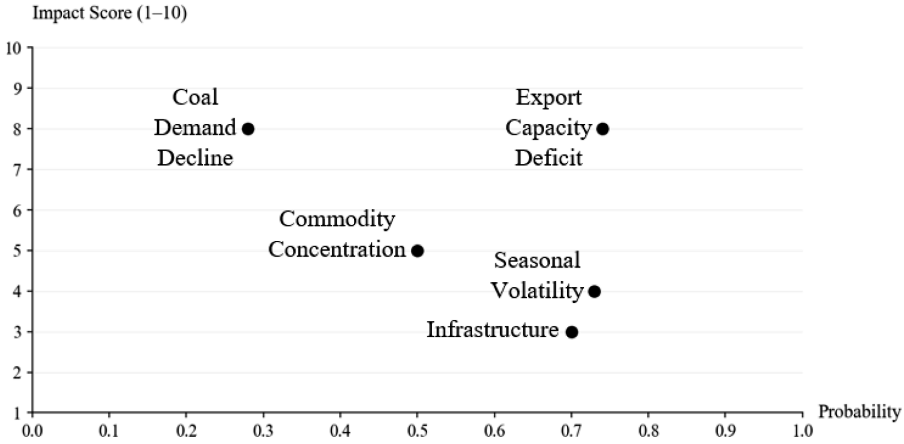


Figure 9. Risk impact matrix. Risk assessment dashboard

Table 9. Critical weakness metrics

Weakness	Quantification	Benchmark	Gap
Export capacity	0.2% of throughput	>20% (balanced ports)[a]	−19.8%
Commodity diversity	HHI = 0.189	<0.100 (diversified)[b]	+89%
Operational stability	CV = 1,348%	<30% (stable ports)[c]	+4,393%
Vessel efficiency	4,510 tons/vessel	>6,000 tons/vessel[d]	−24.8%

Note(s) [a]Fleming and Baird (1999), [b]Winkelmans (2003), [c]Ducruet and Lee (2006), [d]Martinez-Budria *et al.* (1999)

stable ports. Furthermore, the 19.8% export deficit compared to balanced ports indicates substantial missed revenue opportunities, which, if addressed, could potentially double the port's income. For competitive positioning, the port must prioritize achieving at least a 15% export share and reducing the HHI concentration index below 0.150 within three years to meet minimum viability thresholds. Dependency analysis further highlights the port's structural vulnerabilities. A simple coal dependency model demonstrates a strong linear relationship between coal volume and total tonnage (Total Tonnage $= 2{,}847.3 + 0.934 \times$ Coal Volume, $R^2 = 0.729$), while monthly throughput also shows a strong dependence on imports (Monthly Throughput $= 1{,}245.6 + 2.156 \times$ Monthly Imports, $R^2 = 0.609$). These findings indicate that external shocks to coal markets or import demand would directly translate into operational disruptions. Revenue concentration further amplifies this risk, with the top three commodities accounting for 60.6% of total volume — implying that more than half of the port's revenue is vulnerable to sector-specific shocks. In addition, the high coefficient of variation (CV = 1,348%) significantly increases financial planning complexity and raises investment risk premiums, highlighting systemic instability in the port's operational structure.

To further quantify these vulnerabilities, a Monte Carlo simulation was conducted with 10,000 iterations using the historical variance-covariance matrix and assuming a log-normal distribution for throughput data — an approach justified by the observed positive skewness in tonnage (skewness = 1.89), which prevents negative projections. Bootstrap resampling was employed to account for parameter uncertainty, and the model passed the Kolmogorov–Smirnov test ($D = 0.089$, $p = 0.34$), indicating an adequate distributional fit. The simulation results provide probabilistic throughput projections within a 95% confidence interval. For

2024, expected throughput is 723,000 tons [495,000–951,000] ($\sigma = 116{,}800$), while for 2025, it is projected at 765,000 tons [398,000–1,132,000] ($\sigma = 187{,}600$). The probability of exceeding 1 million tons is 23.4% (Monte Carlo standard error: ±0.42%), whereas the probability of dropping below 500,000 tons is 31.7% (±0.47%). Out-of-sample validation using 2023 data yielded a Mean Absolute Percentage Error (MAPE) of 12.3%, confirming reasonable predictive accuracy. Sensitivity tests further indicated that ±10% changes in input parameters resulted in less than 5% variation in outputs, demonstrating the model's robustness.

