

Multiple effects of shore power and its berthing-priority policy on ship-in-port performance

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ABSTRACT

This study aims to systematically investigate the multiple effects of Shore Power (SP) deployment and its berthing-priority policy on ship-in-port performance. For this purpose, an integrated Operation-Environment-Policy-Power (OEPP) simulation framework is developed to embed SP adoption and berthing-priority rules into a discrete-event model of container terminal operations. The framework efficiently links terminal operations, ship emissions, policy intervention, and port electricity demand, and is validated using empirical terminal data, expert consultation, scenario analysis, and sensitivity testing. The results indicate that SP adoption can reduce ship-in-port emissions by up to 43% under full utilisation while berthing-priority policies introduce transitional trade-offs between environmental benefits and operational efficiency. The adverse effects gradually diminish as SP utilisation approaches full adoption. The analysis further reveals that ship-in-port emissions are more sensitive to changes in traffic growth than increases in SP utilisation. Moreover, large-scale SP deployment significantly increases port electricity demand, with an average consumption of approximately 19.5 MWh per SP-equipped vessel, underscoring the need for coordinated port-power infrastructure planning. These findings provide policy-relevant evidence to support adaptive and phased implementation of SP and its berthing-priority policy, highlighting the need to balance emission-reduction objectives with operational efficiency and power-system readiness in port decarbonisation strategies.

1. Introduction

The global shipping industry is a significant contributor to air pollution, emitting substantial amount of Carbon Dioxide (CO₂), Sulphur Dioxide (SO₂), Particulate Matters (PM), and Nitrogen Oxides (NO_x). Emissions generated in port areas are particularly harmful due to their close proximity to residential communities, posing serious environmental and public health risks. To mitigate these adverse impacts, Shore Power (SP), also referred to as cold ironing, alternative maritime power, or shore-to-ship electricity technologies, has emerged as a promising emission-reduction solution. It involves an integrated system that includes shore-side power supply facilities, shore-ship connection infrastructure, and ship-borne receiving equipment, enabling vessels to connect to onshore electricity while berthed (Qi et al., 2020). By utilising SP, vessels can shut down their Auxiliary Engines (AEs) and rely

on electricity for onboard operations, thereby significantly reducing ship-at-berth emissions.

Given its substantial environmental benefits, SP adoption has been actively promoted by governments and industry stakeholders worldwide. For instance, under the European Union's "European Green Deal", all container and passenger vessels of 5000 gross tonnage or above are required to connect to SP at major ports within the trans-European transport network by 2030 (European Commission, 2023). The California Air Resources Board (CARB) in the United States (U.S.) mandates that a specified proportion of vessel calls must utilise SP or CARB-approved emission control technologies, with financial penalties imposed for non-compliance (Port of Los Angeles, 2024). According to the Green Transportation Development Plan for the 14th Five-Year Period, approximately 7500 berths in China are expected to be equipped with SP by 2025 (MoT of the PRC, 2022). In addition to mandatory

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regulations, various incentive policies, including construction subsidies, electricity price discounts, and tax exemptions, have been introduced to support both SP deployment and operation.

Among the policy instruments designed to promote SP adoption, berthing-priority policies have proven particularly effective (Zhen et al., 2022). Such policies grant docking preference to vessels equipped with or utilising SP, thereby providing operational advantages that incentivise shipping companies to invest in SP technologies. By aligning operational incentives with environmental objectives, berthing-priority policies contribute to the broader sustainability of port operations. Existing studies have examined multiple aspects of SP adoption, including implementation barriers (Wang et al., 2023), environmental benefits (Wang et al., 2024b), economic feasibility (Merkel et al., 2023), deployment strategies across port and shipping routes (Wang et al., 2024c), and stakeholder interactions under different policy schemes (Zhen et al., 2023). The multiple effects of SP and its berthing-priority policy on ship-in-port performance remain insufficiently understood. In particular, their joint impacts on port operational performance, environmental outcomes, and energy demand have yet to be comprehensively evaluated. It is noteworthy that port operational performance in this study refers exclusively to vessel time-related indicators, i.e. ship-in-port time (including both anchorage waiting time and berth service time) and the utilisation rates of berths and quay cranes. This definition is more specific than the broader notion of overall port performance adopted in the port management literature.

To bridge this gap, this study incorporates SP and its berthing-priority policy into the operational characteristics of containership-in-port operations and develops an integrated Operation-Environment-Policy-Power (OEPP) simulation model. This model enables a holistic assessment of the multiple effects of SP and its berthing-priority policy on ship-in-port performance while identifying associated opportunities and challenges. The main contribution of this study includes:

- (1) Develop an integrated OEPP simulation framework that quantitatively evaluates the combined effects of SP adoption and its berthing-priority policy on containership-in-port operations, emissions, and electricity demand, which differs from single-dimension or static assessments in the existing SP studies.
- (2) Validate the proposed OEPP framework through theoretical consistency checks, behavioural verification, empirical calibration, sensitivity analysis, and expert evaluation, demonstrating its robustness and transferability as a decision-support tool for evaluating the operational, environmental, and energy-system impacts of port decarbonisation policies.
- (3) Capture transitional trade-offs between environmental benefits and operational efficiency, revealing how berthing-priority policies generate short-term congestion and emission spillovers at low SP uptake that diminish as adoption increases, providing evidence to support adaptive and phased policy design.
- (4) Quantify SP-related electricity demand across vessel classes and utilisation scenarios, highlighting the need to coordinate emission-reduction policies with port energy planning and grid readiness.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature on SP applications and associated policy interventions, identifying research gaps to be addressed. Section 3 presents the research methodology. Section 4 presents the development of a container terminal operational simulation model incorporating SP and its application to berthing-priority policy analysis. Section 5 reports the numerical experiments and their analysis. Policy implications of new findings are outlined in Section 6. Section 7 closes the paper up with a set of concluding remarks.

2. Literature review

Emission reduction in the shipping industry relies on a range of specialised technological and policy measures. As an emerging mitigation technology, SP has attracted growing attention from governments, academic researchers, and industry practitioners. To thoroughly present the state-of-the-art in SP research and practice, this section is structured into three parts: (1) an overview of SP applications and associated policies and regulations; (2) a review of recent research progress on SP; and (3) research gap identification.

2.1. Overview of SP applications and related policies and regulations in the shipping industry

Since the first commercial SP for cargo ships was installed in Sweden in 2000 (Wang et al., 2023), the construction of SP in both ports and vessels has made significant progress, driven by a combination of mandatory regulations and incentive-based policies. Table 1 summarises the key characteristics and insights related to SP development across represented countries and regions, drawing on official government documents, institutional reports, and industry data sources. The comparison highlights that policy and regulatory frameworks constitute the primary drivers of SP adoption in major maritime economies, including the U.S., Europe, and China. In addition, economic incentives, such as reductions in operation costs, direct subsidies, and public funding, play a crucial role in encouraging vessels to connect to SP while berthed.

From a vessel perspective, UN Trade and Development reports that the global fleet comprised approximately 112,495 ships in 2025 (UN Trade & Development, 2025). According to the Green Technology Tracker, more than 3940 vessels had either already been fitted with SP or were scheduled for retrofitting by 2025 (Clarksons Research, 2025). This represents approximately 3.5% of the global fleet. These figures suggest that, although the number of SP-equipped vessels continues to increase, overall fleet-level penetration remains relatively low.

There is a broad consensus within the industry regarding the effectiveness of SP in reducing ship-at-berth emissions (Wang et al., 2023).

Table 1

Key characteristics and insights on SP development across represented countries and regions.

Country	U.S.	Europe	China
Characteristics	Most stringent SP regulations	Early adopter (since 1989); renewed expansion after 2020	Rapid progress since 2009; ambitious targets by 2025.
Policies & Regulations	At-berth regulation (2014), updated in 2020.	EU Directive 2014/94/EU; European Green Deal.	National plans, guidelines, regulations, and supporting schemes.
Incentives & Subsidies	Funding support and penalties for non-compliance.	Funding support, investment priority, discounts in electricity price, port fee, and tax exemptions.	Subsidies, electricity and service fee discounts, exemption of capacity charges, berthing and pilotage priority.
Future directions	Expansion to containers, cruise, refrigerated vessels, and oil tankers.	Widespread use for inland vessels; preparation for large ocean-going vessels.	Promotion of wider SP utilisation.
Reference	Environmental Protection Agency (2024) and California Air Resources Board (2020).	European Commission (2023), World Ports Sustainability Program (2024), and European Union (2022).	MOT of the PRC (2019) and MOT of the PRC (2022).

Consequently, an increasing number of ports and shipping companies, particularly in regions with access to low-carbon electricity, recognise the strategic importance of SP. However, given constraints related to renewable energy availability and the coexistence of alternative emission-reduction measures, universal mandatory adoption of SP in the short term remains unlikely. With ongoing advances in port smart grids and microgrid technologies, SP systems are expected to become increasingly mature and integrated into port energy systems.

