Vol. 13 (2026): Proceedings of the 3rd International Conference on Business, Management and Sustainability (ICBMS 2026)
E-ISSN: 3105-0522 P-ISSN：3105-0514
DOI: https://doi.org/10.70267/ icbms.2601.313319

The Economic Impacts of Automation in the Port Industry

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Abstract

The rapid digitalization of global maritime logistics has positioned port automation as a transformative force, but the theoretical understanding of its systemic economic implications is still insufficient. This study investigates the welfare consequences of automation-induced market restructuring across multiple economic agents within oligopolistic port governance frameworks. Through comparative case analysis of Shanghai's Yangshan Deep-Water Port, Qingdao Automated Terminal, and the Port of Rotterdam, the research synthesizes operational data, labor statistics, and cybersecurity incident reports to evaluate distributional effects. The findings reveal three interrelated pathologies: natural monopoly consolidation wherein the top decile of automated ports commands 40% of global container throughput; labor market polarization reducing traditional dockworker complements by approximately 70% while generating substantial skill premiums; and negative externalities manifesting as systemic cyber-vulnerability, with documented disruptions demonstrating cascadic supply chain contagion and unpriced social costs. These findings challenge efficiency-centric narratives by demonstrating that automation amplifies market concentration, exacerbates income stratification, and externalizes digital risk. The study contributes to transportation economics literature by formalizing the efficiency-resilience-equity trilemma inherent in port digitalization and provides an evidence base for regulatory interventions including cybersecurity subsidies and just-transition labor frameworks.

Keywords

port automation, intelligent economy, cybersecurity vulnerability, supply chain resilience

1. Introduction

In an era of rapidly expanding international trade, ports, as the backbone of maritime transportation, are under increasing pressure to enhance production efficiency in order to survive intense global competition. The rise of port automation, referring to the integration of advanced technologies and artificial intelligence into port systems, has brought about a profound transformation in the port infrastructure market. Shanghai’s Yangshan Deep-Water Port, the world’s largest automated container terminal, exemplifies this transformation by handling 51% of Shanghai’s total container throughput and achieving over 90% of its operational efficiency through AI-driven systems. However, this efficiency-driven transformation comes with substantial social and economic risks that are rarely fully addressed. Such as natural monopoly, negative externalities and factor income polarization.

Forty percent of global container throughput is concentrated in the top 10% of ports, all of which are pioneers in automation [1]. Yangshan Port handles approximately 26 million TEUs of container throughput, accounting for about 51% of Shanghai Port's total cargo volume. Over half of Shanghai Port's cargo throughput is located at Yangshan Port, situated in the outer sea, and Yangshan Port contributes more than 90% of Shanghai Port's container throughput [2]. It captured the majority of the market share, subsequently forming a natural monopoly trend.

These smart ports rely heavily on digital systems due to their high level of automation, even with over 90% of tasks performed by computer systems. As port systems become increasingly digitized and automated, cyberattacks could paralyze servers, cause automated equipment to malfunction, or compromise data integrity, ultimately disrupting logistics operations. In recent years, cyberattack shave disrupted infrastructures at the ports of Antwerp [3]. The most impactful cyberattack on the maritime sector to date was NotPetya in 2017, when the Danish logistics and transports company Maersk suffered significant business disruption and 76 port terminals were affected [4, 5]. Navigating cyber resilience in seaports: challenges of preparing for cyberattacks at the Port of time Rotterdam.

Port automation is often accompanied by significant job opportunities losses, particularly in traditional manual labor positions. In the UK alone, automation caused the number of port workers to decline from 140,000 in the early 1960s to 30,000 by 2000 [6]. Furthermore, taking Qingdao Port in China as an example, as one of the world's most automated container terminals, its automation system has reduced labor costs by 70%, leading to a sharp decline in demand for traditional labor [7]. Moreover, Automation will result in are duction of $476.32 million to $743.89 million in local traditional port worker expenditures and a decrease of 2,445 to 3,818 jobs [8]. But in Prince Rupert, some highly skilled dockworker positions command annual salaries exceeding $100,000 [9]. This has only served to widen the wealth gap between different workers.

