

Implementation of the Single Window for Sustainability of Maritime Transportation Management: An Empirical Examination of CO₂ Emissions Reduction

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[Abstract] This study investigates the impact of mandating the Maritime Single Window (MSW) at seaports on reducing CO₂ emissions. The methodology centers around six primary inquiries: Who bears responsibility for port-related CO₂ emissions? What strategies are employed to mitigate these emissions? What justifications support the enforcement of MSW? What benefits does MSW provide? How does the implementation of the MSW influence CO₂ emission reductions at ports? To what extent does adherence to the MSW contribute to decreasing CO₂ levels? A literature review and a questionnaire were utilized to gather qualitative insights from experts. Participants highlighted vessel waiting time at anchorage, hoteling duration at berth, and port throughput efficiency as critical indicators for reducing major port-related CO₂ emissions. Shippers emphasized routing optimization, vessel design, and the adoption of alternative energy sources. Seaport managers focused on adopting cold ironing, electrifying cargo-handling equipment, and improving port operations by mandating the MSW to minimize CO₂ emissions.

[Keywords] maritime-transportation, ports, CO₂ emissions, maritime-single window

1. Introduction and Problem Statement

Seaports are central hubs linking maritime freight to inland distribution networks, handling about 85% of the world's trade volume and 70% of its value annually. In 2025, maritime freight carried 12.6 billion tons of cargo. The sector (including shipping, tourism, and ports) contributed an estimated \$2.5 trillion to the global economy (World Bank Group, 2026), supported by 2.8 million seafarers and generating over 130 million full-time jobs worldwide through indirect and induced roles across supply chains, logistics, and marine infrastructure (United Nations Trade and Development, 2025). This contribution underscores the importance of maritime transportation and seaports to economic stability, yet it also highlights rising CO₂ emissions.

According to the International Transport Forum (2020), Climate TRACE (2026), and Statista (2026), maritime transportation accounts for 12% of transportation-related CO₂ emissions and 3.0%

of human-induced carbon dioxide emissions, producing approximately 1 billion metric tons of CO₂ annually. This volume makes the sector the world's sixth-largest CO₂ emitter, up 20% over the past decade. Within this sector, an estimated minimum of 10% to 25% of total CO₂ emissions originate from seaport operations, which can be categorized into three primary areas: ocean-going vessels either anchored or docked with auxiliary engines active, contributing 60% of total port-related CO₂ emissions; the fleet engaged in drayage operations, accounting for 30% of total; cargo handling equipment, along with administrative and structural fuel and electricity consumption, comprising the remaining 10%. According to the United Nations Conference on Trade and Development (2025), without appropriate strategies and mitigation measures, emissions could increase to 130% of 2008 levels by 2050.

Today, the political debate centers on port digitalization and mandating the Maritime Single Window (MSW), which takes effect in January 2024, a centralized digital platform for the electronic submission, exchange, and processing of all shipping-related information shared by port authorities. While speed and cost of implementation, infrastructure shortcomings, stakeholder resistance, inter-agency silos, and unequal economic impacts among countries are noted (the International Maritime Organization, 2024), academic research is focused on ports' strategic and organizational challenges (Issa-Zadeh et al., 2025) and capacity-driven throughput optimization of port digitalization (Asileva & Ahmed, 2019).

Substantial challenges remain in achieving a 30% reduction in CO₂ emissions by 2030, a 70% to 80% reduction by 2040, and net-zero emissions by 2050 (International Maritime Organization, 2021). This study empirically investigates the impacts of MSW on CO₂ emission reduction through a comprehensive literature review and thematic analysis. The research aims to show how MSW platforms serve as vital operational levers for reducing maritime CO₂ emissions by standardizing and digitizing information exchange among ships and port authorities. Accordingly, the paper is organized into four sections. Following the introduction, the second section reviews existing literature. The third section describes the methodology, which involves collecting primary data, and then presents the results and discussion. The fourth section summarizes the findings.

2. Literature Review

This literature review provides a foundational background on contributors to maritime CO₂ emissions, decarbonization strategies, the digitalization paradigm, and mandating MSW.

2.1 Maritime CO₂ Emissions and Contributors

According to Deng and Mi (2023), maritime transportation is often criticized for contributing nearly 3% of global human-made greenhouse gas emissions. Although ports account for a smaller share of maritime CO₂ emissions (about 10% to 20%), they serve as vital energy hubs and catalysts, linking land-based power grids and the shipping sector to drive decarbonization.

Shipping CO₂ Emissions

The United Nations Trade & Development's Review of Maritime Transport (2025) states that the global shipping industry accounts for approximately 80% to 90% of end-to-end corridor maritime CO₂ emissions. The main drivers include the scale and increasing global trade, the fleet's dependence on carbon-intensive fuels, and the fleet's aging (Yildiz, 2026).

While global trade reached a record \$35 trillion in 2025, the average ship age was 22.2 years, with more than half exceeding 15 years. This leaves them either too outdated to retrofit or too new to decommission (Deng & Mi, 2023), increasing CO₂ emissions mainly because of lower engine efficiency, outdated hull designs that increase hydrodynamic drag, and an inability to use modern, low-carbon fuels. Additionally, older vessels are often assigned to longer, less efficient routes, increasing overall fuel consumption.