Based on current development trends, future SP development is likely to focus on the three key directions: (1) With the large-scale deployment of renewable energy, the emission-reduction advantages of SP are expected to be significantly enhanced (Wang et al., 2024b). (2) Driven by national SP initiatives and incentives, SP is projected to achieve widespread global development by 2030. (3) As the installation and utilisation continue to expand, the associated electricity demand is increasing, indicating a trend towards high energy intensity (Uzun et al., 2024). Consequently, it is essential to investigate the effects of SP on ship-in-port performance to address these emerging challenges and effectively accommodate future operational and energy demands.

2.2. Review of research on SP-related issues

Existing research on SP has primarily focused on specialised themes, including implementation barriers and challenges, environmental and economic impacts, emission-reduction strategies, deployment and optimisation problems, and interactions among stakeholders across different policy and regulatory frameworks. Collectively, these efforts aim to promote SP adoption, maximise its environmental benefits, and minimise associated economic and operational costs within the shipping industry (Wang et al., 2024b). Table 2 summarises the main strands of SP-related research.

Research on barriers and challenges to SP adoption typically relies on surveys, expert elicitation, and multi-criteria decision-making methods to examine technological constraints, economic feasibility,

standardisation gaps, regulatory barriers, and electricity demand requirements. These studies provide qualitative and semi-quantitative insights into the key obstacles hindering SP implementation and offer policy-oriented recommendations to facilitate its uptake. Research on the environmental impact of SP has expanded rapidly with the availability of big data and improved emission estimation techniques, enabling more detailed and comprehensive assessments of ship-at-berth emissions. Meanwhile, economic analyses have examined costs and benefits from the perspectives of ports, shipping companies, and governments, taking into account subsidies, electricity pricing, and externalities. Such evaluations are inherently context-specific and sensitive to local policy and energy conditions. Building on environmental and economic assessments, an increasing number of studies have developed optimisation and simulation models to address SP deployment problems, including berth allocation, quay crane assignment, and ship scheduling. These studies typically aim to promote SP adoption and emission reduction while minimising operational and economic costs under various incentive schemes, including subsidies and priority-based policies. In addition, stakeholder interaction studies, often based on game-theoretic approaches, have investigated strategic decision-making among governments, ports, shipping companies, and power suppliers.

Despite these advances, the broader impact of combined SP with its berthing-priority on overall ship-in-port performance remains under-explored. For instance, Zhen et al. (2022) demonstrate the effectiveness of berthing-priority as an incentive for SP adoption, and Wan et al. (2021) estimate the emission reduction potential of SP using simulation methods, few studies have systematically examined the joint environmental, operational, and energy-demand effects of SP and berthing-priority policies. Addressing this gap is essential for supporting evidence-based policy design and for guiding sustainable port development under increasing decarbonisation and energy constraints.

2.3. Research gaps

Given the foregoing review of the research progress and practical applications, this paper reveals the following research gaps:

- (1) While existing studies have extensively explored a wide range of SP-related issues, an integrated assessment of SP and its berthing-priority policy on ship-in-port performance has not yet been conducted.
- (2) It is challenging to holistically evaluate the impact of SP and its berthing-priority policy on ship-in-port performance, including operations, environment, and power demand, due to the complexity of real-time port operations systems, the uncertainty in ship arrivals and berth occupancy, and the variability in SP utilisation.
- (3) SP is primarily implemented to reduce ship-at-berth emissions, while berthing-priority is designed to promote SP's utilisation. However, the net effectiveness of these strategies for ship-in-port performance remains uncertain. Further research is therefore required to evaluate the overall environmental and operational impacts of these strategies, with explicit consideration of potential trade-offs between reductions in ship-at-berth emissions and increases in ship-at-anchor emissions.
- (4) Few studies have investigated the challenges that the application of SP brings to the port power system. As a megawatt-scale power demand facility, widespread SP adoption poses significant challenges to the port's power infrastructure in terms of capacity adequacy, system reliability, and the need for infrastructure upgrades or reinforcement. It is essential to gain insights into SP energy consumption under varying utilisation levels to support effective planning for large-scale implementation.

In light of these gaps, there is a clear need for evaluating the multiple effects of SP and its berthing-priority policy on ship-in-port

Table 2

Summary of research on SP-related issues within the shipping industry.

Themes	Methodology	Research focus	References
Barriers and challenges	Surveys, fuzzy decision-making methods, structural equation modelling, and cognitive maps.	Identification of technological, economic, regulatory, and institutional barriers to SP adoption in different regions	Wang et al. (2023), Radwan et al. (2019), and Bullock et al. (2023).
Environmental issues	SWOT analysis; bottom-up emission models; dispersion model; multi-source data analysis.	Emission reduction effects of SP on CO ₂ , NO _x , and SO ₂ at berth.	Daniel et al. (2023), Nguyen et al. (2021), Stolz et al. (2021), and Wang et al. (2024a).
Environmental and economic issues	Bottom-up and top-down emission estimation; simulation; cost-benefit analysis.	Joint environmental and economic impacts of SP and alternative mitigation options.	Wan et al. (2021), Merkel et al. (2023), and Chen et al. (2025).
Deployment problem	Optimisation algorithms; mixed-integer programming; evolutionary algorithms.	SP deployment under subsidy-based and berthing-priority-based incentive policies.	Zhong et al. (2024), Zhen et al. (2022), and Wang et al. (2024c).
Stakeholders interactions between	Stackelberg game, Nash game, and evolutionary games.	Subsidy design, policy selection, and strategic interactions among stakeholders.	Zhen et al. (2023), Peng et al. (2023), and Song et al. (2022).

performance, including operational, environmental, and energy demand dimensions. Such an assessment would enable stakeholders to better understand dynamic policy outcomes and make timely adjustments. It would also support informed decision-making by key stakeholders in the formulation and implementation of effective decarbonisation policies.

3. Methodology

To investigate the impacts of SP and its berthing-priority policy on ship-in-port performance, this section presents the proposed research framework and associated methods.

3.1. Research framework

The research framework, depicted in Fig. 1, provides a systematic approach for analysing the multiple effects of SP and its berthing-priority policy on ship-in-port performance at container terminals. The framework encompasses three main stages: model construction, model verification and experimental analysis, and derivation of findings and

implications.

In the model construction phase, the operational processes of an SP-equipped container terminal are integrated with ship-in-port emission estimation and SP-related energy demand within a Discrete-Event Simulation (DES) framework. Based on the operational characteristics of the case terminal, an integrated OEPP simulation model is designed to capture the interactions among vessel arrivals, berth allocation, SP utilisation, environmental performance, and electricity demand. To ensure transparency, consistency, and reproducibility, explicit assumptions, clearly defined system boundaries, and specified input-output indicators are incorporated into the model.

During the model verification and experimental analysis phase, the proposed OEPP model is assessed through theoretical consistency checks, behavioural verification, empirical calibration, baseline analysis, sensitivity testing, and expert evaluation to ensure its credibility, robustness, and practical applicability. Following model validation, a series of numerical experiments is conducted under different SP utilisation rates, vessel arrival rates, and berthing-priority settings. The analysis examines three key dimensions: ship-in-port operations,

