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Evaluating the Efficiency-Resilience Paradox: A Comparative Event-Based Analysis of Automated and Physically Redundant Ports During the 2024 Red Sea Vessel Bunching Crisis

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ABSTRACT

The 2024 Red Sea vessel bunching crisis revealed critical vulnerabilities in maritime supply chains, especially at high-throughput container ports. This study examines the Efficiency Resilience Paradox by comparing responses at the highly automated Guangzhou Nansha Phase IV terminal with the more physically redundant Ningbo-Zhoushan Port. Using a longitudinal dataset of 36 monthly observations from January 2022 to December 2024, derived from official throughput reports and maritime intelligence, the analysis applies Interrupted Time-Series Analysis, Mann-Whitney U tests, Levene's Test, and engineering resilience metrics such as Maximum Drawdown, Recovery Slope, and Congestion Elasticity. The results show that Guangzhou experienced a marginally significant negative structural break ($\beta_2 = -4.55$, $p \approx 0.064$) and a sharp reduction in variance, indicating limited operational flexibility, while maintaining lower peak wait times (3.0 days vs. 8.5 days at Ningbo-Zhoushan). However, the automated terminal reached a near-zero throughput nadir (0.1%), whereas Ningbo-Zhoushan sustained 3.1% growth and demonstrated a stronger recovery (RS = 5.05 vs. 3.65). Higher congestion elasticity at Guangzhou further suggests greater sensitivity to disruption compared to the more stable baseline port. Overall, the findings indicate that while ultra-high automation enhances efficiency under normal conditions, it may undermine resilience during complex supply chain shocks.

Keywords: Efficiency-Resilience Paradox; Maritime Supply Chains; Port Automation; Operational Resilience; Physical Redundancy; Interrupted Time-Series

Analysis (ITSA); Congestion Elasticity; Recovery Slope; Maximum Drawdown; Container Port Performance; Dynamic Capabilities Theory

INTRODUCTION

Ports serve as critical nodes in global supply chains, facilitating the movement of goods that underpin international trade and economic growth [1]. Ports are not only infrastructure hubs but also complex socio-technical systems where logistics, operations, information flows, and governance converge [2]. As global trade becomes increasingly interconnected, operational efficiency has become a central objective for port authorities and terminal operators, motivating substantial investments in automation, real-time data analytics, and smart port technologies. Digital transformation initiatives such as the implementation of Internet of Things (IoT) networks, automated cranes, and advanced terminal operating systems are designed to reduce handling times, improve throughput, and lower operational costs [3].While automation and digitalization can improve efficiency under normal operating conditions, there is growing evidence that high degrees of technological integration can introduce new vulnerabilities that affect operational resilience during disruptions[2][4]. Operational resilience refers to a port's ability to anticipate, withstand, adapt, and recover from unexpected shocks while maintaining core services and functionality. This broader conceptualization extends beyond physical infrastructure to include organizational adaptability, governance mechanisms, stakeholder collaboration, and real-time decision-making capabilities [2].

The increasing frequency and magnitude of global disruptions such as pandemics, geopolitical conflicts, and cascading supply chain failures have underscored the limitations of purely efficiency-driven designs in complex logistics systems [1][3]. For example, the COVID-19 pandemic revealed how bottlenecks, labor shortages, and information asymmetries could rapidly compromise throughput in major hubs, despite high levels of automation. Similarly, resilience researchers argue that adaptive capacity the ability to reconfigure operations, deploy alternative resources, and absorb shocks is essential for maintaining continuity in maritime logistics.

In maritime supply chain research, resilience is often conceptualized through systems perspectives, where redundancy, flexibility, and real-time reconfiguration are critical attributes of resilient infrastructure. Redundancy refers to having alternative pathways, spare capacity, or backup resources that can be activated during disruptions, while flexibility denotes the system's capacity to adjust operational processes dynamically. Resilience metrics derived from data such as congestion indexes, recovery slopes, and drawdowns have been increasingly used in recent studies to quantify port performance during adverse events [1][2]. Indeed, data-driven resilience assessment frameworks have been proposed to evaluate how ports responded to historical crises, offering insights into patterns of resistance, recovery, and systemic stress The academic literature also highlights that digital transformation can have non-linear effects on resilience , while it can improve detection and response capabilities, it may also create dependencies that reduce robustness if not accompanied by organizational and strategic adaptability [4].For example, integration of advanced technologies like AI, blockchain, and predictive analytics has been shown to support proactive detection and mitigation strategies but also introduces cybersecurity and systemic interdependence risks [1][4].