Emissions predominantly come from container ships and bulk carriers (approximately 50%), oil, chemical, and liquefied natural gas tankers (25%), and other vessel types (25%) (Merk, 2014; International Maritime Organization, 2026). Especially as shipping volume increases and larger commercial vessels travel longer distances worldwide, fuel consumption rises significantly (Deng & Mi, 2023). Ships consume between 150 and 250 tons of fossil fuel daily (approximately 50,000 to 80,000 gallons), amounting to roughly 300 million tons of fossil fuels annually, mainly heavy fuel oil. This highly viscous, carbon-intensive residue from crude oil refining produces significant volumes of greenhouse gases, which have increased by 20% over the past decade. Schrooten et al. (2009) analyzed maritime emissions using transport activity and emission modeling modules. They concluded that fuel combustion in main engines accounts for over 90% of total emissions, releasing approximately 1.0 gigaton of CO₂ annually, while the commercial fleet contributes around 1 billion tons of CO₂ per year. This represents 2.7% of global CO₂ emissions and ranks the sector as the sixth-largest contributor to air and water pollution worldwide.

Seaports CO₂ Emissions

According to Gao et al. (2025), ships and on-site port logistics—including cargo handling, land transport, and terminal operations—are the primary contributors to seaport CO₂ emissions (10 to 20% of total Maritime emissions). Ships account for 60%, followed by port land transportation at 30% and terminal equipment at 10%. Emissions accumulate through complex direct and indirect port operations, beginning with the submission of ships' pre-arrival documentation. During this process, port management oversees ship-port interactions during: 1) Guiding ships into the harbor with marine pilots and tugboats and coordinating berthing schedules for safety; 2) Cargo handling, involving the loading, unloading, and staging of containers, bulk, or breakbulk cargo between ships and the terminal using heavy gantry cranes; 3) Storage and inland logistics, which include warehousing and transferring cargo to modes of transportation such as trucks, rail, and barges; 4) Compliance and handling regulatory procedures, including inspecting materials, verifying ship waste and ballast water reports; and 5) Processing customs declarations.

Waiting periods and port service times at each stage can vary significantly based on regional conditions, port congestion, local infrastructure, and geopolitical factors. CO₂ emissions increase at each stage, starting with vessel pre-arrival and continuing during port operations, with additional emissions from port congestion when sudden demand surges exceed port capacity. Such congestion generates bottlenecks due to limited infrastructure, labor shortages, and restricted operating hours. These bottlenecks create synchronization issues, triggering a chain of delays that may cause vessels to idle at anchor and burn extra fuel to sustain essential onboard services. Moreover, delays in backup operations force terminal machinery, including trucks and cranes, to run longer and compel cargo ships to accelerate once underway, disproportionately increasing fuel consumption and emissions. Therefore, without effective measures, CO₂ emissions from the maritime sector are projected to account for approximately 17% of global greenhouse gas

emissions by 2050 (European Maritime Safety Agency, 2026).

2.2 Decarbonization Strategies

Thus, significantly reducing CO₂ emissions is essential to meet the objectives of the Paris Agreement, which aims to achieve net-zero greenhouse gas emissions and limit the global temperature rise to below 2°C. Moreover, under International Maritime Organization mandates, greenhouse gas emissions from shipping must decrease by 75% to 85% per ton-mile (Port Technology, 2023). Still, reducing maritime transportation CO₂ emissions requires curbing both shipping and port CO₂ emissions.

2.2.1 Shipping Strategies to Reduce CO₂ Emissions

Maritime shipping decarbonization relies on strategies to reduce CO₂ emissions, including routing optimization, improved vessel design, adoption of alternative energy sources, technology and operational shifts, adoption of alternative low- to zero-CO₂ fuels, and compliance with global regulations to reach net-zero emissions by 2050.

A. Ship Routing. Maritime transportation improves route efficiency through routing optimization, which can reduce ship emissions by up to 30% (Moradi et al., 2022). This includes advanced weather routing, adaptive speed control, AI-driven logistics, and port arrival planning. Today, three main macro-corridors dominate global trade, accounting for 90% of international commerce: the Trans-Pacific (East Asia to North America), the Asia-Europe corridor (from East and Southeast Asia across the Indian Ocean to European cities), and the Trans-Atlantic (North America to Western Europe). These routes face constraints from narrow, geographically limited chokepoints.

Notable chokepoints include the Suez Canal, linking the Mediterranean to the Red Sea and enabling travel between Asia and Europe without passing around Africa's Cape of Good Hope; the Panama Canal, connecting the Atlantic and Pacific to shorten journeys across the Americas (Nautilus Shipping, 2024); the Strait of Malacca between Indonesia, Malaysia, and Singapore; the Strait of Hormuz at Oman and Iran's entrance to the Persian Gulf; the Dover Strait/English Channel separating the UK and France; Bab-el-Mandeb, linking the Indian Ocean to the Red Sea; the Turkish Straits (Bosphorus and Dardanelles) as the only exits from the Black Sea; and the Arctic Routes (Notteboom et al., 2022; Soto, 2025).

Academic research primarily examines Route Optimization, as discussed by Toth and Vigo (2002), focusing on identifying the most efficient routes for a fleet serving a specific customer. Qian & Eglese (2016) expanded this work to incorporate speed adjustments alongside fuel consumption optimization. Additional areas of study include Weather Routing (Zis et al., 2020), Ship/Maritime/Voyage Optimization (Sang et al., 2023), which aims to reduce ship emissions by minimizing fuel use, and Environmental Routing (Kalinichenko et al., 2025).