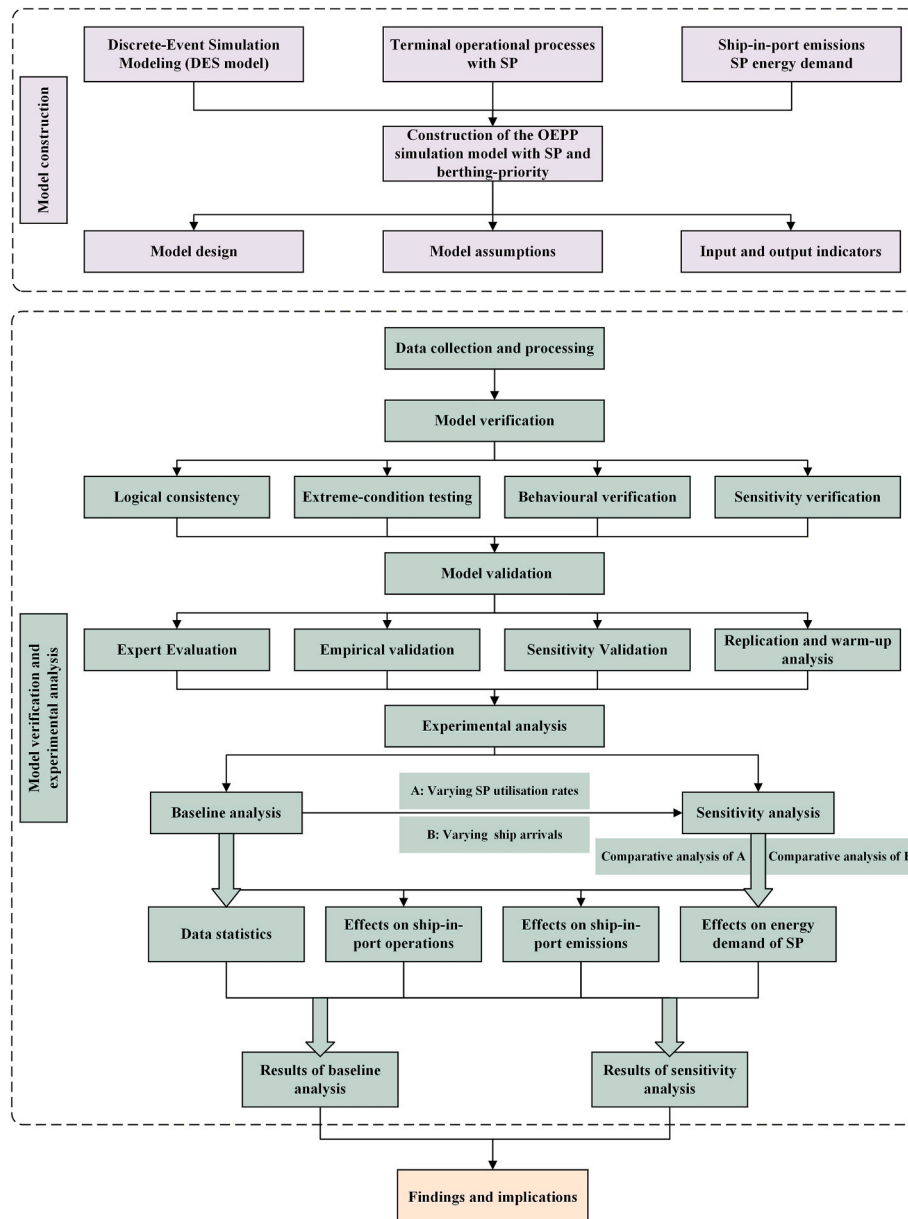


Fig. 1. The proposed framework.

environmental performance, and SP-related energy demand. Through baseline and sensitivity analyses, the framework systematically evaluates the effects of SP deployment and berthing-priority policies under varying operational conditions.

By comparing the outcomes of baseline and sensitivity analyses, the study derives key findings and policy-relevant implications in the final stage. These results highlight the value of a holistic and rigorously validated modelling framework for understanding the trade-offs associated with SP and berthing-priority policies, and for supporting evidence-based decision-making aimed at optimising port operations and advancing port decarbonisation strategies.

3.2. OEPP modelling approach

The implementation and promotion of SP for docked ships have encountered numerous technological, economic, and institutional challenges. The applications of SP and the implementation of berthing-priority policy introduce complex interactions that affect ship-in-port performance, including berth utilisation, operational efficiency, environmental emissions, and energy demand. Hence, this study adopts a discrete-event simulation-based methodology to evaluate the multiple operational, environmental, and energy-related impacts of SP and its berthing-priority policy within an integrated analytical framework.

3.2.1. Discrete-event simulation modelling

DES models system behaviour as a sequence of discrete events and are particularly suitable for analysing complex systems characterised by stochastic processes, limited resources, and interacting operational components (AnyLogic Simulation Software, 2023; Rockwell, 2024).

In the maritime industry, DES has been widely applied to analyse sea-side and land-side terminal operations, particularly to assess the impacts of infrastructure configurations and operational strategies on berth productivity, congestion, and service efficiency (Neagoe et al., 2021).

In this study, a DES model is developed to represent the operational process of a container terminal in China. Building on this foundation, an integrated OEPP simulation model is established by embedding ship-in-port emission estimation, SP utilisation, berthing-priority policies, and SP-related electricity demand into the DES framework. The resulting model captures the dynamic interactions among terminal operations, environmental performance, policy interventions, and energy demand. Implemented using AnyLogic, the model is designed to reflect real-world terminal operating practices. A total of eight experimental scenarios are simulated, representing different combinations of SP utilisation and vessel arrival rates. The proposed simulation model is rigorously verified and validated through theoretical consistency checks, behavioural verification, empirical calibration, baseline analysis, sensitivity testing, and expert evaluation. This comprehensive evaluation process demonstrates the model's credibility, robustness, and applicability, providing a reliable decision-support tool for assessing SP-related policies and port decarbonisation strategies.

3.2.2. Ship-in-port emission estimation

To evaluate the environmental impacts of SP and its berthing-priority policy, this paper focuses on emissions generated during ship-in-port activities, specifically ship-at-berth and ship-at-anchor emissions. Following established practice, ship-at-berth emissions are estimated by considering AEs, Auxiliary Boilers (ABs), and low-load Main Engines (MEs), which constitute the primary onboard power sources during berthing operations. In contrast, ship-at-anchor emissions are assumed to originate from AEs and ABs.

The emission estimation approach and associated parameters are based on the methodology proposed by Wang et al. (2024a), which systematically reviews existing ship emission estimation methods and synthesises classical frameworks, including those from the IMO GHG Study series, the Ports Emissions Inventory Guidance issued by the

Environmental Protection Agency, and the Port of Los Angeles Air Emission Inventory report series, which is widely applied in ship-in-port emission assessments. As noted by Starcrest (2023), ship emissions are influenced by multiple technical and operational factors. Accordingly, the emission model incorporates detailed input parameters, including fuel type, emissions factors, installed Maximum Continuous Rating (MCR) of ME, Load of AEs and ABs (LAE and LAB), operational characteristics, and the functional relationships among these variables. The detailed mathematical formulation of the emission estimation model is presented in Eqs. (1)–(12).

$$\sum E_{port} = \sum E_{berth} + \sum E_{anchor} \quad (1)$$

$$\sum E_{berth} = \sum E_{AE_berth} + \sum E_{AB_berth} + \sum E_{ME_low\ load} \quad (2)$$

$$\sum E_{AE_berth} = \sum_{i=1}^n \sum_{j=1}^5 (L_i^{AE} \times t_i^{AE_berth} \times EF_{j-AE}) \quad (3)$$

$$\sum E_{AB_berth} = \sum_{i=1}^n \sum_{j=1}^5 (L_i^{AB} \times t_i^{AB_berth} \times EF_{j-AB}) \quad (4)$$

$$\sum E_{ME_low\ load} = \sum_{i=1}^n \sum_{j=1}^m (MCR_i \times EL_{i-ME} \times t_i^{ME_berth} \times EF_{j-ME} \times LLF_j) \quad (5)$$

$$t_i^{berth} = t_i^{AE_berth} = t_i^{AB_berth} \quad (6)$$

$$t_i^{ME_berth} = 5\% \times t_i^{berth} \quad (7)$$

$$\sum E_{anchor} = \sum E_{AE_anchor} + \sum E_{AB_anchor} \quad (8)$$

$$\sum E_{AE_anchor} = \sum_{i=1}^n \sum_{j=1}^5 (L_i^{AE} \times t_i^{AE_anchor} \times EF_{j-AE}) \quad (9)$$

$$\sum E_{AB_anchor} = \sum_{i=1}^n \sum_{j=1}^5 (L_i^{AB} \times t_i^{AB_anchor} \times EF_{j-AB}) \quad (10)$$

$$t_i^{anchor} = t_i^{AE_anchor} = t_i^{AB_anchor} \quad (11)$$

$$Energy_{sp} = \sum_{i=1}^n (L_i^{AE} \times t_i^{AE_berth}) \quad (12)$$

The notations used in Eqs. (1)–(12) are listed in Table 3. Ship-in-port emissions (E_{port}) consist of ship-at-berth (E_{berth}) and ship-at-anchor emissions (E_{anchor}). Ship-at-berth emissions originate from AEs, ABs, and low-load MEs, denoted as E_{AE_berth} , E_{AB_berth} , and $E_{ME_low\ load}$, respectively. Ship-at-anchor emissions come from AEs, and ABs, represented by E_{AE_anchor} and E_{AB_anchor} . The MCR_i is sourced from the China Classification Society (CCS), while L_{AE} and L_{AB} values are derived from the Port of Los Angeles emission inventory (Starcrest, 2023). In accordance with current environmental regulations, low-sulphur fuel oil is assumed for all vessels. The corresponding emission factors (EF_{e-AE} , EF_{e-AB} , and EF_{e-ME}) depend on pollutant type and engine characteristics and are drawn from multiple authoritative sources to ensure appropriate value ranges (Wang et al., 2024a). The simulation period spans 8760 h, equivalent to one full year, to maximise the robustness and representativeness of the results.