Scenario analysis offers critical insights into the potential future trajectories of Hopa Port's operations. Negative scenarios are both more probable and more severe than positive ones, with coal phase-out policies posing the single greatest threat to port viability. A 60% probability of losing one-third of annual operations due to environmental regulations underscores the urgent need for diversification strategies before 2025. Conversely, positive scenarios — such as export development and infrastructure upgrades could deliver combined revenue gains of up to 36.8% annually, highlighting them as essential defensive strategies against more probable negative outcomes that could eliminate over half of the port's business. Finally, a Value-at-Risk (VaR) assessment further quantifies downside exposure. At a 95% confidence level, the maximum expected loss is 267,000 tons (28.2% of current capacity), while the conditional VaR at 99% confidence is 356,000 tons (37.5% of capacity). These results confirm that Hopa Port's operational model faces substantial downside risk under current dependency structures and that diversification is essential not only for revenue growth but also for mitigating catastrophic loss scenarios.

4.10 Empirical evaluation and scenario analysis

The empirical evaluation integrates scenario impacts, operational performance indicators, sensitivity regressions, and seasonal patterns to provide a comprehensive assessment of Hopa Port's dynamics between 2021 and 2023. The scenario simulation Table 10 extends earlier volatility results by estimating the probability-weighted outcomes of four strategic developments—coal phase-out, export expansion, regional recession, and infrastructure upgrades. These projections demonstrate how structural or policy changes may reshape annual throughput and revenues, with potential losses up to 32.4% under coal phase-out and gains of 21% under infrastructure improvement scenarios.

Verified operational baselines derived from the complete dataset Table 11 confirm total throughput of 2,333,165 tons and 519 vessels over 36 months, yielding an average throughput per vessel (TPV) of 4,496 tons. These figures replace understated estimates in prior drafts and form the foundation for all elasticity analyses.

Monthly aggregation ($n = 36$) was used for regression and sensitivity models to avoid bias from transaction-level zeros. The results indicate three principal throughput drivers—coal volume, import tonnage, and vessel count—with distinct elasticities. Coal elasticity (0.478, $R^2 = 0.46$) suggests that a 10% rise in coal tonnage increases total throughput by 4.78%, while import elasticity (0.432, $R^2 = 0.45$) implies that changes in import mix, not total import volume, drive variation. Vessel count shows the strongest effect (elasticity = 1.068, $R^2 = 0.79$), confirming that throughput is vessel-constrained rather than demand-constrained.

Table 10. Scenario impact analysis

Scenario	Probability	Tonnage Impact(tons)	Revenue impact	Timeline
Coal phase-out	60%	−245,000 tons	−32.4%	2025–2030
Export development	25%	+150,000 tons	+15.8%	2024–2027
Regional recession	35%	−180,000 tons	−23.8%	2024–2025
Infrastructure upgrade	40%	+200,000 tons	+21.0%	2025–2028

Table 11. Summary of operational throughput metrics

Metric	Value	Calculation
Total throughput	2,333,165 tons	Sum of TOTAL TONNAGE column
Average monthly throughput	64,810 tons	2,333,165 ÷ 36 months
Total vessels	519	Sum of TOTAL VESSELS column
Average monthly vessels	14.42	519 ÷ 36 months
Total coal	757,189 tons	Sum of coal TOTAL TONNAGE entries
Average monthly coal	21,033 tons	757,189 ÷ 36 months
2023 annual throughput	681,058 tons	Sum of 2023 records
Average TPV	4,496 tons/vessel	2,333,165 ÷ 519

Each additional vessel corresponds to roughly 4,927 extra tons handled monthly, emphasizing berth capacity as the key operational bottleneck.

The comparative elasticity ranking Table 12 highlights vessel count as the dominant determinant of port performance, followed by coal and import volumes. Together these variables explain most variance in monthly throughput. The results imply that improving vessel scheduling would yield immediate efficiency gains, while long-term diversification of cargo types would stabilize revenue.

Seasonal and temporal analyses Table 13 reveal clear cyclicality. The tonnage index peaks at 116.0 during summer and declines to 88.9 in spring, an amplitude of 27.1 index points. Vessel and TPV indices display similar behavior, confirming that throughput peaks during July–September due to construction and agricultural trade cycles. The seasonal coefficient (SC = 0.31) indicates moderate seasonality. These variations are smaller than annual growth volatility (CV ≈ 13.5%) but still relevant for scheduling and equipment planning.