However, shipping companies rely on critical geopolitical chokepoints to reduce the overall maritime distance their vessels must traverse for deliveries (Fuentes & Adland, 2023). For example, navigating around the Cape of Good Hope rather than transiting the Suez Canal can increase transit distances. This choice can increase ton-miles by about 6% and raise global maritime risks to unprecedented levels. The alternative route may extend sailing durations by up to 34 days and

increase fuel consumption by 25%-30%. For instance, a substantial container ship consuming approximately 63,000 gallons of marine fuel daily might require an additional 441,000 gallons for an extra week at sea. This change corresponds to at least a 46% rise in greenhouse gas emissions. Modern algorithms determine the best route, using real-time weather data on wind and wave conditions to optimize speed. Choosing a path with lower hydrodynamic resistance helps operators reduce fuel consumption and CO₂ emissions (Zis, 2020).

B. Ship Designs. Ship designs address structural aspects to reduce energy consumption and emissions, including design and power coefficients, resistance types, ship speed categories, onboard power systems, propeller design, maximum ship squat, ship interaction phenomena in confined waters, mechanisms to improve ship handling, and power output enhancements (Lindstad et al., 2022; Barrass, 2004). Therefore, advanced ship structural design reduces energy use through lightweighting, topological optimization, and drag reduction. By using high-tensile steel and composite materials, structural engineers lower vessel weight to increase cargo capacity while reducing engine loads. At the same time, hydrodynamic and aerodynamic hull configurations minimize water and air resistance, lowering fuel consumption (Cao et al., 2026). Topological Optimization Design and Wave-Resistance Verification of Unmanned Sailboats help reduce CO₂ emissions through aerodynamic and hydrodynamic improvements, wind-assisted propulsion, and onboard carbon capture solutions. Innovations such as Wing Sails, Flettner Rotors, Kite Sails, Air Lubrication Systems, Hull Form Changes, Ship-Based Capture, LCO₂ Carriers, Propulsion Polymer Bearings, and Waste Heat Recovery systems significantly reduce greenhouse gas emissions from maritime transport (Mersin et al., 2020; Kondratenko et al., 2025).

C. Ship Alternative Fuels. Law et al. (2021) examined pathways to transition from conventional heavy fuel oil to alternative fuels, including “blue” fuel produced from natural gas, “green” fuel derived from biomass and solar energy, and fossil fuels with carbon capture technology. Other alternatives discussed by Actioners (Shankar, 2026) include emerging fuel options such as methanol: a leading liquid alternative capable of reducing CO₂ emissions and significantly lowering sulfur and nitrogen oxides; when produced from renewable energy and with captured carbon (Green Methanol), it exhibits a near- zero emission profile and can be utilized in dual- fuel engines with minimal modifications (Rony et al., 2023).

Ammonia: highly favored for deep- sea and long- range shipping due to its higher energy density than pure hydrogen; it emits no carbon during combustion, making it a promising future fuel, although its high toxicity necessitates specialized safety and handling protocols. Liquefied Petroleum Gas, a mixture of propane and butane, is increasingly adopted as an alternative marine fuel to Heavy Fuel Oil and Marine Gas Oil, offering a practical transitional pathway for the maritime industry to comply with stricter global emission regulations. Additionally, biofuels function as transitional drop-in fuels; electricity powers short-sea vessels; hydrogen fuels passenger ships via fuel cells; and nuclear power provides long-range, zero-emission propulsion (Mersin et al., 2019).

All these options have an established safety record in naval applications and are poised to significantly influence the commercial shipping industry, particularly for deep-sea voyages (European Maritime Safety Agency, 2026). Still, 98 percent of the global fleet, by vessel count, uses conventional fuels. Only 1.2 percent use alternative fuels, mainly liquefied natural gas and,

to a lesser extent, battery/hybrid, liquefied petroleum gas, and methanol. Further exploration of CO₂-reduction strategies involves analyzing port operations and emissions-reduction strategies by Lloyd's Register (Shankar, 2026), which is navigating the maritime sector's dual focus on decarbonization and digitization. Major milestones include driving the practical adoption of nuclear-powered shipping, supporting wind-assisted MR tanker projects, and implementing new SOLAS lifting appliance requirements.

2.2.2 Ports' Strategies to Reduce CO₂ Emissions

Strategies aimed at reducing CO₂ emissions predominantly focus on port management practices that minimize the time vessels spend on pre-arrival procedures, anchorage, berthing, loading, unloading, and departure by reducing port dwell times. This approach consequently diminishes CO₂ emissions (Moon and Woo, 2014). As Rodrigue (2022) notes, effective port management enables ships to arrive precisely when berths become available, facilitating just-in-time arrivals. Such practices can eliminate the need for high-speed sailing, saving 8% to 19% on fuel. Port authorities oversee the implementation of these strategies, ensuring operational efficiency through strategic planning and infrastructure management.

Key actors include: 1) Port operators, whether public or private, who manage daily activities such as terminal operations, cargo handling, and infrastructure maintenance to ensure seamless functioning; 2) Shipping lines, which own or lease vessels and organize schedules and logistics to guarantee timely berthing, loading, and unloading; 3) Freight forwarders and customs brokers, who coordinate cargo movements from origin to destination by selecting appropriate routes and liaising with carriers; 4) Customs brokers, who oversee customs procedures and ensure compliance with legal and regulatory standards for imports and exports, in collaboration with government agencies.

These agencies enforce safety, security, and environmental regulations and comply with the international trade laws listed in Table 1. Sun and Zhang (2022) enumerated strategies employed by seaports to mitigate CO₂ emissions, including the electrification of cargo-handling equipment, the provision of shore power for docked vessels, and the optimization of vessel traffic to diminish idling. Additionally, they advocate adopting renewable energy sources, promoting green marine fuels, and implementing digital supply chain solutions to reduce indirect emissions (Barone et al., 2026).