4. Simulation model construction

4.1. Port OEPP model design

The port OEPP model is developed to represent the operational system of a container terminal under SP and its berthing-priority policy. It comprises two primary components: (i) a detailed representation of

Table 3
Definitions of the notations used in this study.

Notations	Definitions
$i = 1, 2, 3, \dots, n$.	Index of ship i berthed at the port, where $i = 1, 2, 3, \dots, n$.
$j = 1, 2, 3, 4, 5$.	Index of pollutants, where $j = 1, 2, 3, 4, 5$ denotes CO_2 , NO_x , PM , and SO_2 .
E_{port} , E_{berth} , E_{anchor} .	Emissions from ships in port, berth, and anchor, respectively (g).
E_{AB_berth} , E_{AE_berth} , and $E_{ME_low\ load}$.	Ship-at-berth emissions from ABs, AEs, and low-load MEs, respectively (g).
E_{AE_anchor} and E_{AB_anchor} .	Ship-at-anchor emissions from AEs and ABs, respectively (g).
$Energy_{sp}$.	Energy consumption of SP (kWh).
EF_{j_AE} , EF_{j_AB} , and EF_{j_ME} .	Energy-based emission factors of pollutant j for AEs, ABs, and MEs, respectively (g/kWh).
EF_{CO} , EF_{CO_2} , EF_{NO_x} , EF_{PM} , and EF_{SO_2} .	Emission factors of CO , CO_2 , NO_x , PM , and SO_2 , respectively (g/kWh).
EL_{i_ME} .	Load factor of the MEs for ship i (%).
L_i^{AB} and L_i^{AE} .	Load of ABs and AEs for ship i (kW).
LLF_j .	Low load emission adjustment factor of pollutant j .
LLF_{CO} , LLF_{CO_2} , LLF_{NO_x} , LLF_{PM} , and LLF_{SO_2} .	Low-load adjustment factors for individual pollutants.
MCR_i .	Installed maximum continuous rating of MEs (kW) of ship i (kW).
$t_{i_berth}^{AE_berth}$, $t_{i_berth}^{AB_berth}$, and $t_{i_berth}^{ME_berth}$.	Berth time of ship i , together with the corresponding operating durations of AEs, ABs, and MEs while the vessel is at berth (h), derived from simulation.
$t_{i_anchor}^{AE_anchor}$ and $t_{i_anchor}^{AB_anchor}$.	Anchorage time of ship i , together with the corresponding operating durations of AEs and ABs while the vessel is at anchor (h), derived from simulation.

actual container terminal operational processes, and (ii) their abstraction and formalisation for discrete-event simulation modelling.

4.1.1. Actual terminal operations with SP and berthing-priority policies

Container terminal operations typically commence with vessel arrival and proceed through a sequence of interrelated stages, including port entry, anchorage queuing, berth allocation, mooring and unmooring operations, cargo handling at berth, and eventual departure from the

port. The detailed operation workflow, illustrated in Fig. 2, can be summarised by the following steps:

(1) Ship's arrival and pre-arrival reporting.

Ships arrive at the port within a planned time window, generally following predefined schedules. Prior to arrival, shipping agents submit advance notices, including the Estimated Time of Arrival (ETA), SP service requirements, and relevant documentation related to the vessel, cargo, and crew. This information enables port authorities to coordinate berth allocation and cargo-handling operations.

(2) Berth availability and anchorage queuing.

Upon arrival, a ship's ability to proceed directly to berth depends on berth availability, weather conditions, tidal states, and the readiness of pilotage and tug services. If any of these conditions are not satisfied, the ship is required to wait at either an external or internal anchorage area until clearance is granted.

(3) Berth operations.

Once all berthing conditions are satisfied, the vessel proceeds to berth with the assistance of pilotage and tug services and formally commences berthing operations.

(4) Cargo handling and departure assessment.

After cargo loading and unloading operations are completed, the conditions for departure are assessed. If weather, tidal, and operational conditions permit, the vessel departs from the berth. Otherwise, it remains berthed until departure conditions are met.

(5) Preparation-to-handling and pre-departure operations.

Before cargo handling begins, vessels undergo a preparation-to-handling period following berthing, during which necessary

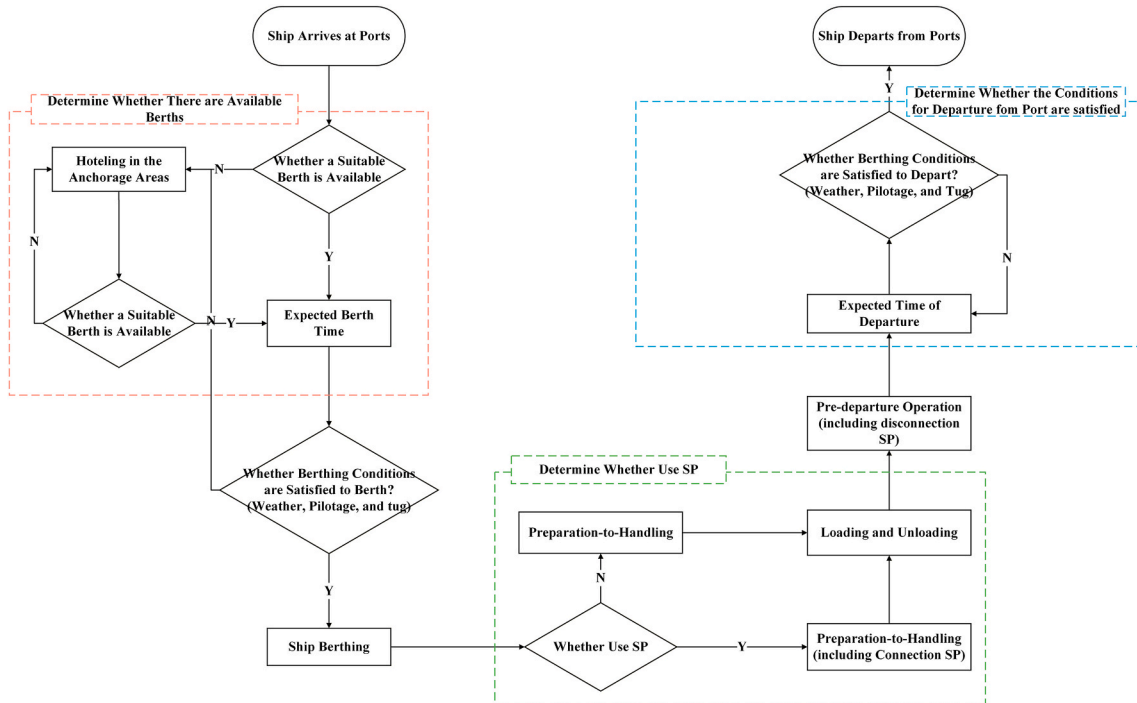


Fig. 2. Production and operational processes of container terminals with SP.

operational preparations are completed. Similarly, a pre-departure operation period is required prior to departure. The connection and disconnection of SP facilities are performed during these respective periods when SP is utilised.

(6) Port departure.

The vessel departs the port and continues its voyage to the next destination.

Although additional operational details may exist in practice, these six steps capture the essential processes governing vessel entry, service, and departure within a container terminal.

From the vessel perspective, the application of SP and its associated berthing-priority policy may alter the sequence in which ships are berthed and served. Moreover, the berthing-priority policy in this model is implemented as a non-preemptive priority rule, which means that priority is granted only among vessels awaiting berth allocation and does not interrupt, displace, or reorder vessels that have already been assigned a berth or have commenced service. Specifically, at each berth-allocation decision point, only the vessels that have already arrived and are currently waiting for berth assignment are considered. Among the vessels eligible for berth allocation, those requesting SP may be given priority when berth and SP resources are simultaneously available, thereby leading to a reordering of the service sequence. Within each priority class, however, vessels are allocated berths according to the First-Come-First-Served (FCFS) rule based on their arrival times. Accordingly, the berthing-priority policy functions as a conditional queue-based priority mechanism layered on top of the FCFS rule rather than replacing it.

Importantly, this mechanism does not imply that all vessels arrive simultaneously, nor does it require earlier-arriving non-SP vessels to wait indefinitely for later-arriving SP-requesting vessels. For example, as illustrated in Fig. 3, without SP prioritisation, Ships 3, 7, and 10 would be served in the 3rd, 7th, and 10th positions, respectively, according to their original arrival sequence and queue order. Under the SP-based berthing-priority policy, these vessels may move forward in the queue and be serviced in the 1st, 2nd, and 3rd positions, respectively, provided that they are eligible for priority at the corresponding berth-allocation decision points. Nevertheless, even with SP prioritisation, the actual berthing and service sequence remains jointly determined by vessel arrival times, berth availability, SP availability, and SP demand. A non-SP vessel, such as Ship 1, would therefore not undertake indefinite postponement as a result of SP prioritisation; rather, its service time would depend on its arrival time and the prevailing resource constraints. This design ensures that the allocation process remains operationally efficient while maintaining fairness among vessels and preventing

unreasonable delays for those not requesting SP. Such changes in the berthing and service sequence may, in turn, influence several ship-in-port performance indicators, including vessel waiting times, emissions generated both at berth and at anchor, and overall port operational efficiency. Consequently, it is essential to quantitatively evaluate the impacts of SP deployment and the associated berthing-priority policy on ship-in-port performance within an integrated modelling framework.