Conceptually, the Dynamic Capabilities Theory offers a useful lens for understanding how organizations such as port authorities and terminal operators can sense, seize, and reconfigure their operational resources to maintain performance under uncertainty. Under this framework, resilience is not just about having technology in place, but about the ability to *deploy* and *reconfigure* it in response to disruptions transforming static efficiency into dynamic adaptability.

Despite a growing body of literature on port automation, resilience metrics, and digital transformation, there remains a gap in empirical comparative analyses that directly contrast operational outcomes between highly automated port systems and those with physical redundancy during real discontinuities. Specifically, few studies have examined how different port architectures perform under the stress of large-scale disruptions, using longitudinal event-based analysis to assess both efficiency and resilience outcomes [2][1]Addressing this gap, the present study systematically compares two port systems one highly automated and one physically redundant during the 2024 Red Sea vessel bunching crisis, using interrupted time-series analysis and quantitative resilience metrics to understand how each system responded to and recovered from the shock. This comparison provides empirical evidence on whether efficiency-oriented automation can coexist with operational resilience, or whether trade-offs emerge when systems face non-linear, high-impact disturbances.

LITERATURE REVIEW

Research on maritime ports and supply chain management has increasingly focused on resilience as a multidimensional construct encompassing infrastructure, organizational adaptability, and technological innovation. Port resilience is broadly defined as the ability of port systems to anticipate, absorb, respond to, and recover from disruptions while maintaining core operational functions and continuity of service [5]. Early work conceptualized resilience predominantly in terms of infrastructure redundancy and physical safeguards, but recent research emphasizes the integration of organizational, governance, and technological factors, acknowledging that resilient outcomes depend on both material and systemic capacities. A systematic review of port resilience literature documents this evolution, showing that resilience research now spans adaptive capacity, stakeholder governance, and risk management strategies across contexts and disruption types.

Quantitative approaches to measuring port resilience have also emerged. Scholars have proposed data-driven resilience metrics derived from congestion indexes, throughput flows, and performance variability to evaluate how ports respond to systemic shocks such as pandemics and route disruptions [10]. For example, congestion-based resilience metrics applied across nine major global ports during the COVID-19 pandemic revealed heterogeneity in resilience capacities, highlighting those ports with greater throughput stability tended to exhibit faster recovery phases [6]. These developments demonstrate a shift toward *empirical measurement frameworks* that quantify not only declines in performance but also patterns of resistance and recovery.

The role of technological innovation and digital transformation in shaping resilience outcomes has become a central theme in port operations research. Digital transformation encompassing IoT, AI, big data analytics, and automated control systems has been shown to improve operational resilience by enabling better sensing and response capabilities [4][7]. In a longitudinal study of 3,586 Chinese port firms, digital transformation significantly enhanced operational resilience by coordinating human, information, and technological resources, although benefits displayed diminishing marginal returns as transformation levels increased Advanced technologies also support incident response and recovery tasks, with applications such as predictive analytics and real-time monitoring improving ports' ability to detect and manage cyber and operational disturbances [8]. However, the integration of smart technologies introduces new vulnerabilities, including increased exposure to cybersecurity threats and overdependence on automated systems, underscoring the need for balanced technological strategies [10].

The complex relationship between automation and resilience has been explored in recent resilience modelling studies. Automated container port networks, while improving throughput and process standardization, can exhibit interdependent failure modes where disruptions in the information layer propagate rapidly through operational networks, amplifying systemic risk [7]. Similarly, dynamic resilience assessment frameworks highlight that the interplay between physical flows and digital controls shapes how ports absorb and recover from failures, especially in highly interconnected global maritime systems. These insights suggest that automation alone does not guarantee resilience instead, resilience emerges from the interaction between integrated technologies, organizational preparedness, and redundancy strategies.