2. Economic Mechanism

2.1 Market Power

Oligopoly refers to a market structure in which a small number of firms dominate a large share of the market and exercise substantial control over pricing and output levels. In the port infrastructure market, geographical location creates high barriers to entry, allowing a limited number of ports—such as Shanghai's Yangshan Deep-Water Port and the Port of Rotterdam—to gain significant market power due to their uniquely advantageous locations. However, oligopolistic markets are often subject to the prisoner's dilemma, a game-theoretic concept in which firms acting to maximize individual utility ultimately fail to achieve collective welfare optimization. Each port strives to outperform its competitors by enhancing efficiency and profitability, which incentivizes all firms to continuously increase their level of automation. This competitive dynamic encourages excessive investment in automation, potentially leading to an unreasonably high level of technological adoption without corresponding welfare gains.

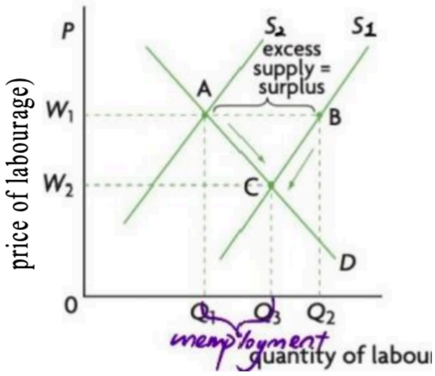
2.2 Unemployment & Labor Market

Furthermore, port automation is frequently accompanied by substantial job losses, particularly in traditional manual labor positions. Automated machinery allows ports to operate continuously, 24 hours a day, without incurring additional wage costs, leading ports to increasingly substitute capital for labor, as discussed previously. This shift directly results in the reduction in traditional port worker expenditures, along with the a substantial cut in job vacancies; these consequences are directly associated with port automation to some extent [10]. According to Figure 2.2, low-income groups may experience further wage reductions, leading to an overall decline in living standards. Moreover, demand-pull inflation may emerge in low-income countries, resulting in lower national output and rising price levels, which further depress living standards.

2.3 Externalities

Heavy reliance of smart ports on digital systems increases the vulnerability and volatility of the marine supply chain, which amplifies the impact of cyber threats, as the breakdown of a single subsystem may trigger cascading failures across the entire port. As global supply chains become increasingly interconnected, with over 90% of operational tasks performed by computer-based systems, successful cyberattacks have the potential to generate widespread disruption on a global scale. Such cyberattacks often involve actions that paralyze servers, cause automated equipment to malfunction, or compromise data integrity, thereby directly disrupting port logistics operations. Empirical evidence demonstrates the severity of this risk. Consequently, both directly target identities, such as terminal operators, and downstream stakeholders, including logistics companies and cargo owners, are exposed to significant operational risks.

Figure1: Impact on Labor Market



3. Case & Data Analysis

3.1 Qingdao Port

As a leader in smart maritime operations, Qingdao Port has transitioned from “Made in China “to “Created in China” [11]. The fully automated terminal marks a strategic shift toward a high-tech operational paradigm. Its single-crane efficiency reaches 42. 23 containers per hour with a world- record peak of 60. 2 [12], significantly exceeding the global conventional average of25-28 containers per hour. This efficiency reduces marginal costs and serves as the core competitiveness for attracting cargo flow. In the Bohai Rim, this technological edge has consolidated Qingdao's market power, with annual throughput exceeding 700 million tons [13]. Within the Shandong port cluster, Qingdao Port accounts for approximately 36% of total cargo throughput and a dominant 71% of container volume [14], establishing it as the region's primary container hub. Studies confirm that such high efficiency accelerates the concentration of cargo toward top-tier hubs [15]. Furthermore, the deployed Port Center ICT System enhances port community synergy, while BIM-based smart construction [16] secures a long- term, resilient supply chain advantage.

Qingdao Port's highly digitized ecosystem—with 90%of its operational tasks relying on digital systems—exemplifies the “single point of failure” risk inherent in over-automation [11]. While BIM and Smart Worksite technologies enable a record 60. 2 TEU/hour efficiency, this dependency ensures that any cyber-interference triggers cascading effects. Disruptions discussed by Baixun [17] export operational risks to downstream providers as uncompensated negative externalities. As annual throughput exceeds 700 million tons, localized paralysis causes a cyber-contagion. According to Ma et al. [18], these disruptions impose unpriced social costs, such as inventory spoilage for local manufacturers. Given Qingdao Port handles 25-30% of China-Japan-South Korea trade (valued at 150-180 billion euros annually) and over 700 million tons of annual throughput, even a temporary localized paralysis could spark a “cyber-contagion” across East Asian supply chains.