4.1.2. Simulation logic of the port OEPP model

AnyLogic is a multi-method simulation platform that supports DES, agent-based modelling, and system dynamics within a unified environment. Its DES capabilities are particularly suitable for modelling port and terminal operations characterised by stochastic arrivals, limited resources, and complex process interactions. The platform provides a range of visual modelling tools, including process flowcharts and state charts, and allows model extension through Java-based customisation, enabling flexible scenario design and performance analysis. In addition, AnyLogic supports direct interaction with external data sources (e.g., Excel), facilitating the calibration of input parameters and the analysis of simulation outputs.

In a typical DES representation of container terminal operations, vessels arrive at the port, wait at anchorage if necessary, receive service at berth, and subsequently depart. Building on the operational processes described in Section 4.4.1 and the DES modelling capabilities of AnyLogic, the study develops an integrated port OEPP simulation model to analyse the multiple impacts of SP and its berthing-priority policy on ship-in-port performance. The corresponding simulation process flow is depicted in Fig. 4.

The definitions and functions of the main modelling components shown in Fig. 4 are summarised in Table 4. In the simulation, the **ShipArrival** block represents vessel arrivals and generates ship entities with specific attributes, including deadweight tonnage (DWT), cargo loading and unloading volumes, and SP utilisation status. Vessel arrivals are modelled following a negative exponential interarrival time distribution, which is commonly adopted to represent stochastic ship arrivals at ports (Wan et al., 2021). Upon arrival, the vessel may enter a **Queue**, representing temporary waiting at anchorage while berth availability is assessed under the FCFS discipline. When a berthing-priority policy is applied, a priority-based queue discipline is introduced. The **Queue1** block performs a similar anchorage function but represents vessels that have already progressed through the initial queuing stage and are therefore prioritised over those remaining in **Queue**. The **SelectAvailableBerth** block determines whether a suitable berth is available based on vessel characteristics and berth constraints, such as tonnage capability and current occupancy. If a suitable berth is available ('YES'), the vessel proceeds to berth selection; otherwise ('NO'), it is routed back to

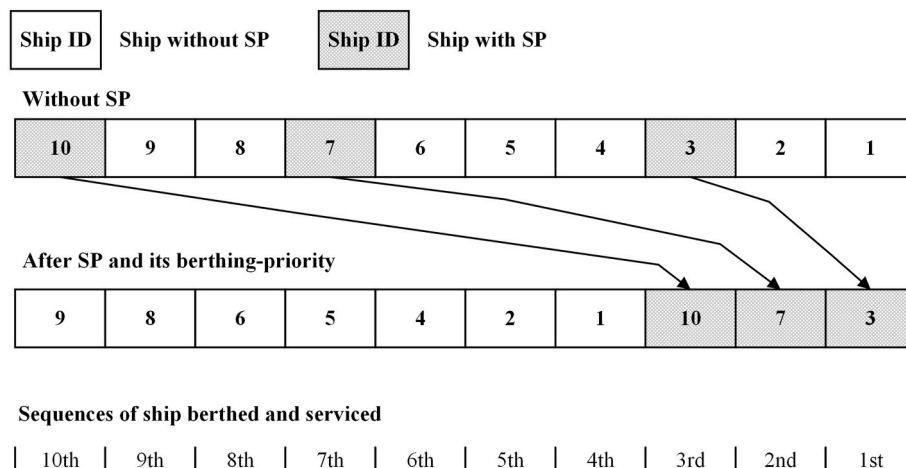


Fig. 3. Schematic illustration of the reordering of vessel berthing and service sequences following the implementation of SP and its berthing-priority policy.

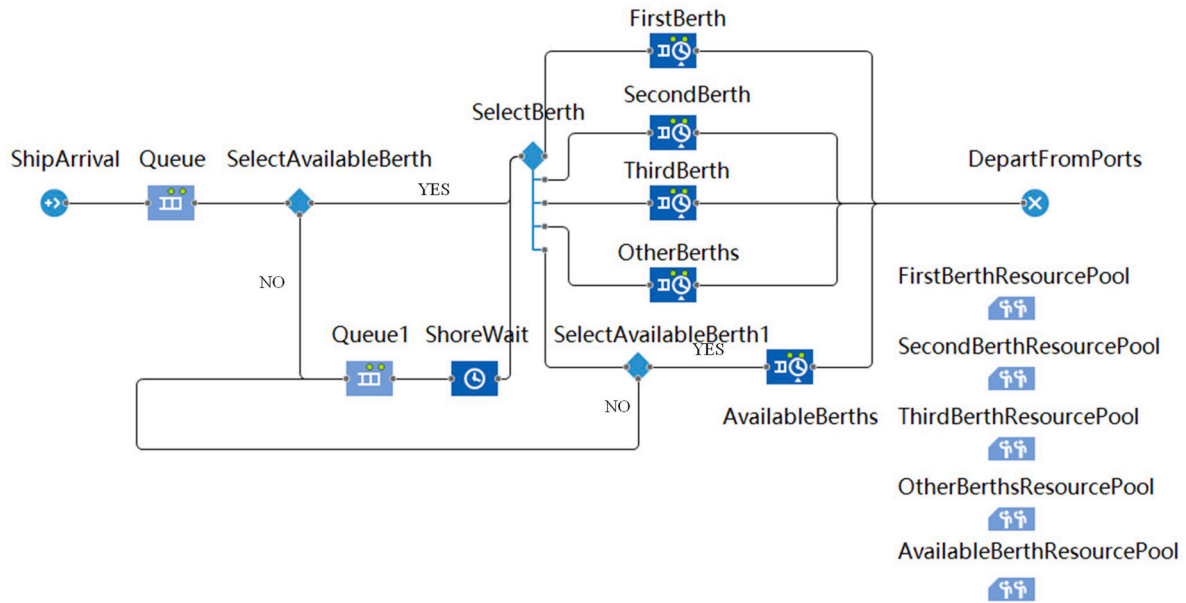


Fig. 4. Simulation modelling flowchart of container terminal operations.

Queue1 to wait for berth availability. The **FirstBerth**, **SecondBerth**, and **ThirdBerth** blocks represent explicitly modelled berth service stations with dedicated resources. The **OtherBerths** block represents the remaining berth groups with similar operating characteristics, while **AvailableBerths** represents a generic service block corresponding to any berth that becomes available after berth re-evaluation for vessels already waiting at anchorage. These service blocks incorporate queuing, resource allocation, and delay functions to capture berth preparation and cargo handling processes. Service times depend on factors such as vessel size and the number of available quay cranes. Resource availability at each berth, such as quay cranes, Automated Guided Vehicles (AGVs), and trucks, is represented by corresponding **ResourcePool** blocks, which also allow the collection of resource utilisation statistics. If no berth is available following berth selection, the vessel enters the **ShoreWait** block, which imposes a shore delay before berth availability is re-evaluated. After the waiting period, the **SelectAvailableBerth1** block performs a second berth-availability check and routes the vessel either to the **AvailableBerths** service block or back to **Queue1** for continued waiting. Once all services are completed, vessels proceed to the **'DepartFromPorts'** block, which represents departure from the terminal and marks the end of the vessel's lifecycle within the simulation.

4.2. Assumptions, inputs, and outputs

This paper employs the integrated OEPP simulation model to evaluate the impacts of SP and its berthing-priority policy on ship-in-port performance. It covers three interrelated dimensions: port operational performance, ship-in-port emissions, and port power demand. The processes governing vessel entry, service, and departure at container terminals are inherently complex and influenced by numerous interacting factors. Explicitly modelling all such factors would result in excessive computational burden and may obscure key mechanisms of interest. Therefore, to balance model tractability and analytical validity, the following assumptions are adopted:

- (1) The inner and outer anchorages are each treated as a single aggregated unit without explicit capacity constraints.
- (2) Extreme weather events, such as typhoons and heavy rainfall, are not considered. It is assumed that the terminal operates

continuously throughout the year (24 h/day), corresponding to 8760 operating hours annually.