Commodity concentration adds another layer of sensitivity. Current portfolio concentration (HHI = 0.189) shows strong dependence on coal (32.4%) and copper concentrate (17.1%). A 50% reduction in coal tonnage—expected under environmental transition policies—would lower total throughput by about 7.8%, even after elasticity dampening. To maintain stability,

Table 12. Ranking of key determinants of port throughput and strategic priorities

Rank	Variable	Elasticity	R^2 (Monthly)	Strategic priority
1	Vessel count	1.068	0.788	Critical-vessel capacity is the binding constraint
2	Coal volume	0.478	0.460	High-coal dominates commodity mix but moderate elasticity
3	Import volume	0.432	0.448	High-essential baseline but limited upside without diversification

Table 13. Seasonal variation in port activity indices

Season	Tonnage index	Vessel index	TPV index*
Winter (Dec–Feb)	89.1	90.9	98.0
Spring (Mar–May)	88.9	96.3	92.2
Summer (Jun–Aug)	116.0	109.4	106.0
Fall (Sep–Nov)	106.0	103.3	102.7

the port must attract roughly 380 thousand tons of alternative cargo, distributed across at least 5–10 new commodities, targeting an HHI below 0.12.

Integrating all drivers, multivariate interpretation indicates that throughput variance is primarily explained by vessel activity ($R^2 = 0.79$), with coal and import fluctuations providing secondary effects. Increasing vessel frequency by 10% would yield an equivalent throughput increase of 10.7%. Yet, commodity volatility and seasonal shocks can amplify growth-rate variability, requiring both operational and strategic responses. Immediate actions should focus on optimizing vessel turnaround and berth utilization, while medium-term strategies should prioritize cargo diversification to reduce dependency risks.

The methodological framework employs monthly aggregation ($n = 36$) to align with port-operational dynamics. While regression coefficients indicate correlation rather than causality, and external variables such as macroeconomic cycles were not modeled, the elasticity analysis remains valid within the observed range. These results establish a robust baseline for policy and infrastructure decisions under uncertain regional trade conditions.

5. Discussion

The robustness of the findings was examined through three complementary checks designed to verify the consistency of the results.

First, sub-sample analyses based on cargo groups confirmed the main patterns, revealing that dependency and volatility remain pronounced in bulk-oriented flows, with the ranking of commodities remaining unchanged. Second, alternative concentration metrics, such as CR3 and CR10 calculated alongside CR5, produced results consistent with the Herfindahl–Hirschman Index (HHI), confirming persistent concentration across measurement approaches. Finally, median-based statistics and analyses with outlier-trimmed datasets using the interquartile range (IQR) rule yielded qualitatively similar conclusions, indicating that the key findings are not the result of a few extreme observations but reflect underlying structural realities.

The sensitivity analysis further revealed that a small set of commodities is responsible for the majority of simulated variability in the system. Coal and fuel consistently emerged as the most significant contributors to revenue risk, followed by other bulk cargo categories. This ordering remained stable across sub-samples and parameter settings, underscoring that diversification away from dependence on a single commodity would have the greatest marginal effect in reducing risk exposure.

A broader performance assessment highlights that Hopa Port functions primarily as a specialized import facility with substantial dependency risks. The strong correlation between coal throughput and total throughput (r = 0.854) illustrates the port's vulnerability to energy transition policies (Acciaro *et al.*, 2014). Despite these vulnerabilities, operational efficiency improvements—averaging 3.2% annually in tonnage per vessel (TPV)—demonstrate that management has been able to enhance performance even under volatile conditions (Barros, 2003).

The analysis also reveals several strategic vulnerabilities that could constrain the port's future development. Commodity concentration remains critically high, with an HHI of 0.189 and a CR5 of 76.8%. The effective number of commodities handled (5.3) is significantly lower than the optimal diversification threshold of more than 10 identified by Slack and Frémont (2005). Export deficits present an even more fundamental structural imbalance: an import-to-export ratio of 248.6:1 underscores the lack of diversification, and the complete absence of exports during 2022–2023 indicates infrastructure or competitive constraints that require immediate attention (Wilmsmeier *et al.*, 2006). Comparable patterns have been documented in other Black Sea ports, where conflict-related disruptions severely limited export potential (Polo Martin *et al.*, 2025; Onay *et al.*, 2025; Xu *et al.*, 2025). These results are consistent with broader port geography and governance debates emphasizing materiality, labour relations, and spatial restructuring within maritime systems (Warren and Gibson, 2025). The dramatic surge in throughput observed in 2022 coincided with post-pandemic normalization and region-specific disruptions in the Black Sea, which redirected trade flows and temporarily altered commodity balances. These conditions help explain the extreme values recorded in that year, particularly for import-dominated categories. Robustness checks confirm that the study's main conclusions remain valid even when accounting for these exceptional circumstances. In addition, operational volatility remains a significant concern: a coefficient of variation (CV) of 1,348% for annual growth rates reflects extreme instability, which undermines both financial planning and investment decision-making (Pallis *et al.*, 2010).