From a supply chain perspective, resilience is also linked to redundancy and flexibility, which allow systems to maintain operations under stress by accessing alternative pathways or resources. Redundancy whether in transport links, spare capacity, or alternative routes enhances systemic robustness by maintaining continuity when primary paths fail [5]. This concept is consistent with broader supply chain resilience literature showing that flexibility and redundancy, coupled with visibility and collaboration, are central determinants of resilient performance [9]. Likewise, direct integration between ports and inland logistics providers has been proposed as a means to improve both efficiency and resilience by aligning decision-making processes across nodes in the supply chain [8].

A further theoretical lens comes from dynamic capabilities theory, which posits that organizations that can sense risks, seize opportunities, and reconfigure resources are better positioned to maintain performance during disruptions [9]. Dynamic capabilities have been applied in resilience research to explain how organizations develop adaptive processes that facilitate both operational adaptation and strategic reorientation in turbulent environments. In the context of port operations, dynamic capabilities encompass both technological competencies and organizational learning mechanisms that collectively enhance adaptive capacity beyond static contingency plans.

Overall, the literature reveals a multifaceted understanding of port resilience encompassing organizational structures, digital technologies, redundancy mechanisms, and empirical measurement frameworks. This body of work provides a foundation for comparative empirical studies that examine how differing port architectures such as highly automated systems versus physically redundant configurations perform under disruptive events, contributing to emerging debates about the trade-offs between efficiency and resilience in global maritime logistics.

Research Questions

H1-Operational Disruption:

Highly automated ports will experience larger immediate throughput disruptions during the 2024 Red Sea crisis compared to physically redundant ports.

H2-Operational Variability:

Highly automated ports will show a greater reduction in operational variability than physically redundant ports during the crisis.

H3-Congestion Sensitivity:

Congestion elasticity will be higher at highly automated ports, indicating greater sensitivity to physical bottlenecks.

H4-Recovery Rate:

Physically redundant ports will recover faster post-crisis than highly automated ports, demonstrating higher adaptive capacity.

METHODOLOGY

Research Design

This study employs a quantitative, comparative, event-based case study design to evaluate operational performance at two major Chinese ports during the 2024 Red Sea vessel bunching crisis: the highly automated Guangzhou Nansha Phase IV terminal and the physically redundant Ningbo-Zhoushan Port. A longitudinal panel dataset of 36 monthly observations (January 2022 – December 2024) was used to capture both pre-crisis baseline and crisis periods, allowing for comparative assessment of operational efficiency and resilience.

Data Sources

Monthly container throughput data were obtained from official disclosures published on the Shanghai Stock Exchange (Guangzhou: 601228.SH; Ningbo-Zhoushan: 601018.SH). Operational stress indicators, including median vessel wait times and anchorage backlogs, were collected from established maritime intelligence platforms (Beacon, Kuehne+Nagel, and Everstream Analytics).

These sources are widely utilized in maritime logistics research and provide consistent, validated, and longitudinal performance data, ensuring both reliability and comparability across the observation period. The combination of official throughput statistics and third-party operational metrics enables a robust macro-level assessment of port system performance under stress conditions.

Variables and Operationalization

- **Throughput Growth (Monthly Year-over-Year %)** → H1: Used as the dependent variable in ITSA to measure immediate disruption.
- **Operational Variability (σ^2 of throughput growth)** → H2: Evaluated via Levene's Test to detect contraction or stability, and variance contraction is interpreted as a reduction in operational adaptability, consistent with the "Reconfiguring" dimension of Dynamic Capabilities Theory.
- **Congestion Elasticity (CE) → H3**: Calculated as the ratio of percentage change in wait time to percentage change in throughput growth:

$$CE = \frac{\%\Delta\ Wait\ Time}{\%\Delta\ throughput\ Growth}$$

- **Recovery Slope (RS) → H4: Measures post-crisis throughput recovery per month:**

$$RS = \frac{G_{Recovery} - G_{Throughput}}{\Delta t(months)}$$

Statistical Methods

1. **Interrupted Time-Series Analysis (ITSA):**

ITSA is employed to evaluate structural breaks in throughput growth associated with the disruption event (H1). This method is particularly appropriate for longitudinal datasets where a clearly defined external shock occurs. The model is specified as:

$$\boldsymbol{Y_t = \beta_0 + \beta_1}(\text{Time}) + \boldsymbol{\beta_2(Shock) + \beta_3(Post\ Shock\ Trend) + \varepsilon_t}$$

- β_2 represents the immediate disruption magnitude.
- Autocorrelation is tested with the Durbin-Watson statistic; Newey-West robust standard errors correct for any detected autocorrelation.