- (3) Seasonal variations are not considered; inter-arrival times of ships follow a negative exponential distribution.
- (4) All berths are assumed to be SP-ready, with sufficient electrical supply available from the port power system.
- (5) The number of berths is fixed, and each berth accommodates only one ship at a time.
- (6) Smaller vessels may berth at facilities designed for larger vessels; however, the number of quay cranes deployed corresponds to the berth's designed capacity.
- (7) The number of quay cranes assigned to each berth is fixed, and cross-berth cranes sharing is not considered.
- (8) Quay crane productivity is assumed to follow a uniform distribution, and equipment failures are not considered.
- (9) Yards, AGVs, and other landside transport equipment that could constrain terminal efficiency are not explicitly modelled.
- (10) All containers are assumed to be 20-foot equivalent units (TEUs) during loading and unloading operations.
- (11) Container reshuffling or re-handling during stacking operations is not considered.
- (12) Vessel manoeuvring speed within the port area, transit time to berth, and associated emissions are not considered.
- (13) The preparation-to-handle and pre-departure operation periods are each fixed at 0.5 h. Based on operational practice at the case terminal and consultations with terminal operational personnel, the time required for SP connection and disconnection is assumed to be included within these operational phases and is therefore not modelled separately.
- (14) The primary pollutants considered are CO₂, SO₂, PM, NO_x, and CO.

The entry and exit of container ships constitute a sequence of independent discrete events, which is well-suited to DES modelling. Accordingly, the OEPP simulation model incorporates standard DES components for arrivals, queuing, service, and departure. Based on the modelling structure, the key inputs and outputs of the simulation model are summarised in Table 5.

Generally, ship arrivals are modelled using a time-based negative exponential distribution, consistent with the properties of Poisson arrival processes and prior port simulation studies (Wan et al., 2021).

Table 4
Definitions of modelling components used in Fig. 4.

Label	Block type	Definitions
ShipArrival	Source	Generates vessel entities entering the simulation system.
Queue	Queue	Temporary holding areas where vessels wait for downstream processing; Initial anchorage queue before berth allocation.
Queue1	Queue	Secondary anchorage queue for vessels already waiting and given higher priority during subsequent berth allocation.
SelectAvailableBerth,	SelectOutput	Performs the initial berth availability check immediately after vessel arrival.
SelectAvailableBerth1	SelectOutput	Re-evaluates berth availability after vessels complete the ShoreWait period.
SelectBerth	SelectOutput5	Directs vessels to specific berth service blocks.
FirstBerth, SecondBerth, ThirdBerth, OtherBerths	Service	Represents berth service processes, including resource seizure, delay, and release.
AvailableBerths	Service	Represents the generic service block for vessels assigned to any remaining available berth after rechecking berth availability.
ShoreWait	Delay	Imposes a short waiting period before rechecking berth availability.
FirstBerthResourcePool, SecondBerthResearchPool, ThirdBerthResearchPool, OtherBerthsResearchPool, AvailableBerthsResearchPool	ResearchPool	Defines and tracks the availability and utilisation of terminal resources.
YES, NO	Decision logic	Determines routing outcomes in selection blocks.
DepartFromPorts	Sink	Removes vessels from the system upon service completion.

Source: adapted from AnyLogic (2022).

Ship size distributions are derived from empirical or historical terminal data, with arrival times randomly assigned. The decision to use SP is based on a probability-driven random distribution. The default queuing discipline follows an FCFS rule; vessels utilising SP are granted berthing priority under the relevant policy scenarios. Berth assignment is determined based on ship tonnage and berth capacity, using specifications corresponding to actual terminal data. Quay crane productivity is assumed to follow a uniform distribution ranging from 30 to 50 TEU/hour (Wan et al., 2021).

Vessel characteristics include ship size, corresponding DWT, loading capacity, handling volume per ship, Maximum Continuous Rating (MCR) of MEs, and loads of AEs and ABs (L_{AE} and L_{AB}). Container handling volumes depend on ship sizes and follow corresponding uniform distributions. Recommended handling volumes are drawn from the General Layout Design Standards for Seaports, detailed in Table 6. Emission factors for low-sulphur fuel oil across different engine types are presented in Table 7, while low load-adjusted factors are provided in Table 8, following Wang et al. (2024a) and Starcrest (2023).

Table 5
Inputs and outputs of the OEPP simulation model.

Category	Indicator	Description
Inputs	Ship arrival discipline	Guidelines governing vessel arrival processes.
	Ship characteristics	Attributes and features of the ships.
	SP utilisation rate	Proportion of vessels using SP.
	Queue discipline	FCFS or SP-based priority queuing.
	Berth specifications	Number of berths, quay cranes per berth, and handling efficiency.
Outputs	Simulation duration	Total simulation time horizon.
	Number of ships	Total vessels served during the simulation.
	Time metrics	Time port, anchorage waiting time, and berth time.
	Utilisation rates	Utilisation of berth and quay cranes.
	Power demand	Electricity demand associated with SP.
	Emissions	Emissions from ships in-port, at-berth, and at-anchorage.

Finally, a set of simulation scenarios was developed to evaluate the effects of SP adoption and the associated berthing-priority policy under varying operational conditions. The scenario design is based on two considerations. First, the scenarios are constructed to represent different stages of SP adoption, ranging from no SP utilisation to full utilisation, to examine the multiple effects of SP deployment on ship-in-port performance. This approach is consistent with existing studies; for example, Zheng et al. (2025) adopted SP utilisation levels of 0%, 20%, 40%, 60%, 80%, and 100% for sensitivity analysis. Second, the scenarios are designed to test whether the introduction of a berthing-priority policy strengthens or weakens these effects under different levels of SP utilisation and traffic demand. This design is supported by both previous studies (e.g., Zhen et al. (2022) and Daniel et al. (2025)) and the current policy context encouraging the use of berthing-priority incentives for SP-equipped vessels (MoT of the PRC, 2023; MoT of the PRC, 2025). Specifically, comparisons between cases with and without berthing priority enable a systematic evaluation of their operational and environmental implications. These scenarios are summarised in Table 9. Scenario 1 (S1) is defined as the baseline case, in which neither SP utilisation nor berthing-priority is implemented. S2 represents an early-stage SP adoption scenario characterised by a relatively low utilisation level and is evaluated under both SP-only and SP with berthing-priority settings; this scenario serves as the primary case for detailed analysis. Scenarios 3–8 are designed for sensitivity analyses and systematically investigate the effects of varying SP utilisation rates (0%–100%) and increased vessel arrival volumes under both policy settings. This structured experimental design enables a comprehensive assessment of how SP adoption and the berthing-priority policy affect ship-in-port performance, providing useful insights for port management and policy development.

In addition, the scenario design reflects both the policy context and current terminal practice. Although the terminal is equipped with SP facilities and SP is technically available at the berth, the actual utilisation rate remains relatively low. Therefore, this study takes into account a range of hypothetical SP utilisation levels rather than focusing solely on the currently observed level to capture both the current early-adoption stage and possible future development pathways. Regarding

Table 6
Handling volume per ship at port (TEU).

Ship size	A	B	C	D	E	F
Loading capacity	200-900	901-1900	1901-3500	3501-5650	5651-9500	≥9501
Handling volume per ship	200-1000	300-1200	600-1500	800-2500	2000-3000	3000-4000

Source: MoT of the PRC, 2013.

Table 7
Emission factors for low-sulphur oil in different engine categories (g/kWh).

Engine categories	EF_{CO_2}	EF_{SO_2}	EF_{PM}	EF_{NO_x}	EF_{CO}
AEs	607-716	3.8053-4.4884	0.8218-0.9379	2-10.5	0.54-1.1
ABs	950-1059	5.9520-6.6350	0.5692-1.1109	2-2.1	0.2
MEs	545-716	3.4151-4.4884	0.8218-0.9481	2.6-14.4	0.044-1.4

Source: Wang et al. (2024a).

Table 8
Low load adjusted factors in different engine loads and pollutants.

Engine loads	CO_2	SO_2	NO_x	PM	CO
2%-20%	1	1	1-4.63	1-7.29	1-9.68

Source: Wang et al. (2024a) and Starcrest (2023).

Table 9
Simulation scenarios.

Scenarios	Ship arrival pattern	SP utilisation rate	Berthing-priority policy
S1	Baseline arrivals	0%	No
S2		20%	No
S2'			Yes
S3		40%	No
S3'			Yes
S4		60%	No
S4'			Yes
S5		80%	No
S5'			Yes
S6		100%	No
S7	Arrivals increase by	0	No
S7'	10%	20%	No
S7''			Yes
S7'''		40%	No
S7''''			Yes
S8	Arrivals increase by	0	No
S8'	20%	20%	No
S8''			Yes
S8'''		40%	No
S8''''			Yes

Note: Scenarios S1, S7, and S8 represent the no-SP settings under baseline, +10%, and +20% vessel arrival rates, respectively; Scenarios S2–S6, S7', S7'', S8', and S8''' denote the corresponding SP-only settings; Scenarios S2'–S6', S7'', S7''', S8'', and S8'''' denote the corresponding SP with berthing-priority settings.

berthing priority, although it has been proposed in policy documents and discussed in the literature, its practical implementation in terminal operations remains uncertain. It is therefore treated as a counterfactual policy intervention introduced solely for evaluating its potential operational and environmental impacts prior to possible large-scale implementation.