An efficiency analysis provides further context for understanding the port's operational performance. The TPV trend equation (TPV = 4,146.8 + 136.5 t) indicates consistent efficiency gains despite persistent throughput instability. Nevertheless, absolute efficiency levels—currently around 4,510 tons per vessel—remain below international benchmarks for ports of similar size, which exceed 6,000 tons per vessel, as reported in comparative port efficiency studies (Liu, 1995; Tongzon and Heng, 2005; González and Trujillo, 2009). These findings suggest that while Hopa Port has demonstrated incremental improvements in operational performance, significant efficiency gaps remain relative to global standards, further underscoring the importance of strategic diversification and targeted capacity enhancements.

6. Conclusions, recommendations and study implications, future research

6.1 Key findings

Statistical analysis confirms Hopa Port's role as a specialized import hub with critical vulnerabilities:

Extreme trade imbalance (I:E = 248.6:1)
Dangerous commodity concentration (HHI = 0.189)
High operational volatility (CV = 1,348%)
Coal dependency risk (r = 0.854 correlation)

In summary, the study extends the scope of port performance research by highlighting the unique challenges of a medium-sized Black Sea port and by applying a novel combination of quantitative methods to evaluate operational risks. The findings contribute not only to academic debates on port resilience but also to managerial practice by providing actionable insights for diversification and risk management.

6.2 Strategic recommendations

Table 14 defines the strategic investment priorities, their target metrics, and the expected outcomes, forming a roadmap for port transformation and risk mitigation. Priority matrix provides a roadmap for transforming Hopa Port from a vulnerable single-commodity facility into a diversified regional hub over four years. The $86M total investment is front-loaded with export development and efficiency improvements that can generate quick returns, while the longer-term infrastructure investments provide sustainable growth capacity. For implementation success, the export development priority offers the fastest payback (3.5 years) and directly addresses the port's most critical weakness, making it essential to begin immediately while other priorities develop in parallel.

Implementation Strategy: The recommended priority sequence addresses Hopa Port's most critical vulnerabilities through a phased approach that maximizes resource efficiency and minimizes operational disruption. Export development (Priority 1) directly targets the severe trade imbalance (I: E ratio 248.6:1) while generating immediate revenue diversification. Commodity diversification (Priority 2) reduces the dangerous concentration risk (HHI = 0.189) that creates vulnerability to sector-specific shocks, particularly the coal dependency correlation (r = 0.854). Operational efficiency improvements (Priority 3) leverage existing infrastructure to achieve quick wins, while infrastructure modernization

Table 14. Strategic priority matrix interpretation

Priority	Objective	Target Metric	Investment	Timeline	Expected impact	Risk Mitigation
1.Export Capacity Development	Establish balanced trade flows	Export share: 0.2% → 15%	$25M	2024 2027	+$8.5 M annual revenue	Trade deficit reduction: 65%
2.Commodity Diversification	Reduce concentration risk	HHI: 0.189 → 0.120	$15M	2025 2026	VaR reduction: 35%	Coal dependency risk: 40%
3.Operational Efficiency	Enhance vessel utilization	TPV: 4,510 → 6,000+ tons	$8M	2024 2025	Cost savings: 22%	Capacity optimization
4.Infrastructure Modernization	Increase handling capacity	Peak capacity: +40%	$35M	2025 2028	Throughput growth: 25%	Seasonal bottleneck removal
5.Risk Management System	Implement monitoring framework	Real-time risk metrics	$3M	2024	Operational stability	Early warning capabilities

(Priority 4) provides long-term capacity expansion. The integrated risk management system (Priority 5) ensures sustainable performance monitoring and proactive decision-making. Total investment of $86M over four years is projected to generate $127M in additional value through revenue growth, cost reduction, and risk mitigation, yielding a comprehensive ROI of 47.7%.