Qingdao Port's automation has triggered a radical structural shift in labor demand. The transition to fully automated terminals has achieved a 70% reduction in labor costs, leading to a sharp decline in demand for traditional manual roles [19] While the port sets global benchmarks for Intelligent Manufacturing, “this progress masks significant job losses. Historically, port automation has decimated worker counts as seen in the UK where workforce numbers fell from 140, 000 to 30, 000 and Qingdao mirrors this through capital-labor substitution for quay crane operators and drivers [20]. The shift has institutionalized a stark wage stratification. The market now aggressively favors a technical elite, creating a substantial skill premium. While high-skill dockworkers in automated hubs can command salaries exceeding $100, 000, displaced manual workers face income erosion. This disparity reflects a polarized distribution where the financial rewards of innovation are concentrated among technical insiders, while the marginalized manual workforce bears the brunt of structural unemployment [21].

3.2 Port of Rotterdam

Another concrete real-life case is the Port of Rotterdam. Container throughput at the Port of Rotterdam stood at 6. 28 million TEUs in 2000, prior to large-scale automation, and rose to 13. 8 million TEUs by 2024 following automation, with further productivity improvements expected as technology continues to evolve. However, despite awareness of the potential welfare losses associated with automation, the Port of Rotterdam faces a classic prisoner's dilemma, as do other major European ports. If competing ports such as Hamburg adopt automated systems, Rotterdam must do the same to avoid profit losses. Conversely, even if competitors refrain from automation, Rotterdam still has an incentive to automate in order to increase profits. Consequently, the dominant strategy for each port is to expand automation, resulting in similar profit levels across ports while imposing welfare losses on third parties within the economy.

Figure 2: Prisoner dilemma between ports

Port B	Port A	
use automated systems	Port A receives same profit Port B receives same profit	Port A receives lower profit Port B receives higher profit
do not use automated systems	Port A receives higher profit Port B receives lower profit	Port A receives same profit Port B receives same profit

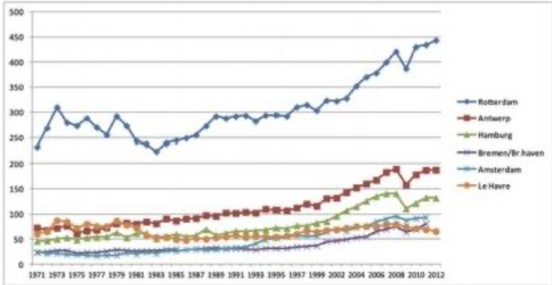
To increase its level of automation, the Port of Rotterdam has allocated a substantial proportion of its budget to acquiring and developing advanced technologies. Estimates suggest that developing an automated crane system alone requires approximately USD 80-120 million. Investment in AI software alone can exceed USD 6. 5 million, excluding additional integration and operational costs

such as data infrastructure development. Reports indicate that the Port of Rotterdam has invested approximately EUR 200 million in automation and AI infrastructure. Despite rapid technological progress, the cost of automation has declined only gradually. As a result, the initial investment required for automated ports is expected to remain high in the foreseeable future, with average payback periods estimated at approximately six years.

High financial costs have prevented smaller ports in the region from adopting automation technologies. Even prior to widespread automation, the European port sector already exhibited a high concentration ratio, with container throughput dominated by a small number of leading ports. In 2008, the Port of Rotterdam accounted for 26. 8%of total container volume in the Hamburg-Le Havre range. Over time, superior efficiency and lower unit handling costs at major ports have attracted shipping lines and cargo owners, further intensifying market concentration. Ports handling fewer than 0. 5 million TEUs annually typically operate with profit margins of only 15%to 25%, which are insufficient to finance large-scale automation investments.