5. Numerical experiments and analysis

5.1. Scenario settings

5.1.1. Data collection and processing

Shekou Container Terminal (SCT) is strategically located on the south-eastern coast of Shenzhen, on the eastern bank of the Pearl River Estuary. It serves as a major hub for domestic and international container transport, linking the economically developed Pearl River Delta with global shipping networks and functioning as a key maritime gateway within China's port system. As an essential component of Shenzhen Port, SCT specialises in container handling operations. It

covers approximately 140 hectares and comprises nine deep-water container berths capable of accommodating the latest generation of mega container vessels, together with five barge berths. The total berth length is approximately 4090 m, as illustrated in Fig. 5. SCT is equipped with 33 quayside cranes and 107 yard cranes, supporting a designed annual handling capacity of 6.6 million TEU.

In recent years, SCT has actively promoted green port initiatives, with a particular focus on energy efficiency and emission reduction. It has been recognised by the Ministry of Transport of the People's Republic of China (MOT of PRC) as a demonstration unit for low-carbon operations. In 2012, SCT implemented an SP system capable of supporting both high- and low-voltage connections, becoming the first commercial container port worldwide to do so and ranking among the leading SP pilot initiatives in China. By August 2022, SCT had installed three SP systems, operating at 60 Hz and 6600 V, one set of 5000 kVA and two sets of 4000 kVA, providing full SP coverage across all nine container berths (Shenzhen Municipal Transportation Bureau, 2022).

Table 10 provides the main characteristics of SCT's berths and handling facilities. On average, approximately 87 international shipping routes call at SCT each week, with an average berth utilisation rate of 60%. The terminal operates continuously on a 24/7 basis throughout the year and provides services for most of the world's top 20 shipping companies (China Merchants Group, 2018). In 2022, SCT handled a total cargo throughput of 51.46 million tons, representing a year-on-year increase of 7.57% and accounting for 18.89% of the total throughput of Shenzhen Port. Container throughput reached 6.15 million TEU, representing an increase of 7.89% compared with the previous year, and accounting for approximately 20% of the total container throughput of Shenzhen Port (China Ports and Harbors Association Container Branch, 2023).

Based on the operational characteristics of SCT and the structure of the DES model, the simulation flowchart representing SCT's terminal operations is shown in Fig. 6. Following Gligor et al. (2021), vessel arrivals are modelled using a negative exponential distribution with an average inter-arrival time of 2.66 h. This parameter is derived from operational data collected from SCT, which recorded approximately 3300 vessel calls annually, equivalent to an average arrival rate of about nine vessel calls per day. SCT is assumed to operate continuously under a three-shift system, resulting in a total simulation horizon of 8760 h. Vessel characteristics and berth-quay crane configurations are specified using data from Wan et al. (2021), the China Port Yearbook, and terminal surveys, as summarised in Table 11 and Table 12. Emission-related parameters, including emission factors and low-load adjustment factors, are adopted from Table 7 and Table 8. In scenarios without SP, ships are serviced according to the FCFS rule, whereas under SP and its berthing-priority policy, SP-equipped vessels are granted service priority. All simulations are implemented using AnyLogic 8.8.5 Professional.

5.1.2. Model verification and validation

To enhance the reliability and applicability of the proposed DES-based OEPP simulation model, a two-stage evaluation procedure consisting of model verification and validation is adopted. Following established practices in simulation modelling, verification is conducted to assess whether the model is implemented correctly according to the specified inputs, assumptions, and logical rules, whereas validation evaluates its ability to represent real-world terminal operations (Altioik and Melamed, 2007; Rossetti, 2015).

1) Model verification

In this study, the verification process is conducted through four complementary procedures:

- Conceptual and logical consistency checks. The implemented DES model is systematically examined to ensure full consistency with the conceptual framework, including vessel arrival processes, queuing discipline, berth allocation mechanisms, and SP-

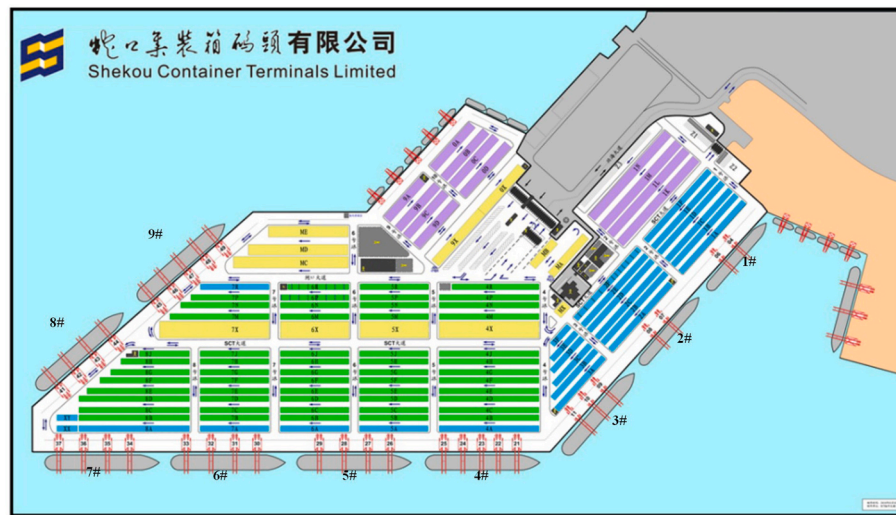


Fig. 5. Layout of SCT.

Table 10

Characteristics of berths and handling facilities at SCT.

Phases	Berth No.	Berth length (m)	Max draft (m)	No. of quay cranes	Design capacity (10 ⁴ tons)	Opening year
Phase 1	Berth 1#	325	13.49	2	5	1991
	Berth 2#	325	13.49	2	5	1991
Phase 2	Berth 3#	330	17	3	10	2003
	Berth 4#	370	17	5	10	2004
	Berth 5#	400	18	4	10	2005
	Berth 6#	400	18	4	10	2006
	Berth 7#	400	18	4	10	2007
	Berth 8#	421.68	18	4	10 & 15	2009
	Berth 9#	467.5	18	5	10 & 15	2009

related decision rules. The results confirm that the model structure correctly represents the operational logic of container terminal systems, particularly the interaction between anchorage waiting, berth allocation, and SP utilisation.

- (b) Extreme-condition testing. A set of boundary scenarios is designed to assess whether the model produces reasonable outputs under extreme conditions. The results show that when vessel arrival rates are set to unrealistically high levels, anchorage congestion increases rapidly, leading to a sharp rise in the number of waiting vessels and associated emissions. Conversely, under very low arrival rates, vessels are served almost immediately with negligible waiting time. In addition, under full SP utilisation, ship-at-berth emissions are significantly reduced, whereas under zero SP utilisation, emissions remain at baseline levels. These outcomes are consistent with theoretical expectations and demonstrate that the model behaves predictably under extreme conditions.
- (c) Trace-driven debugging and behavioural verification. Individual vessel entities are tracked throughout the simulation process, including arrival, anchorage, berth assignment, service, and departure. The observed event sequences and service orders are consistent with the predefined FCFS rule and the non-preemptive

berthing-priority mechanism. In particular, SP-equipped vessels are prioritised only within the waiting queue without interrupting ongoing services, confirming the correct implementation of the priority logic. These results verify that event scheduling, state transitions, and time accounting are correctly executed.

- (d) Sensitivity-based verification. Key input parameters, such as SP utilisation rates and vessel arrival rates, are systematically varied to examine the responsiveness of model outputs. The results show that increasing SP utilisation leads to a near-linear reduction in ship-at-berth emissions, while ship-at-anchor emissions exhibit a non-linear pattern under berthing-priority policies, initially increasing due to congestion effects and subsequently declining as SP adoption increases. In addition, higher arrival rates result in longer anchorage waiting times and increased emissions. These trends are consistent with operational logic and queueing behaviour, confirming the robustness and internal consistency of the model.

2) Model validation

Model validation is conducted to evaluate the extent to which the proposed DES-based OEPP model represents real-world terminal operations. In contrast to model verification, which focuses on implementation correctness, validation emphasises the realism, credibility, and applicability of the model. In this study, a multi-layered validation approach is adopted, combining expert-based validation, case-based empirical validation, sensitivity-based assessment, and replication and warm-up assessments.