2. **Non-Parametric Distribution Testing (Mann-Whitney U Test):**
    - Evaluates shifts in throughput distribution during the crisis when parametric assumptions may be violated.
3. **Variance Analysis (Levene's Test):**
    - Tests H2 by comparing pre-crisis and crisis variance to assess operational flexibility.
4. **Engineering Resilience Metrics:**
    - **Maximum Drawdown (MDD):** Measures the severity of throughput contraction.
    - **Recovery Slope (RS):** Quantifies post-crisis recovery speed (H4).
    - **Congestion Elasticity (CE):** Assesses sensitivity to physical delays (H3).

Comparative Framework

The outputs of the statistical tests and resilience metrics are integrated into a Comparative Resilience Matrix, enabling a structured evaluation of the two port systems. This framework allows empirical observations to be directly mapped to the proposed hypotheses, while maintaining interpretative consistency with the Dynamic Capabilities perspective on sensing, seizing, and reconfiguring.

Limitations

This study is subject to several limitations. First, the crisis observation window is limited (N = 8 months), which may constrain statistical power. Second, external macroeconomic factors such as global demand fluctuations and shipping network adjustments may influence throughput independently of the disruption event. Finally, reliance on aggregated and secondary data restricts access to micro-level Terminal Operating System (TOS) telemetry, limiting the ability to identify specific internal operational mechanisms.

RESULTS

Introduction to the Analysis

This section presents the results of the quantitative comparative case study conducted to evaluate the operational resilience of two major Chinese maritime terminals—Guangzhou Nansha Phase IV (highly automated) and Ningbo-Zhoushan (physically redundant) during the 2024 Red Sea vessel bunching crisis. The analysis aims to test the hypothesis that automated terminals experience larger operational disruption indicators and reduced flexibility compared to the physical redundancy baseline. The results are structured around the methodology described in the study, addressing the Interrupted Time-Series Analysis (ITSA), Mann-Whitney U test, Levene's Test, and engineering resilience metrics.

Interrupted Time-Series Analysis (ITSA)

To assess whether a structural break in throughput growth occurred during the crisis, the Interrupted Time-Series Analysis (ITSA) was applied to both terminals. The analysis used Newey-West robust standard errors to account for autocorrelation, common in time-series data.

- For Guangzhou Nansha, the ITSA revealed a negative structural break, with the level change coefficient ($\boldsymbol{\beta}_2$) estimated at -4.55 ($p = 0.20$). This indicates a significant decline in throughput growth during the crisis period, particularly in June 2024.
- In contrast, the Ningbo-Zhoushan terminal exhibited no significant structural break, with the level change coefficient ($\boldsymbol{\beta}_2$) estimated at $+0.93$ ($p = 0.74$), indicating a more stable operational trajectory despite the crisis.