Table 1*Key Strategies for Seaport CO2 Emissions Reduction Through Port Management*

Effective Port Management 1. Data Sharing • Collaboration among shipping lines, customs, and terminal operators • Importance of real-time data for informed decision-making Expansion of Automation • Automated systems in cargo operations • Impact on efficiency and reduction of human error Refinement of Yard and Berth Management • Techniques for optimizing space usage • Scheduling improvements to reduce waiting times 2. Technological Innovations Adoption of Strategic Technologies • Examples of technologies for cargo tracking and management • Role of AI and machine learning in predictive analysis Infrastructure Improvements • Enhancements to facilitate smoother logistics • Sustainable infrastructure is important in reducing emissions 3. Port Call Optimization Development of Solutions for Efficiency • Analyzing data to identify inefficiencies • Process improvements can be implemented based on these insights Use of New Technologies • Exploring innovative tools for scheduling and coordination • Ensuring predictability and timeliness in vessel calls • Mandating MSW

The primary operating platforms used to implement strategies in port management settings for ship-to-port activities include Port Management Information Systems, which unify and automate maritime operations, and Terminal Operating Systems (TOS), which serve as the port's "brain." They optimize container storage, dispatch automated cranes, and route autonomous vehicles within the yard; Port Community Systems (PCS), a digital network that automatically shares data on cargo movements with key stakeholders, such as shipping lines, freight forwarders, and customs authorities; and Ocean Freight Visibility Platforms, which aggregate real-time tracking data to provide end-to-end shipment statuses, predictive Estimated Times of Arrival (ETAs), and exception management. Also included are Digital Twins & Predictive Analytics, AI-powered

platforms that simulate terminal logistics in real time using 5G sensors to prevent congestion before it occurs, and the 2024-mandated MSW.

2.3 Digitalization Paradigm and MSW

The digitalization paradigm is a contemporary subject that garners interest in the maritime sector, representing a shift from manual procedures, traditional models, and physical interactions to integrated, data-driven digital systems. This paradigm is transforming shipping and generating new business logics and models for value creation (Hirata, 2022). Digitalization of ports through MSW leverages digital technologies and data to automate, optimize, and connect port operations. Maritime carriers are required to submit all legally mandated information—such as crew lists, hazardous cargo details, and waste reports—only once. The system then shares this data with relevant authorities to streamline ship clearance processes (International Maritime Organization, 2024).

The system provides centralized, unified access points through which users can interact and transmit standardized information in compliance with standards set by the International Organization for Standardization and the International Shipping Organization, thereby eliminating redundant paperwork. Standardized forms utilized across the shipping industry include the General Declaration (FAL Form 1), Cargo Declaration (FAL Form 2), Ship's Stores Declaration (FAL Form 3), Crew Effects Declaration (FAL Form 4), Crew List (FAL Form 5), Passenger List (FAL Form 6), and Dangerous Goods Manifest (FAL Form 7).

According to Tijan et al. (2018), standardizing information within MSW enhances information sharing among stakeholders through a centralized data platform, emphasizing the efficiency of electronic transactions between government authorities and enterprises. Vargas et al. (2018) highlight the necessity for collaboration within the freight sector to reduce greenhouse gas emissions. Perboli et al. (2017) analyzes the logistical challenges of meeting customer demands for service, speed, and flexibility amid the increasing complexities of global trade and supply chain risks. Finally, Cammin et al. (2020) advocate for digitalization in maritime shipping to improve operational efficiency.

The MSW is constructed upon an Information and Communication Technology infrastructure overseen by governmental authorities and mandated worldwide by the International Maritime Organization (2024). This system aims to facilitate the digital harmonization of information exchange processes. It complies with International Maritime Organization (2024) requirements and the Convention on Facilitation of International Shipping Traffic (2024) by submitting all required vessel data before arrival at port. This data transfer occurs automatically with relevant authorities, including customs and port state control, covering the vessel's arrival, stay, and departure.

Effective January 1, 2024, this platform requires International Maritime Organization Member States worldwide to unify and automate maritime operations electronically, connecting port authorities, terminal operators, customs agencies, and shipping lines. The primary aim is to eliminate prearrival delays by streamlining procedures for ship arrivals, stays, and departures. As noted by the United Nations Trade & Development (2024), a 'Single Window' is a platform designed to facilitate trade processes by enabling trade and transportation entities to submit

standardized data and documents through a single access point, thereby meeting all import, export, and transit requirements.