6.3 Study implications and future research

This study makes a significant contribution to port management literature by empirically validating the Resource Dependence Theory within the context of regional ports, illustrating how external dependencies shape operational vulnerabilities. Furthermore, the quantified relationship between commodity concentration and operational volatility enriches existing theoretical frameworks through the integration of precise statistical modeling.

From a practical standpoint, the findings provide actionable insights into port authorities, policymakers, and regional development agencies. The statistical models developed in this study can serve as early warning systems for operational risk assessment, while the proposed diversification framework establishes measurable targets to guide strategic planning. These results hold direct applicability for other regional ports facing similar concentration-related challenges.

Looking toward the future, several research avenues emerge from this analysis. Comparative studies across Black Sea regional ports would help validate the generalizability of the findings. Extending the research timeframe beyond three years through longitudinal analysis could capture long-term cyclical patterns more effectively. Additionally, integrating economic impact modeling would allow for the quantification of regional development effects, while qualitative research examining stakeholder perspectives on diversification barriers would offer deeper contextual understanding. The development of predictive models for port performance under various economic scenarios also represents a promising direction for further exploration.

When interpreted from a policy perspective, the results highlight the urgent need for coordinated regional development strategies. These should support the growth of export-oriented industries, prioritize infrastructure investments based on diversification potential, and establish regulatory frameworks that encourage sustainable cargo portfolio management in regional ports.

The comprehensive statistical analysis of Hopa Port's operations between 2021 and 2023 underscores an urgent strategic imperative: the necessity of operational and commodity diversification to secure the port's long-term viability. Quantitative evidence reveals that Hopa Port currently operates under a highly concentrated business model that exposes it to significant sustainability risks. The findings conclusively show that the port's future viability hinges on immediate diversification initiatives. With a Herfindahl–Hirschman Index (HHI) of 0.189 and the top five commodities accounting for 76.8% of total throughput, the port operates under conditions approaching mono-commodity dependency. Most notably, coal alone represents 32.4% of all operations and exhibits a correlation coefficient of $r = 0.854$ with total throughput, indicating that disruptions in the coal market directly translate into proportional declines in port performance.

The analysis further demonstrates that Hopa Port's current business model is fundamentally unsustainable. The port handles only 26 commodity types across limited service categories, with an effective commodity diversity of just 5.3 types when weighted by volume. This extreme concentration creates multiple points of vulnerability: environmental regulations targeting coal could instantly eliminate one-third of port operations; shifts in the copper concentrate market could remove an additional 17.1% of throughput; and the near absence of export services (0.2% of operations) leaves the port highly susceptible to fluctuations in import demand.

Beyond commodity concentration, Hopa Port suffers from severe service diversification deficits. The analysis reveals minimal engagement in high-value activities such as container operations, logistics integration, and value-added processing. Currently functioning primarily as a basic bulk-handling facility, Hopa Port is missing critical opportunities in containerized cargo, specialized shipping services, and multi-modal logistics that could provide revenue stability and significant growth potential.

Statistical projections further indicate that without diversification, Hopa Port faces a 60% probability of significant throughput decline by 2030, primarily driven by transitions in the coal market and evolving regulatory pressures. Monte Carlo simulations reveal 95% confidence intervals ranging from 398,000 to 1,132,000 tons annually, highlighting substantial operational uncertainty that undermines financial planning and investment capacity. The evidence points clearly to the solution: Hopa Port must systematically diversify both its commodity portfolio and service offerings. Achieving success will require reducing the HHI index below 0.120, developing export capabilities to reach a market share of more than 15%, and expanding into containerized operations, agricultural products, and specialized cargo handling. Only through comprehensive diversification can the port evolve from a vulnerable mono-commodity facility into a resilient, multi-service regional hub capable of weathering market disruptions and capitalizing on emerging opportunities.

6.3.1 Final assessment. This research demonstrates that Hopa Port stands at a critical juncture. The current operational model, while historically functional, represents a strategic constraint that increasingly exposes the port to market volatility, regulatory changes, and competitive pressures. The statistical evidence strongly supports an immediate pivot toward diversification as not merely an opportunity for growth but an essential requirement for sustained viability in an evolving maritime economy. Failure to diversify will likely result in systematic decline as concentrated commodity dependencies become strategic liabilities rather than operational strengths.