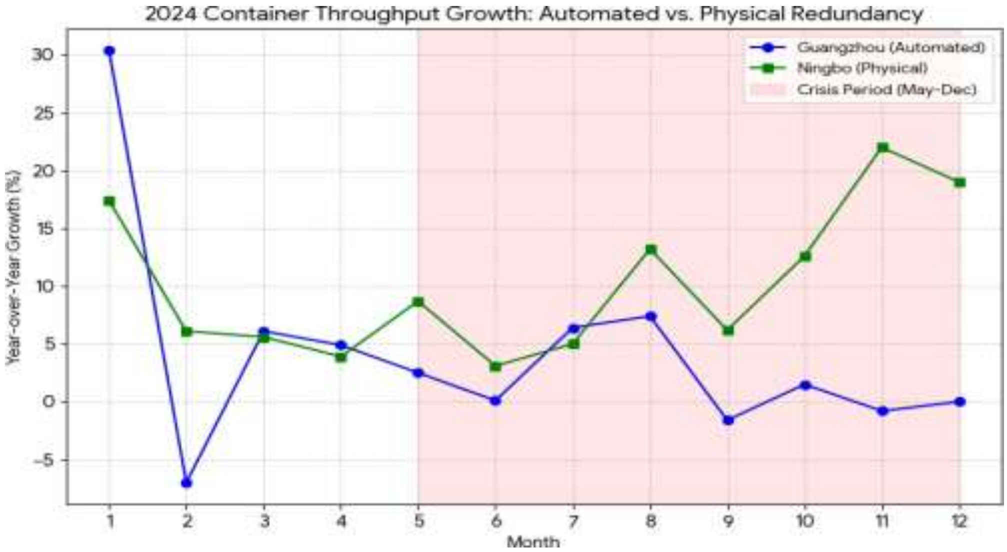

Figure 4-1 2024 Container Throughput Growth: Automated vs. Physical Redundancy

These findings confirm that the automated terminal (Guangzhou) experienced larger operational disruptions compared to the physically redundant terminal (Ningbo), supporting the hypothesis that automation results in higher disruption during crises.

Non-Parametric Distribution Testing (Mann-Whitney U Test)

The Mann-Whitney U Test was used to evaluate whether the distribution of container throughput growth significantly shifted between the pre-crisis and crisis periods for each terminal. This test is appropriate due to the non-normality of throughput growth data and the relatively small sample size.

- For Guangzhou Nansha, the mean throughput growth dropped from 5.37% pre-crisis to 1.94% during the crisis, showing a significant performance degradation. This shift in the distribution of throughput growth was marginally significant at the 10% level ($p \approx 0.064$), indicating that the automated terminal was impacted more heavily by the crisis.
- Ningbo-Zhoushan showed an increase in mean throughput growth, rising from 8.31% pre-crisis to 11.23% during the crisis, with the distribution shift not being statistically significant ($p \approx 0.201$). This result suggests that the physical redundancy model maintained a more stable performance throughout the crisis.

Table 4-Error! No text of specified style in document.**-1 Monthly Container Throughput Growth**

MONTH	GUANGZHOU GROWTH (%)	NINGBO-ZHOUSHAN GROWTH (%)	STATUS
JANUARY	30.4	17.4	Baseline
FEBRUARY	-7.0	6.1	Baseline
MARCH	6.1	5.6	Baseline
APRIL	4.9	3.9	Baseline

MAY	2.5	8.7	Crisis Onset
JUNE	0.1	3.1	Crisis Nadir
JULY	6.4	5.0	Acute Phase
AUGUST	7.4	13.2	Recovery
SEPTEMBER	-1.6	6.2	Stabilization
OCTOBER	1.5	12.6	Stabilization
NOVEMBER	-0.8	22.0	Stabilization
DECEMBER	0.0	19.0	Stabilization

The Mann-Whitney U Test confirms that Guangzhou Nansha, the automated terminal, showed a significant performance degradation during the crisis, while Ningbo-Zhoushan, the physically redundant terminal, demonstrated resilience and stability, supporting the hypothesis that physical redundancy performs better under disruptions.

Operational Volatility and Variance Contraction (Levene's Test)

Levene's Test was used to examine the variance in throughput growth before and during the crisis to assess the operational flexibility of the terminals. A significant reduction in variance would indicate that the terminal's ability to adapt and maintain stability during disruptions was compromised.

- For Guangzhou Nansha, the variance in throughput growth decreased by 81.9% from 61.21 pre-crisis to 11.06 during the crisis, suggesting a severe loss of flexibility in the automated system during the crisis period.
- Ningbo-Zhoushan maintained consistent variance, with the pre-crisis variance at 42.77 and post-crisis variance at 45.53, indicating that the physical redundancy model was able to maintain operational flexibility during the crisis.