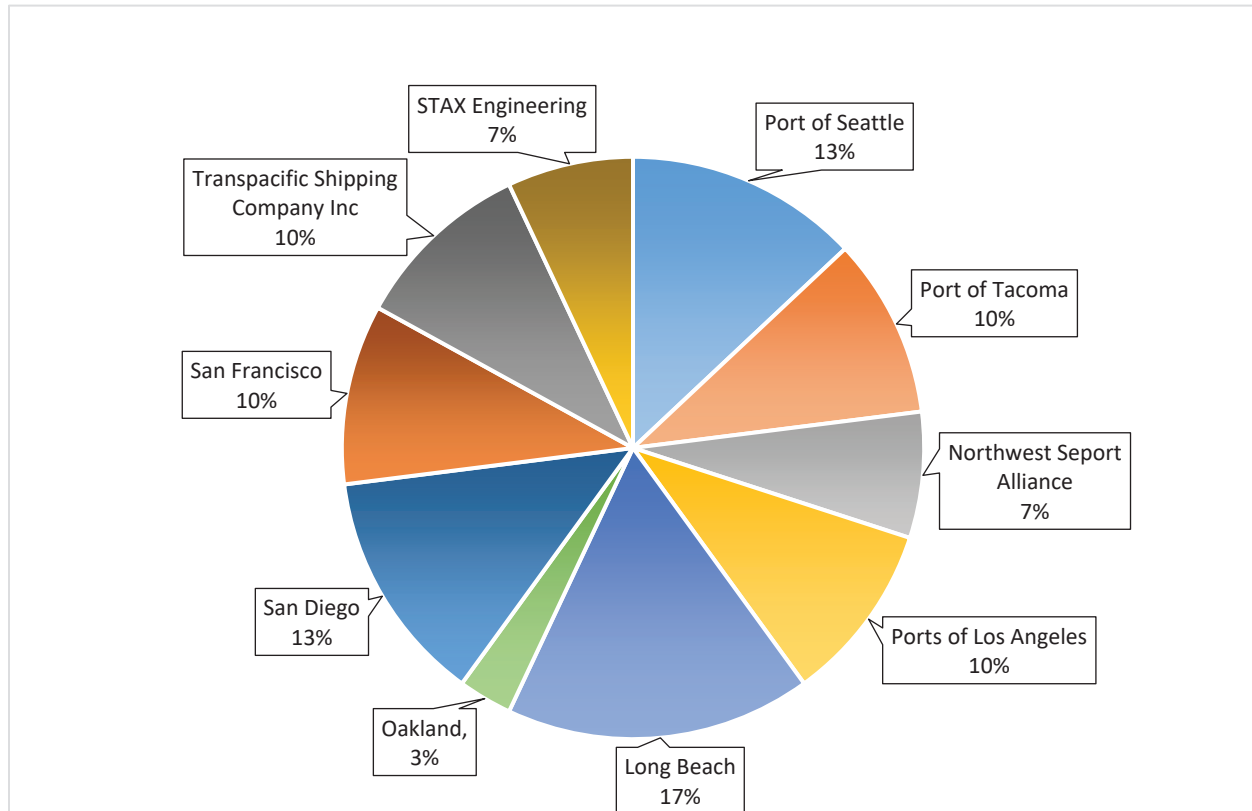
Given that global maritime ports handle nearly 1.5 to 2 million vessel arrivals and calls annually, encompassing both international and domestic ships engaged in commercial activities, managing these port calls across over 13,000 seaports involves a complex, lengthy process of customs declarations for cargo, immigration clearances for crews and passengers, baggage clearance, and import/export permits issued by various agencies (United Nations Trade & Development, 2024). In this context, four additional questions arise: 1. What justifies mandating MSW? 2. What advantages does MSW offer? 3. How does the MSW affect CO₂ emission reductions at ports? 4. To what extent does enforcing the MSW contribute to CO₂ reductions? This study addressed these questions through an empirical analysis.

3. Research Methodology

The study's methodology is based on thematic analysis, following a systematic six-step qualitative research process developed by Braun and Clarke (2012) to identify, analyze, and interpret patterns of perspectives on CO₂ emission reduction through mandatory MSW.

3.1 Qualitative Survey Design & Sample Profile

This study employed Lazarsfeld's questionnaire to conduct an exploratory qualitative survey (Fleck & Stehr, 2025). The researchers constructed a comprehensive, four-part questionnaire designed to elicit descriptive, open-ended textual responses from thirty experts affiliated with shipping companies and port authorities. The respondents' demographic profile (Figure 1) included leadership teams—comprising mid- and upper-management as well as commercial strategy officers—from STAX Engineering, a firm specializing in environmental services and clean-tech solutions that offers barge-based, land-based, and mobile emissions capture and control technologies for the maritime and data center sectors; the Port of Seattle and the Port of Tacoma, operating collaboratively as the Northwest Seaport Alliance; Transpacific Shipping Company Inc., a provider of comprehensive transportation and trade services; and the Ports of Los Angeles, Long Beach, Oakland, San Diego, Hueneme, and San Francisco. The respondents were invited to answer the following questions.

Figure 1*Respondents' Demographic Profile*

3.2 Data Collection

Data collection in this study follows the recommendations of Terry et al. (2017), using objective measurements and descriptive statistical analysis to assess the relationship between CO₂ emission reduction and the implementation of Mandatory Shipment Waste (MSW). This methodology requires collecting quantitative data to support or refute the proposed hypotheses through systematic analysis and interpretation. The study exceeded the recommended sample size for data saturation to ensure comprehensive contextual understanding and to account for potential hidden subgroup variations. From a total of 30 questionnaires, 25 responses with complete answers to four specified questions were selected for analysis.

The study also used a structured qualitative framework rooted in Braun & Clarke's methodology. The research questions addressed include: 1. What Rationales Support the Imposition of the MSW? 2. What Benefits Does the MSW Provide? 3. How Does the MSW Influence CO₂ Emission Reductions at Ports? 4. To What Degree Does Enforcement of the MSW Contribute to CO₂ Reductions? These inquiries were examined using thematic analysis to identify and report recurring patterns or themes in the collected survey data.