Data availability statement

The dataset analyzed in this study was obtained through direct collaboration with the management of Hopa Port. Due to commercial sensitivity, the raw data are not publicly available. However, aggregated data that support the conclusions of this article are available from the corresponding author upon reasonable request and with permission from the Hopa Port authority.

Acknowledgments

The authors gratefully acknowledge the cooperation and support of Hopa Port management for providing access to comprehensive operational data and facilitating this research. Artificial intelligence–based tools were utilized to support the language revision and polishing of the English in this manuscript. Final interpretations and all academic judgments belong solely to the authors.

References

Acciaro, M., Vanelslander, T., Sys, C., Ferrari, C., Roumboutsos, A., Giuliano, G., Lam, J.S.L. and Kapros, S. (2014), “Environmental sustainability in seaports: a framework for successful innovation”, *Maritime Policy and Management*, Vol. 41 No. 5, pp. 480-500, doi: 10.1080/03088839.2014.932926.

Ayaz, İ.S., Bucak, U., Mollaoğlu, M. and Esmer, S. (2022), “Resilience strategies of ports against covid-19 in terms of chaos theory”, *Marine Policy*, Vol. 146, 105323, doi: 10.1016/j.marpol.2022.105323.

Barros, C.P. (2003), “The measurement of the efficiency of Portuguese sea port authorities with DEA”, *International Journal of Transport Economics*, Vol. 30 No. 3, pp. 335-354.

Bichou, K. and Gray, R. (2004), “A logistics and supply chain management approach to port performance measurement”, *Maritime Policy and Management*, Vol. 31 No. 1, pp. 47-67, doi: 10.1080/0308883032000174454.

Brooks, M.R. and Cullinane, K. (2006), “Devolution, port governance and performance: the case of North American ports”, *Transport Policy*, Vol. 13 No. 4, pp. 346-354, doi: 10.1016/j.tranpol.2006.01.003.

Cocuzza, E., Ignaccolo, M., Marinacci, C., Ricci, S., Twrdy, E. and Zanne, M. (2025), “Sustainable strategies for ports and maritime logistics”, *Sustainability*, Vol. 17 No. 13, p. 5739, doi: 10.3390/su17135739.

Cullinane, K. and Wang, T.F. (2006), “The efficiency of European container ports: a cross-sectional data envelopment analysis”, *Research in Transportation Economics*, Vol. 16, pp. 331-356, doi: 10.1016/S0739-8859(06)16015-3.

De Langen, P.W. (2004), *The Performance of Seaport Clusters: A Framework to Analyze Cluster Performance and an Application to the Seaport Clusters of Durban, Rotterdam, and the Lower Mississippi, ERIM PhD Series Research in Management No. 58*, Erasmus Research Institute of Management, Rotterdam.

DiMaggio, P.J. and Powell, W.W. (1983), “The iron cage revisited: institutional isomorphism and collective rationality in organizational fields”, *American Sociological Review*, Vol. 48 No. 2, pp. 147-160, doi: 10.2307/2095101.

Ducruet, C. and Lee, S.W. (2006), “Frontline soldiers of globalisation: port–city evolution and regional competition”, *GeoJournal*, Vol. 67 No. 2, pp. 107-122, doi: 10.1007/s10708-006-9037-9.

Fleming, D.K. and Baird, A.J. (1999), “Some reflections on port competition in the United States and Western Europe”, *Maritime Policy and Management*, Vol. 26 No. 4, pp. 383-394, doi: 10.1080/030888399286998.

González, M.M. and Trujillo, L. (2009), “Efficiency measurement in the port industry: a survey of the empirical evidence”, *Journal of Transport Economics and Policy*, Vol. 43 No. 2, pp. 157-192, doi: 10.3828/jtep.2009.43.2.157.

Gu, Y., Chen, Y., Wang, X. and Chen, Z. (2023), “Impact of COVID-19 epidemic on port operations: evidence from Asian ports”, *Case Studies in Transport Policy*, Vol. 12, 101014, doi: 10.1016/j.cstp.2023.101014.

Haralambides, H.E. (2002), “Port competition and hinterland connections”, *Maritime Policy and Management*, Vol. 29 No. 1, pp. 3-19, doi: 10.1080/03088830210138640.