As illustrated in Figure 3, container throughput increased from 2 million TEUs in 1980 to 12 million TEUs in 2010, while employment levels declined sharply. Container throughput increased from 2 million TEUs in 1980 to 12 million TEUs in 2010, while employment levels declined sharply. Historically, the port employed approximately 180, 000 workers, accounting for 19%of total employment in the Rotterdam-Rijnmond region. Automation is projected to reduce employment in the Dutch maritime sector by 25%, implying that around 45, 000 workers associated with the Port of Rotterdam may face displacement. By the end of 2024, only 1, 392 employees and 185 external contractors remained directly employed by the Port Authority.

Figure 3: Total cargo output in main NW-European ports [22]



Finally, excessive reliance on digital systems increases vulnerability across the European supply chain. Cyberattacks may paralyse servers, disrupt automated equipment, or compromise data integrity. Despite investing approximately EUR 50 million in cybersecurity, the Port of Rotterdam has experienced cyber incidents that temporarily shut down internet and website services. Estimates suggest that a large-scale cyberattack could generate losses of up to USD 110 million if disruptions spread to other ports simultaneously

4. Practical Proposal

4.1 Policy I: Government Subsidies for Data Security

Cyber threats targeting the Port of Rotterdam have become increasingly frequent in recent years. Given the port's critical role in national trade and essential supply chains, prolonged shutdowns could severely disrupt the Dutch economy. As the development of advanced cybersecurity systems can cost hundreds of millions of euros, government subsidies could support ports in strengthening digital defences. This policy would ensure continuity in international trade and prevent large-scale economic losses arising from cyberattacks. Without adequate protection, supply chain disruptions could undermine firm profitability and investor confidence, reducing aggregate demand and national output in the long run.

4.2 Policy II: Re-training program

One good policy to address the problem of structural unemployment is the agreement on the duration of employment contracts, providing job security and offering the re-training programs. Aim to ensure the employment of labour by legal protection, thus the workers will not be laid off after the introduction of automation. Taking Port of Rotterdam as an example, in 2016, the employment guarantee agreement reached between the port authority, the trade union [23], and the terminal operator provided job security and re-employment mobility measures for employees who had obtained permanent contracts before 2015 during the agreement period, including early retirement support and internal job reallocation mechanisms, thereby alleviating the impact of automation on the employment of port workers [24]. Moreover, the Port of Rotterdam region has made up for the shortcomings of a single agreement through multi-party cooperation such as the "Port of Energy" project and other re-training and labour market support programs, that are supported by Just Transition Fund, to improve cooperation between the education system and the labour market, aimed at motivating, training and re-educating the necessary human resources, by the end of 2024, 370 job seekers have successfully found employment in port enterprises, indicating that such policies have achieved concrete results in attracting talents and promoting employment [25].

5. Conclusion

Port automation represents a paradoxical paradigm in global maritime logistics, simultaneously enhancing operational efficiency while exacerbating systemic vulnerabilities. This study demonstrates that automated terminals, exemplified by Qingdao Port and Port of Rotterdam, achieve unprecedented throughput rates yet concentrate market power, creating natural monopolies that marginalize smaller competitors. Furthermore, digitalization introduces critical supply chain fragilities through cyber- vulnerability and cascading disruption risks. The socioeconomic consequences manifest as structural unemployment and widening wage disparities, with manual laborers displaced while technical elites capture disproportionate economic rents. Effective policy interventions—including transparent pricing protocols, employment security agreements, and workforce retraining programs—remain essential to balance technological advancement with equitable labor transitions and supply chain resilience. However, such subsidies would place pressure on government budgets, potentially limiting funding for welfare or infrastructure development. In addition to the subsidies, the plan of offering re-training program has obvious limitations: the employment guarantee has a time limit and does not cover all types of workers. During the subsequent negotiations regarding the implementation of automation, conflicts still arose between the unions and the port authority. This indicates that the social dialogue mechanism needs to be more institutionalized and long-term.

References

[1] Li, Y., Chang, D., Gao, Y., Zou, Y., & Bao, C. (2021). Automated Container Terminal Production Operation and Optimization via an AdaBoost-Based Digital Twin Framework. Journal of Advanced Transportation, 2021(1), 1936764.

[2] Zou, Y., & Wang, R. (2025). Decoupling analysis and scenario prediction of port carbon emissions: A case study of Shanghai Port, China. Sustainability, 17(13), 6192.