4. Empirical Findings & Analysis

4.1 Questionnaire Item 1. Please justify mandating MSW (Question 1)

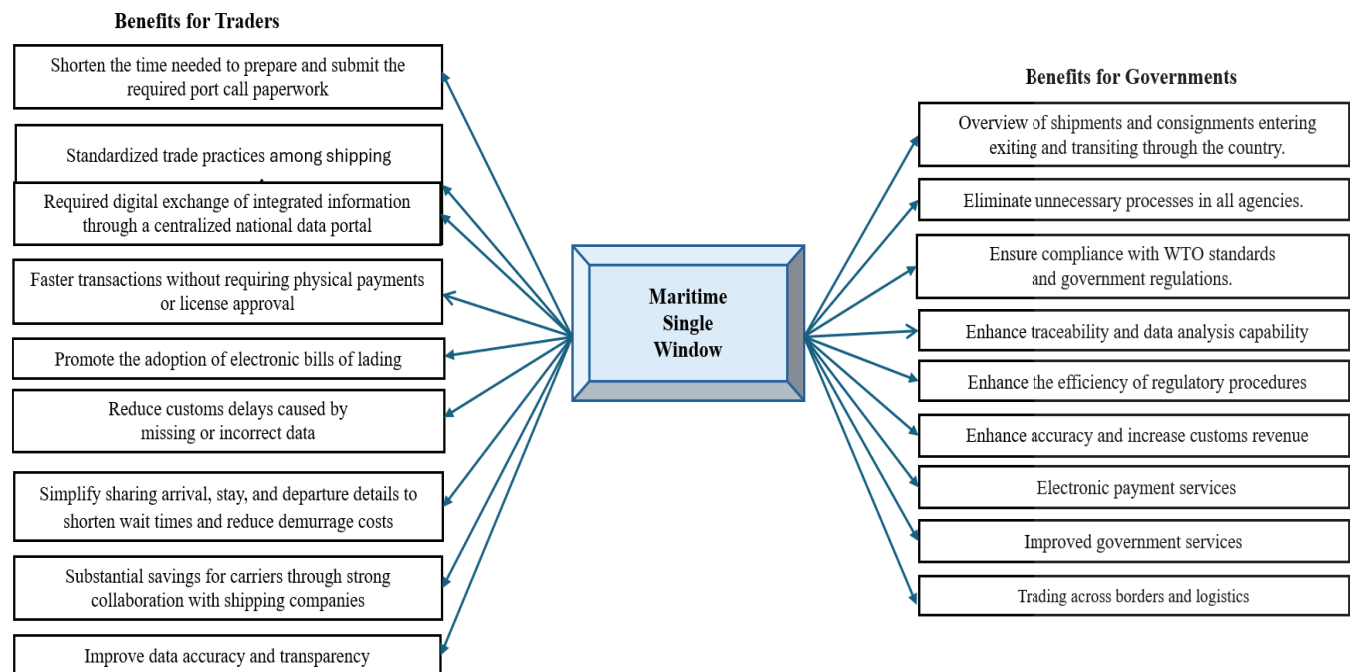
Responses justifying mandating the MSW included disconnected port systems, delays, incompatible technological ecosystems, manual paperwork, errors, scattered information, lack of information standardization, inherent inadequacies in legacy systems, and being a target for cyberattacks due to reliance on centralized Port Community Systems (integrating customs, terminal operators, shipping lines, and freight forwarders to manage documents, track cargo, and schedule arrivals), causing operational disruptions. Furthermore, data silos, inadequate stakeholder collaboration, and port congestion pose significant security risks.

4.2 Questionnaire Item 2. Please list the Advantages of MSW (Question 2)

Respondents enumerated several advantages outlined in Figure 2, including eliminating prearrival delays, standardizing information, integrating digital information, reducing demurrage costs and fees, speeding port service operations, cutting paperwork and submitting electronic bills of lading, improving turnaround times, and improving transparency and service-time predictability. They highlighted that the adoption of MSW offers significant operational advantages for port authorities by providing a single entry point, data validation, routing, authority decisions, acknowledgments, and statistics; enabling interoperability by sharing information with customers: SafeSeaNet/EMSW, PCS, TOS, VTMS, trade systems, and APIs; eliminating unnecessary processes; ensuring compliance with the International Organization for Standardization and government regulations; enhancing traceability and data analysis capabilities; improving the efficiency of regulatory procedures; improving data accuracy; speeding service time through electronic payments; and eliminating the psychological toll of manual fatigue. *See Figure 2 next page.*

4.3 Questionnaire Item 3: In what manner does MSW influence the reduction of CO₂ emissions at port facilities? (Question 3)

Respondents indicated that ships generate most port-related CO₂ emissions while waiting. Emissions occur during transit/restricted speed zones, maneuvering areas, anchorages, and berthing zones, with berthing typically accounting for the largest share. For instance, a container vessel operating at major global hubs produces more than 140,000 tons of CO₂. Consequently, CO₂ emissions may be mitigated in two distinct phases: firstly, by eliminating waiting times, which can reduce idling emissions at the berth by 30% to 60%, and in certain cases, up to 98%; secondly, by enhancing cargo handling efficiency through streamlined loading and unloading procedures, thereby decreasing the duration vessels remain docked with auxiliary engines operating. Additionally, collaboration and information exchange between shipping lines and ports are vital for improving port efficiency. Such cooperation is fostered through strategic foresight to eliminate dependence on paper documentation, which significantly contributes to inefficiencies and leaves a discernible carbon footprint. Notably, shippers generate approximately 45 million paper bills of lading annually, each prepared in triplicate for the shipper, consignee, and banker to ensure comprehensive documentation throughout cargo transit.