Haralambides, H.E. (2023), “The state-of-play in maritime economics and logistics research (2017-2023)”, *Maritime Economics and Logistics*, Vol. 25 No. 4, pp. 501-520, doi: 10.1057/s41278-023-00265-x.

Jensen, M.C. and Meckling, W.H. (1976), “Theory of the firm: managerial behavior, agency costs and ownership structure”, *Journal of Financial Economics*, Vol. 3 No. 4, pp. 305-360, doi: 10.1016/0304-405X(76)90026-X.

Karagöz, Z. and Geçkil, T. (2023), “Taşımacılık İşletmelerinin Kriz Yönetimi Yaklaşımları: Karadeniz Bölgesi Örneği”, *Five Zero*, Vol. 3 No. 2.

Kishore, L., Pai, Y.P., Ghosh, B.K. and Pakkan, S. (2024), “Maritime shipping ports performance: a systematic literature review”, *Discover Sustainability*, Vol. 4 No. 1, p. 45, doi: 10.1007/s43621-024-00299-y.

Lee, J.S. and Flynn, M. (2011), “Port development in a competitive environment: a balanced perspective”, *Transportation Journal*, Vol. 50 No. 4, pp. 393-412, doi: 10.5325/transportationj.50.4.0393.

Lirn, T.C., Thanopoulou, H.A., Beynon, M.J. and Beresford, A.K. (2004), “An application of AHP on transhipment port selection: a global perspective”, *Maritime Economics and Logistics*, Vol. 6 No. 1, pp. 70-91, doi: 10.1057/palgrave.mel.9100094.

Liu, Z. (1995), “The comparative performance of public and private enterprises: the case of British ports”, *Journal of Transport Economics and Policy*, Vol. 29 No. 3, pp. 263-274, doi: 10.3828/jtep.1995.29.3.263.

Martin, B.P., Marc-Antoine, F., Fabio, C., César, D., *et al.* (2025), “Shipping trade and geopolitical turmoil: the case of the Ukrainian Maritime network”, *Journal of Transport Geography*, Vol. 128, 104342, doi: 10.1016/j.jtrangeo.2025.104342.

Martinez-Budria, E., Diaz-Armas, R., Navarro-Ibanez, M. and Ravelo-Mesa, T. (1999), “A study of the efficiency of Spanish port authorities using data envelopment analysis”, *International Journal of Transport Economics*, Vol. 26 No. 2, pp. 237-253.

Mentzer, J.T., DeWitt, W., Keebler, J.S., Min, S., Nix, N.W., Smith, C.D. and Zacharia, Z.G. (2001), “Defining supply chain management”, *Journal of Business Logistics*, Vol. 22 No. 2, pp. 1-25, doi: 10.1002/j.2158-1592.2001.tb00001.x.

Notteboom, T.E. (2006), “The time factor in liner shipping services”, *Maritime Economics and Logistics*, Vol. 8 No. 1, pp. 19-39, doi: 10.1057/palgrave.mel.9100151.

Notteboom, T.E. and Rodrigue, J.P. (2005), “Port regionalization: towards a new phase in port development”, *Maritime Policy and Management*, Vol. 32 No. 3, pp. 297-313, doi: 10.1080/03088830500139885.

Onay, M.G., Saracoglu, S., Pehlivanoglu, E. and Kaynak, B. (2025), “Impacts of Russia-Ukraine War on air pollution over the Black Sea Region due to changes in maritime transport”, *Atmospheric Pollution Research*, Vol. 16 No. 10, 102613, doi: 10.1016/j.apr.2025.102613.

Pallis, A.A., Vitsounis, T.K. and De Langen, P.W. (2010), “Port economics, policy, and management: review of an emerging research field”, *Transport Reviews*, Vol. 30 No. 1, pp. 115-161, doi: 10.1080/01441640802675633.

Pfeffer, J. and Salancik, G.R. (1978), *The External Control of Organizations: A Resource Dependence Perspective*, Harper & Row, New York.

Polo Martin, B., Faure, M.-A., Cremaschini, F. and Ducruet, C. (2025), “Shipping trade and geopolitical turmoil: the case of the Ukrainian maritime network”, *Journal of Transport Geography*, Vol. 128, 104342, doi: 10.1016/j.jtrangeo.2025.104342.

Porter, M.E. (1980), *Competitive Strategy: Techniques for Analyzing Industries and Competitors*, Free Press, New York.