[3] Houston, J., Zuidhof, G., Bergamini, L., Ye, Y., Chen, L., Jain, A., ... & Ondruska, P. (2021, October). One thousand and one hours: Self-driving motion prediction dataset. In Conference on Robot Learning (pp. 409-418). PMLR.

[4] Malone, I., & Strouboulis, A. (2022). Emerging Risks in the Marine Transportation System (MTS), 2001-2021.

[5] Punt, E., Monstadt, J., Frank, S., & Witte, P. (2023). Navigating cyber resilience in seaports: challenges of preparing for cyberattacks at the Port of Rotterdam. Digital Policy, Regulation and Governance, 25(4), 420-438.

[6] Hildyard, N. (2012). More than bricks and mortar. The Corner House) viewed on, 1.

[7] Jiang, B., Haider, J., Li, J., Wang, Y., Yip, T. L., & Wang, Y. (2023). Exploring the impact of port-centric information integration on port performance: the case of Qingdao Port. Maritime Policy & Management, 50(4), 466-491.

[8] Gregory, A. (2023). UCLA Labor Center program advocates for Black equity and career excellence. UWIRE Text, 1-1.

[9] Soufi, G., Voisard, B., Latimer, E. A., Matai, L., Moodie, E. E., & Laliberté, V. (2023). Benefits of the PRISM shelter-based program for attainment of stable housing and functional outcomes by people experiencing homelessness and mental illness: A quantitative analysis. The Canadian Journal of Psychiatry, 68(10), 745-754.

[10] Gregory, A. (2023). UCLA Labor Center program advocates for Black equity and career excellence. UWIRE Text, 1-1.

[11] Xu, F. (2018). The belt and road: The global strategy of China high-speed railway. Springer.

[12] Rosendal, T. (2026). Promoting China's Development Model for the Hambantota International Port: Selling Shekou to Sri Lanka. Journal of Contemporary Asia, 56(1), 87-107.

[13] Li, X., Gu, B., Zhao, H., Tu, T., & Zhu, Z. (2025). Urban shrinkage morphology: A quantitative classifying framework using deep learning. Cities, 162, 105956.

[14] Geng, Y. (2025). Reasons and Effects of Strategic Investors in the New Energy Industry: A Case Study of Chengxin Lithium. Highlights in Business, Economics and Management, 65, 1-8.

[15] Lin, J., Tang, J., Tang, H., Yang, S., Chen, W. M., Wang, W. C., ... & Han, S. (2024). Awq: Activation-aware weight quantization for on-device llm compression and acceleration. Proceedings of machine learning and systems, 6, 87-100.

[16] Abbasnejad, B., Soltani, S., Ahankoob, A., Kaewunruen, S., & Vahabi, A. (2025). Industry 4.0 technologies for sustainable transportation projects: Applications, trends, and future research directions in construction. Infrastructures, 10(5), 104.

[17] Baixun, W. A. N. G. (2012). Logistics Port Development Strategies in Revitalizing Northeast China (Doctoral dissertation, Ritsumeikan Asia Pacific University).

[18] Ma, X., Zeng, T., Zhang, M., Zeng, P., Lin, B., & Lu, S. (2025). Street microclimate prediction based on Transformer model and street view image in high-density urban areas. Building and Environment, 269, 112490.

[19] Zou, Y., Xiao, G., Li, Q., & Biancardo, S. A. (2025). Intelligent maritime shipping: A bibliometric analysis of internet technologies and automated port infrastructure applications. Journal of Marine Science and Engineering, 13(5), 979.

[20] Hossain, K. A. (2025). Evaluation of History and Development of Smart Port.

[21] Chakravarty, S. R. (2015). Inequality, polarization and conflict. Economic Studies in Inequality, Social Exclusion and Well-Being, 12.

[22] Merk, O., & Notteboom, T. (2014). The competitiveness of global port-cities. Paris, France: OECD Publishing.

[23] de Beer, P., & Berntsen, L. (2023). Trade unions in the Netherlands: Erosion of their power base in the stable Polder Model. Notes, 12(1), 54.

[24] Scordamaglia, D. (2017). Road transport: Enforcement and special provisions for posted workers.

[25] Musial, W., Heimiller, D., Beiter, P., Scott, G., & Draxl, C. (2016). 2016 offshore wind energy resource assessment for the united states (No. NREL/TP--5000-66599). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgment

This paper is an output of the science project.

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