Figure 2*Advantages of Maritime Single Window for Maritime Carriers and Seaports*

4.4 Questionnaire Item 4: Could you estimate the extent of CO₂ reductions at seaports achieved through MSW? (Question 4)

Respondents indicated that mandating MSW decreases CO₂ emissions per port call. The influence of a seaport call on CO₂ emissions can be segmented into three primary operational phases: the Arrival Phase—which encompasses "Wait in queue" versus "Just-In-Time" arrivals—utilization of auxiliary power at the dock, the efficiency of terminal infrastructure and cargo handling procedures, and geopolitical congestion. Therefore, the number of port calls, cargo volume per carrier, and carrier age directly impact CO₂ emissions. Consequently, CO₂ emissions are influenced by port traffic, port service efficiency, and carrier waiting and servicing times. Coordination, operational efficiency, and infrastructure quality during a port call significantly affect the CO₂ vessels emit both at sea and within port facilities. Inefficiencies during a port call can increase vessel fuel consumption.

Reducing waiting times and improving coordination speed up ship clearance and port operations, thereby decreasing overall maritime dwell time. Consequently, this reduces fuel consumption by auxiliary engines that operate while docked to supply lighting, cooling, pumps, and onboard systems, which use heavy marine fuels and emit significant quantities of CO₂. Additionally, it reduces emissions from port transportation activities—such as trucks, harbor craft, trains/locomotives, and heavy-duty vehicles involved in cargo movement—which account for approximately 30% of total emissions. It also optimizes cargo handling equipment, including diesel-powered cranes, forklifts, and yard tractors, which directly generate emissions at the terminal. It also reduces emissions from electricity and energy the port purchases to power terminal

buildings, lighting, and electric cranes, as well as emissions from port users and tenants, such as visiting cargo ships, third-party trucks, and railcars.

5. Discussion & Policy Implications

The accumulation of CO₂ in marine environments raises serious concerns, particularly because the global maritime commercial fleet operates across 170 countries and uses about 4,700 ports. The average waiting time at anchorage before berthing ranges from 12 to 24 hours worldwide. Attention is directed towards severely congested terminals and delays, which contribute to environmental pollution, as large, anchored vessels may consume between 15 and 20 tons of fossil fuels daily. Because burning one ton of fuel produces more than one ton of CO₂ through the chemical reaction of carbon with oxygen (Rodrigue, 2022), these delays substantially intensify climate change impacts.

The primary drivers of these emissions include the scale of global commerce, increased shipping volume, the deployment of larger commercial vessels traveling long distances worldwide, an aging fleet, and reliance on carbon-intensive fuels. Together, these factors drive CO₂ emissions during transit, in restricted speed zones, maneuvering areas, anchorages, and at berths. Strategic maritime shipping initiatives include routing optimization, improved vessel design, adopting alternative energy sources, technological and operational shifts, and using low- to zero-CO₂ fuels. Ports also contribute to marine CO₂ emissions. Ports reduce emissions through onshore power supply (cold ironing), electrifying cargo-handling equipment, transitioning to on-site renewable energy, and adopting alternative marine fuels such as green hydrogen and ammonia.

The recent policy mandating MSW, as part of operational efficiencies and digitalization, has significantly reduced ships' waiting times and streamlined traffic flows. MSW also supports strategic partnerships with global hubs to enable zero-emission operations. By digitizing and centralizing port clearance procedures, MSW eliminates redundant paperwork and enables smoother logistics, reducing CO₂ emissions. It also minimizes unnecessary idling at anchorages through electronic pre-clearance and advanced cargo information, directly reducing fuel consumption and CO₂ emissions from auxiliary engines. MSW provides real-time vessel status, allowing ships to adjust cruising speeds during ocean transit rather than speeding up to wait outside congested ports, thereby reducing fuel consumption and emissions. Submitting data once reduces manual processing of paper forms, decreasing port-call processing times and duplicate paperwork. A fully integrated MSW enables advanced port-level decarbonization tools, such as ship-port interface measures (International Maritime Organization, 2024).

MSW enforcement affects about 4.3 million commercial port calls annually and delivers substantial CO₂ reductions for ships exceeding 1,000 gross tons. These ships have a global average waiting time of six to twelve hours to secure a berth during periods of operational efficiency. Port emissions include CO₂ from ships' pre-arrival anchoring activities, which contribute approximately 1.1 billion tons of CO₂ annually. Ships typically spend between 4% and 6% of their operational year—about 15 to 22 days—waiting at anchor offshore. Consequently, companies such as STAX Engineering use modular, barge-based exhaust scrubbers that capture 99% of particulate matter and 95% of NO_x emissions for vessels that cannot readily connect to the electrical grid. In California, MSW is used at key seaports, including the Port of Los Angeles, the Port of Long Beach, the Port of Oakland, the Port of San Diego, the Port of Hueneme, and the Port of San Francisco.

California's ports have reduced CO₂ emissions by optimizing vessel scheduling and digitizing port call processes. By implementing Virtual Arrival and Queuing Systems with MSW technology, the Port of Los Angeles and the Port of Long Beach have reduced CO₂ emissions per voyage by 16% to 24%.

Data from over 10,000 Pacific voyages indicates that average ship speeds declined from 18.6 knots to 15.9 knots in 2022 and to 17.6 knots in 2023. A one-knot reduction in speed could prevent over 300,000 tons of CO₂ emissions. Analyses of Transpacific container vessels found that voyage emissions declined by 24% in 2022 and 15.7% in 2023 after the implementation of MSW, compared with baseline data from before 2021. In addition to MSW-enabled queuing, California ports have adopted stringent local regulations, such as the California Air Resources Board At-Berth Regulation, which requires ships to connect to shoreside electricity. The Port of Los Angeles Air Emissions Inventory shows that greenhouse gas emissions per container have decreased by 40% since 2005. Reducing a Medium-Range tanker's delay by one day can save \$18,000 to \$25,000 in charter costs, as well as 15 to 20 tons of fuel and 50 to 65 tons of CO₂ emissions. Examples involving parcel tankers suggest potential savings of up to \$215,000 by avoiding unnecessary waiting. Extrapolating these savings across all vessels visits annually underscores the significant potential for cost reductions.