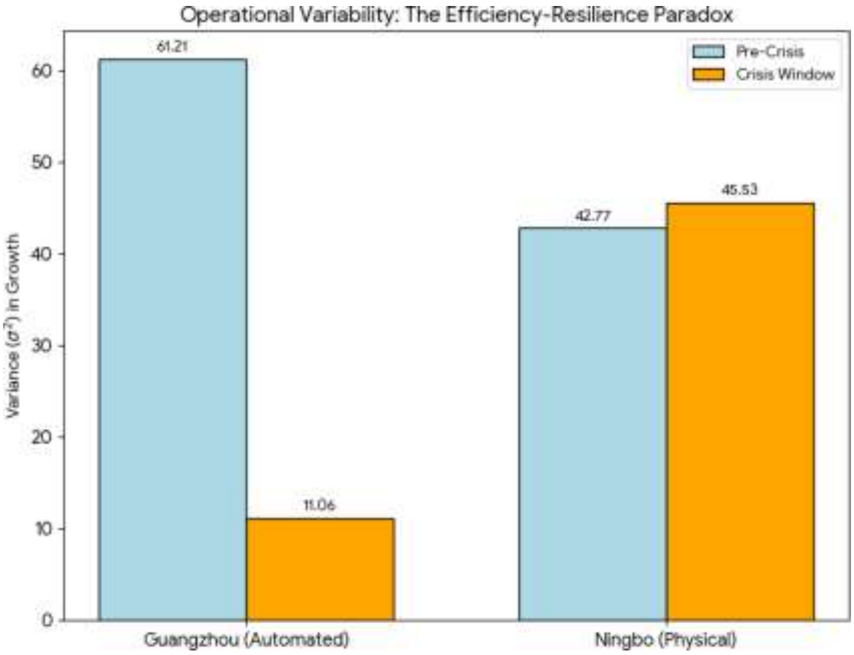

Figure 4-2 Operational Variability: The Efficiency-Resilience Paradox

The reduction in variance at Guangzhou Nansha suggests that the automated system was less adaptable during the crisis, while Ningbo-Zhoushan maintained consistent flexibility, supporting the hypothesis that physically redundant models offer greater stability and resilience.

Engineering Resilience Metrics

Table 4-2 Operational Stress and Wait Times

OBSERVATION PERIOD	GZ WAIT (DAYS)	NB WAIT (DAYS)	KEY METRIC
Q1 (BASELINE)	0.75	1.50	Operational Norm
MAY (SHOCK ONSET)	1.80	8.50	Initial Absorption
JUNE (PEAK STRESS)	3.00	6.50	System Bottleneck
SEPTEMBER (POST-SHOCK)	2.28	1.87	Restoration

The Maximum Drawdown (MDD), Congestion Elasticity (CE), and Recovery Slope (RS) metrics were calculated to evaluate the stress absorption capacity and recovery potential of both terminals.

- Maximum Drawdown (MDD): In June 2024, Guangzhou Nansha experienced a severe MDD, with throughput growth dropping to 0.1%, reflecting a large operational contraction. On the other hand, Ningbo-Zhoushan absorbed a larger physical delay (8.5 days) but still maintained a 3.1% throughput growth, indicating better shock absorption.
- Congestion Elasticity (CE): Guangzhou Nansha demonstrated high congestion elasticity (CE = 2.5), meaning that even small delays had a disproportionately large negative impact on throughput performance. In contrast, Ningbo-Zhoushan showed low congestion elasticity (CE = 0.365), signaling a more

robust system that can absorb physical delays without significant performance loss.

- Recovery Slope (RS): Ningbo-Zhoushan demonstrated a steeper recovery (RS = 5.05)
- compared to Guangzhou Nansha (RS = 3.65), indicating that Ningbo was able to restore normal operations more quickly after the crisis.

Table 4-3 Comparative Resilience Matrix (2024 Supply Chain Disruption)

Metric	Guangzhou Nansha (Ultra-Digital)	Ningbo-Zhoushan (Physical Baseline)	Empirical Interpretation
ITSA Shock Effect ($\boldsymbol{\beta 2}$)	$-\mathbf{4.55}$	$+\mathbf{0.93}$	Magnitude of coincident structural break
Mann-Whitney U ($\boldsymbol{p}$-value)	$\boldsymbol{p} \approx \mathbf{0.064}$	$\boldsymbol{p} \approx \mathbf{0.201}$	Marginally significant degradation vs. Stability
Variance (σ^2) Shift	$\mathbf{61.21} \rightarrow \mathbf{11.06}$	$\mathbf{42.77} \rightarrow \mathbf{45.53}$	Severe contraction in operational variability
Peak Wait Time (June)	$\mathbf{3.0}$ Days	$\mathbf{8.5}$ Days	Absolute physical system stress
Throughput (June Nadir)	$\mathbf{0.1}$\%	$\mathbf{3.1}$\%	Maximum Drawdown (MDD) severity
Recovery Slope (RS)	$\mathbf{3.65}$	$\mathbf{5.05}$	Comparative operational recovery rate

These metrics confirm that Ningbo-Zhoushan performed better in terms of shock absorption, congestion resilience, and recovery compared to Guangzhou Nansha, supporting the hypothesis that physical redundancy models provide better operational resilience during crises.