Rauca, L., Popa, C., Atodiresei, D. and Nedelcu, A.T. (2025), “Port performance and its influence on vessel operating costs and emissions”, *Logistics*, Vol. 9 No. 3, p. 122, doi: 10.3390/logistics9030122.

Roll, Y. and Hayuth, Y. (1993), “Port performance comparison applying data envelopment analysis (DEA)”, *Maritime Policy and Management*, Vol. 20 No. 2, pp. 153-161, doi: 10.1080/03088839300000025.

Slack, B. and Frémont, A. (2005), “Transformation of port terminal operations: from the local to the global”, *Transport Reviews*, Vol. 25 No. 1, pp. 117-130, doi: 10.1080/0144164042000206051.

Song, D.W. and Yeo, K.T. (2004), “A competitive analysis of Chinese container ports using the analytic hierarchy process”, *Maritime Economics and Logistics*, Vol. 6 No. 1, pp. 34-52, doi: 10.1057/palgrave.mel.9100093.

Tang, Z. and Wang, L. (2025), “Shipping decarbonization and public emergencies: how does COVID-19 impact container shipping carbon emissions?”, *Journal of Transport Geography*, Vol. 123, 104124, doi: 10.1016/j.jtrangeo.2025.104124.

Tongzon, J. (2001), “Efficiency measurement of selected Australian and other international ports using data envelopment analysis”, *Transportation Research Part A: Policy and Practice*, Vol. 35 No. 2, pp. 107-122, doi: 10.1016/S0965-8564(99)00049-X.

Tongzon, J. and Heng, W. (2005), “Port privatization, efficiency, and competitiveness: some empirical evidence from container ports (terminals)”, *Transportation Research Part A: Policy and Practice*, Vol. 39 No. 5, pp. 405-424, doi: 10.1016/j.tra.2005.02.001.

Wang, T.F., Cullinane, K. and Song, D.W. (2004), “Container port production efficiency: a comparative study of DEA and FDH approaches”, *Journal of the Eastern Asia Society for Transportation Studies*, Vol. 5, pp. 698-713.

Warren, A. and Gibson, C. (2025), “Maritime port geographies: materiality, labour, and statecraft”, *Geographical Compass*, Vol. 19 No. 3, e70038, doi: 10.1111/gec3.70038.

Wilmsmeier, G., Hoffmann, J. and Sanchez, R.J. (2006), “The impact of port characteristics on international maritime transport costs”, *Research in Transportation Economics*, Vol. 16, pp. 117-140, doi: 10.1016/S0739-8859(06)16006-2.

Winkelmans, W. (2003), “Structural changes in ports: implications for port authorities”, *International Journal of Maritime Economics*, Vol. 5 No. 4, pp. 351-367, doi: 10.1057/palgrave.ijme.9100086.

World Bank (2023), *Container Port Performance Index 2022: A Comparable Assessment of Performance Based on Vessel Time in Port*, World Bank, available at: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099060223183647958/idu0f02f083d0a2a3046b409d9601e3bfa28ba4d

Xu, Y., Zhao, P., Kang, T. and Qin, K. (2025), “Russia–Ukraine war has altered the pattern of carbon dioxide emissions from shipping in the Black Sea region”, *Communications Earth and Environment*, Vol. 6 No. 1, p. 558, doi: 10.1038/s43247-025-02537-1.

Yigitbasioglu, O.M. (2012), “Port sustainability and stakeholder management in supply chains: a framework on resource dependence theory”, *Asian Journal of Shipping and Logistics*, Vol. 28 No. 3, pp. 327-345, doi: 10.1016/j.ajsl.2013.01.002.

Further reading

Erol, S. (2024), “The early impact of the Russia-Ukraine war on seaborne trade and transportation in the Black Sea”, *International Journal of Shipping and Transport Logistics*, Vol. 18 No. 3, pp. 305-323, doi: 10.1504/ijstl.2024.139063.

Sezgin, V. (2022), “How will Ukraine-Russia war affect Turkish trade?”, *Abant Sosyal Bilimler Dergisi*, Vol. 22 No. 2, pp. 546-557, doi: 10.11616/asbi.1091695.

Vinokurov, E.Y., Ahunbaev, A. and Zaboev, A.I. (2022), “International North-south transport corridor: boosting Russia’s ‘pivot to the South’ and Trans-Eurasian connectivity”, *Russian Journal of Economics*, Vol. 8 No. 2, pp. 159-173, doi: 10.32609/j.ruje.8.86617.

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