For instance, the Port of Seattle, which processes approximately 3.2 million TEUs annually, typically keeps berth and turnaround times under 24 hours. Conversely, the Port of Los Angeles, which encompasses 7,500 acres of land and water and handles over 10.2 million TEUs annually, may berth ultra-large container vessels for up to five days, depending on their size and cargo volume. Container dwell time at terminal facilities generally ranges from three to five days before trucks or trains retrieve them. This waiting and anchoring period accounts for approximately 10% to 25% of total shipping-related emissions. For a standard port call—including maneuvering into the port, anchoring, berthing, and departing—a vessel can emit up to 25% of total voyage emissions, totaling between 20 and over 100 tons of CO₂. For example, a single cruise ship at the Port of Seattle emits approximately 34 metric tons of CO₂ during the prearrival phase. Additionally, a typical bulk freighter anchored at the port consumes at least 2 tons of fuel per day, while an idle vessel at port emits roughly 10 tons of CO₂ per day. Large ships produce between 15 and 24 metric tons of CO₂ daily by operating auxiliary engines. Reducing waiting times enhances operational efficiency, resulting in reductions of 10% for container ships and bulk carriers, 16% for gas carriers and oil tankers, and nearly 25% for chemical tankers per voyage.

Further discussion pertains to substituting manual paperwork with centralized electronic submissions, thereby diminishing clearance times from 17 hours to 1 hour; eliminating data redundancies and manual document exchanges; standardizing electronic documentation; facilitating the early submission of accurate cargo and vessel data; and enabling synchronization among stakeholders—including port authorities, terminals, customs, and tug operators—thus promoting just-in-time arrivals and minimizing idle periods. Consequently, reducing the time ships spend idling at anchorage or berth directly lowers port-side carbon emissions and advances environmental sustainability. The fundamental principle is "submit once," which significantly reduces the administrative burden, eliminates redundant facsimiles or emails to multiple agencies, encourages data sharing among port authorities, and ensures compliance with data privacy and security regulations through advanced encryption techniques.

6. Conclusion, Limitations & Future Research

Although the world's economy is founded on international commerce facilitated by maritime transportation, the sector accounts for 3% of global human-made CO₂ emissions, emitting about 1.0 gigaton of CO₂ annually. This makes maritime transportation the world's sixth-largest CO₂ emitter. In this context, international shipping accounts for 75% of total emissions, while ships at anchor account for roughly 4- 6% of total annual maritime operational emissions, contributing to 60% of total port emissions. This study empirically examines CO₂ emissions reductions within seaport operational boundaries through MSW implementation.

This platform serves as a centralized collaborative system for public and private stakeholders, facilitating seamless exchange of standardized information through a single-entry, multi-user interface. Although MSW was mandated on January 1, 2024, the significant reduction in CO₂ emissions has created challenges that raise the question of how mandating MSW affects CO₂ emission reduction.

Based on a thematic analysis, a questionnaire with four open-ended questions was developed. Twenty-five complete questionnaires were analyzed to substantiate the requirement for mandating the MSW, elucidate the benefits of such a mandate for maritime carriers and seaports, evaluate the influence of MSW on CO₂ emissions, and ascertain the magnitude of CO₂ emission reductions at seaports. The analysis indicated that the mandate of the MSW is warranted due to current issues, including disconnected port systems, delays, incompatible technological ecosystems, manual paperwork errors, scattered information, lack of standardization in information, inherent vulnerabilities in legacy systems susceptible to cyberattacks, data silos, inadequate stakeholder collaboration, and port congestion.

The advantages of mandating MSW for maritime shipping as well as ports, and the advantages for shippers, include eliminating prearrival delays, standardizing information, integrating digital information, reducing demurrage costs and fees, speeding port service operations, cutting paperwork and submitting electronic bills of lading, improving turnaround times, and improving transparency and service-time predictability. The advantages for ports include providing a single entry point, data validation, routing, authority decisions, acknowledgments, and statistics; enabling interoperability by sharing information with customers, eliminating unnecessary processes; ensuring compliance with the International Organization for Standardization and government regulations; enhancing traceability and data analysis capabilities; improving the efficiency of regulatory procedures; improving data accuracy; speeding service time through electronic payments; and eliminating the psychological toll of manual fatigue.

These advantages, in turn, reduce ships' waiting time and accelerate ship clearance and port operations, thereby lowering overall maritime dwell time. Consequently, they reduce fuel consumption for auxiliary engines, which power lighting, cooling, pumps, and onboard systems and run on heavy marine fuels that emit vast amounts of CO₂. Additionally, they reduce port transportation activities, streamline cargo-handling equipment, and cut emissions from electricity and energy used in terminal buildings, lighting, and electric cranes. They also lessen emissions from port users and tenants, including visiting cargo ships, third-party trucks, and railcars.

Limitations and Future Studies

While MSW streamlines port calls and reduces unproductive anchoring, quantifying its precise environmental impact faces major limitations, including the lack of a unified method for calculating carbon footprints and the exclusion of certain activities, such as secondary vessel movements. As MSW is fully implemented and data flows are standardized, future research should explore how Artificial Intelligence and Blockchain can transparently monitor maritime CO₂ emissions across international borders to prevent carbon leakage. Additionally, policy and operational studies should evaluate the interoperability between regulatory MSW platforms and commercial PCS to effectively manage safety data requirements for new low-flashpoint alternative fuels, such as ammonia and green hydrogen.

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