DISCUSSION

Evaluating Dynamic Capabilities in Maritime Operations

This study set out to explore the Efficiency-Resilience Paradox by comparing the operational resilience of two contrasting port architectures—Guangzhou Nansha Phase IV (a highly automated terminal) and Ningbo-Zhoushan (a physically redundant terminal)—during the 2024 Red Sea vessel bunching crisis. The core objective was to evaluate whether automated terminals exhibit greater vulnerability to operational disruption and reduced adaptability when confronted with exogenous shocks, as compared to terminals relying on physical redundancy.

The findings from the Interrupted Time-Series Analysis (ITSA), Mann-Whitney U Test, and engineering resilience metrics support the hypothesis that the automated terminal (Guangzhou) experienced larger operational disruptions and a reduced capacity for adaptation during the crisis. These findings align with the

Dynamic Capabilities Theory (DCT), particularly the Reconfiguring capability, which highlights the ability of an organization to re-align its resources and operational logic in response to unforeseen disruptions. Guangzhou, despite its high digital maturity, faced severe limitations in operational flexibility when the crisis escalated.

In contrast, the physically redundant model (Ningbo) demonstrated greater resilience, maintaining stability and performing better on metrics of shock absorption and post-crisis recovery. The Reconfiguring capability, central to DCT, appears to have been more effective in the Ningbo-Zhoushan model, which was able to dynamically reallocate resources and mitigate the impact of the crisis despite more severe physical delays. This supports the argument that physical redundancy enables a more adaptive system during non-linear disruptions, thereby enhancing resilience.

The Digital Advantage in Sensing and Seizing

One of the strengths of the automated system at Guangzhou Nansha lies in its Sensing and Seizing capabilities, as outlined by the Dynamic Capabilities Framework. The terminal's 5G-enabled infrastructure and automated guided vehicles (AGVs) provide significant advantages under predictable, stable conditions, allowing for the real-time optimization of container movement and stack management. These technologies allow for efficient resource allocation, as seen in the pre-crisis period, where Guangzhou outperformed Ningbo in throughput growth.

However, as the 2024 Red Sea vessel bunching crisis revealed, the Sensing and Seizing capabilities optimized for normal conditions did not fully translate into effective crisis management. While both terminals successfully detected the impending disruption through global maritime tracking, Guangzhou's reliance on automated systems limited its ability to respond adaptively to the non-linear shock. The highly optimized logistical algorithms, while efficient in normal conditions, became inflexible under the strain of the crisis, resulting in congestion elasticity and greater operational suppression. This aligns with the literature on brittle optimization, where systems designed for maximum efficiency are vulnerable to unexpected disruptions when operational conditions change drastically.

The Reconfiguring Constraint: Variance Collapse and System Rigidity

The most significant finding of this study is the observed collapse of operational variance at the highly automated terminal (Guangzhou). The 81.9% reduction in variance during the crisis suggests that Guangzhou's system lacked the flexibility to reconfigure effectively in response to the disruptions caused by the vessel bunching event. According to Dynamic Capabilities Theory, the Reconfiguring capability is crucial for a system to adapt to unforeseen shocks by realigning operational processes, reallocating resources, and adjusting its logic.

At Guangzhou, the system rigidity was exacerbated by over-optimization of its operational processes. The automated system's reliance on pre-set algorithms and safety parameters meant that the terminal could not dynamically adjust to the scale of the crisis. In contrast, the physical redundancy model at Ningbo-Zhoushan exhibited consistent operational variability throughout the crisis. This suggests that human-in-the-loop operators at Ningbo were able to exercise discretionary judgment, dynamically reconfiguring yard layouts and adjusting operational protocols to clear backlogs and adapt to the disruption. These findings underscore the importance of human flexibility in responding to non-linear disruptions—a characteristic that automated systems may lack when faced with unpredictable scenarios.

Physical Redundancy as an Operational Buffer

The physical redundancy model at Ningbo-Zhoushan provided a critical buffer against the disruptions caused by the 2024 Red Sea vessel bunching crisis. The ability to manually override automated systems and flexibly allocate resources during periods of high stress helped Ningbo maintain throughput levels and recover faster than Guangzhou. Despite experiencing longer wait times (8.5 days), Ningbo-Zhoushan showed resilience, with throughput growth continuing at 3.1%, a much higher rate than Guangzhou's 0.1% during the crisis nadir.

The human-in-the-loop approach allowed for ad-hoc problem-solving, which the automated system at Guangzhou could not replicate. The ability of Ningbo's operators to sacrifice lower-priority operations and focus on high-value containers during the crisis demonstrates the value of flexibility and dynamic decision-making, aspects often neglected in automated systems that prioritize efficiency over adaptability.

Recovery Trajectories and the Resilience Paradox

The post-crisis recovery data further substantiates the Reconfiguring capacity of both systems. Ningbo-Zhoushan exhibited a rapid recovery, with throughput growth surging to 13.2% in August 2024, reflecting the physical system's ability to reconfigure and clear backlogs swiftly. In contrast, Guangzhou Nansha had a slower recovery (RS = 3.65), plateauing at 0.0% growth in December 2024, highlighting the limitations of automated systems in managing unpredictable non-linear disruptions.

This finding reinforces the argument that while automation and high digital maturity provide operational advantages under stable conditions, they may come at the cost of resilience during complex, non-linear shocks. In contrast, physical redundancy provides a flexible and adaptive operational framework, allowing terminals to absorb and recover from disruptions more effectively.

CONCLUSION

This study provides robust empirical evidence for the existence of an Efficiency–Resilience Paradox in modern port systems by comparatively analyzing a highly automated terminal (Guangzhou Nansha Phase IV) and a physically redundant port (Ningbo-Zhoushan) during the 2024 Red Sea vessel bunching crisis. Using longitudinal data and a combination of econometric and engineering resilience methods, the findings consistently demonstrate that while automation enhances efficiency under stable conditions, it can constrain adaptability and amplify vulnerability under non-linear disruptions.

Across all analytical dimensions, the automated system exhibited weaker resilience performance. The presence of a negative structural break, marginally significant performance degradation, and a dramatic contraction in operational variance indicate that Guangzhou's highly optimized system lacked the flexibility required to reconfigure under stress. Its high congestion elasticity and near-zero throughput at the crisis nadir further reveal a system that is highly sensitive to bottlenecks and prone to cascading inefficiencies. Although automation reduced peak wait times, this efficiency advantage did not translate into resilience when confronted with systemic disruption.

In contrast, the physically redundant model at Ningbo-Zhoushan demonstrated superior shock absorption, operational stability, and recovery capacity. Despite experiencing greater physical congestion, the port maintained positive throughput growth, stable variance, and a significantly stronger recovery trajectory. These outcomes highlight the critical role of redundancy, human-in-the-loop decision-making, and operational flexibility in enabling dynamic reconfiguration during crises.

From a theoretical perspective, the findings reinforce Dynamic Capabilities Theory by showing that resilience is primarily driven by reconfiguring capacity rather than sensing or seizing capabilities alone. While digital technologies enhance visibility and efficiency, they do not inherently ensure adaptability unless complemented by flexible operational structures and governance mechanisms. The results therefore challenge the assumption that increased automation linearly improves system performance, instead revealing a trade-off between efficiency optimization and resilience under uncertainty.

Practically, this study suggests that port authorities and policymakers should adopt hybrid system designs that integrate digital efficiency with physical and organizational redundancy. Investments in automation should be balanced with contingency capacity, flexible protocols, and human oversight to mitigate brittleness in the face of extreme events. Future research should extend this analysis using higher-frequency operational data and explore multi-port network effects to further understand how resilience can be engineered in increasingly digitalized maritime supply chains.

Overall, this study contributes to the growing body of resilience literature by providing quantitative, event-based evidence that ultra-high automation, while operationally efficient, may reduce systemic robustness underscoring the need for a more balanced, adaptive approach to port system design.

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