- (a) Expert-based validation. Expert-based validation is conducted through both iterative engagement during model development and structured consultations after model implementation. Experts with extensive experience in terminal operations are involved in reviewing and refining model assumptions, process logic, and parameter settings, ensuring that the simulation framework accurately reflects real-world operational practices.

In addition, formal consultations are carried out with three senior professionals from China's port sector (see Table 13), including a policymaker, a researcher, and a senior executive, each with 10–20 years of relevant experience in port management, operations, and research. The expert panel is intentionally composed of highly experienced practitioners and researchers with complementary expertise in port policy, terminal operations, and SP deployment. Given that large-scale SP deployment remains at an early stage in many ports, professionals with direct experience in SP operations and related policy implementation are relatively limited. Consequently, a small but highly

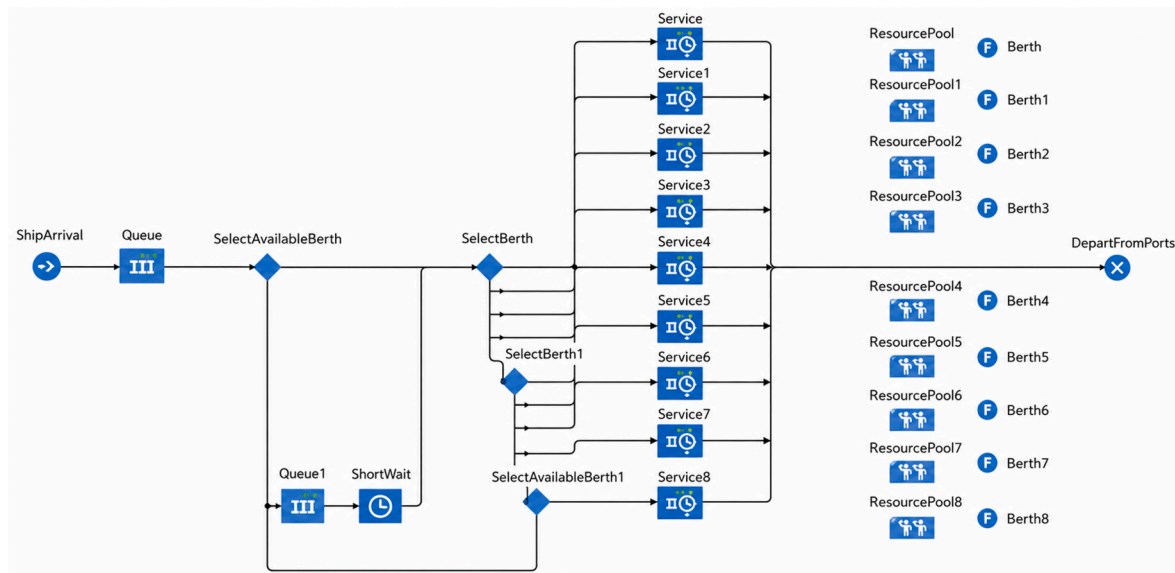


Fig. 6. Simulation modelling flowchart for SCT's operational processes.

Table 11

Distribution characteristics and key parameters of vessels calling at SCT.

Categories		Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9
Proportion (%)		1%	2%	31%	17%	19%	16%	7%	4%	3%
Tonnage (10k tons)		0.5	1	2	3	5	7	10	12	15
DWT (10k tons)	Lower	0.45	0.75	1.25	2.75	4.50	6.50	8.50	11.50	13.50
	Upper	0.75	1.25	2.75	4.50	6.50	8.50	11.50	13.50	17.50
Loading capacity (TEU)	Lower	351	701	1051	1901	3501	5651	6631	9501	11001
	Upper	700	1050	1900	3500	5650	6630	9500	11000	14100
Handling volume per ship (TEU)	Lower	200	300	300	600	800	2000	2000	3000	3000
	Upper	1000	1200	1200	1500	2500	3000	3000	4000	4000
L_{ME} (kW)	Lower	41	66	84	140	287	1094	838	1162	972
	Upper	1197	1848	3976	6946	8698	10868	13018	13725	13725
L_{AE} (kW)	Lower	429	429	966	516	945	945	980	1163	1148
	Upper				916	1148	1225	1225	1341	1780
L_{AB} (kW)	Lower				352	420	597	511	511	354
	Upper	273	273	352	420	597	678	678	694	694

Source: Data of L_{AE} and L_{AB} from LA report.

specialised expert panel is considered appropriate for model validation. Similar expert-based validation approaches have been adopted in recent port and transport studies where specialised domain knowledge is required and the pool of qualified experts is inherently limited (Zhang et al., 2025; Liang et al., 2026). The consultation focuses on three aspects: (i) whether the model adequately reflects terminal operational processes under SP deployment and berthing-priority settings; (ii) whether the model assumptions, parameter settings, and output trends are scientifically reasonable; and (iii) whether the modelling framework applies to other ports with similar operational and regulatory conditions. The feedback indicates that the model structure, logic, and outputs are both operationally realistic and scientifically sound, with strong applicability to comparable port contexts.

- (b) Case-based empirical validation. Case-based empirical validation is conducted using SCT as a representative case study. This selection is motivated by the availability and completeness of operational data, as well as the relevance of SCT to prior port research (Wan et al., 2021). Empirical data from SCT are used to calibrate model inputs and assess whether simulation outputs are consistent with observed terminal performance. The comparison

of key performance indicators demonstrates that the model reproduces realistic operational patterns.

- (c) Sensitivity analysis. Sensitivity-based validation is conducted by running the simulation under multiple scenarios with varying SP utilisation levels and vessel arrival rates. This analysis evaluates whether the model reproduces expected system behaviour under different operating conditions. The results show that the model captures key real-world dynamics, such as increased anchorage congestion under high traffic intensity, reduced berth emissions with higher SP utilisation, and the trade-off effects introduced by berthing-priority policies.
- (d) Replication and warm-up assessments. To reduce the influence of stochastic variability and initialisation bias, each simulation scenario is replicated 10 times using different random seeds, and the reported results correspond to the average values across all replications. Preliminary replication tests are conducted to examine the convergence behaviour of the key performance indicators. The results indicate that the sample means stabilise after approximately 10 replications, with only marginal changes observed in additional runs. Therefore, all scenario results presented in this study are based on the average values obtained from multiple simulation runs rather than a single replication.

Table 12

Characteristics of berths and corresponding quay crane parameters in the simulation.

Berth No.	No. of quay cranes	Capacity (10k ton)	Loading capacity (TEU)	Vessels allowed to berth (berthing rules)
Berth 1#	2	5	351-700	351-700 TEU (Priority berthing order: 351-700)
Berth 2#	2	5	351-700	351-700 TEU (Priority berthing order: 351-700)
Berth 3#	3	10	701-9500	351-9500 TEU (Priority berthing order: 701-9500; 351-700)
Berth 4#	5	10	701-9500	351-9500 TEU (Priority berthing order: 701-9500; 351-700)
Berth 5#	4	10	701-9500	351-9500 TEU (Priority berthing order: 701-9500; 351-700)
Berth 6#	4	10	701-9500	351-9500 TEU (Priority berthing order: 701-9500; 351-700)
Berth 7#	4	10	701-9500	351-9500 TEU (Priority berthing order: 701-9500; 351-700)
Berth 8#	4	10 & 15	9501-14100	351-14,100 TEU (Priority berthing order: 9501-14,100; 701-9500; 351-700)
Berth 9#	5	10 & 15	9501-14100	351-14,100 TEU (Priority berthing order: 9501-14,100; 701-9500; 351-700)

Note: Berthing priority implies that, when multiple berths are available, vessels are preferentially assigned to the berth whose capacity most closely matches the vessel's tonnage.

Table 13

Expert backgrounds and responses for model validation.

Role	Polymaker (department director)	Researcher (professor)	Senior executive
Organisation	Port-related industry	University	Port enterprise
Working experience	Over 10 years	Over 20 years	Over 20 years
Areas	Port industry management	Port and shipping emission reduction research	Port production and operational management
Main validation focus	Does the model reasonably reflect terminal operational processes and policy implementation logic?	Are the assumptions, parameters, and output trends scientifically reasonable?	Does the model reflect practical terminal operations and decision-making processes?
Applicability assessment	The model is considered suitable for analysing SP deployment and berthing-priority policies in ports with similar operational and regulatory settings.	The modelling framework is regarded as scientifically sound and generalisable to ports with similar facilities, emission-control requirements, and operational characteristics.	The model is considered operationally realistic and transferable to comparable container terminals with similar production and management conditions.

In addition, a warm-up period is introduced to eliminate initialisation bias associated with the model's starting conditions. An event-based mechanism is implemented in AnyLogic to activate data collection only after completion of the warm-up period. Based on preliminary simulation runs and observations of key performance indicators, a 240-h warm-up period is adopted. Statistics generated during this period are excluded from performance evaluation. Accordingly, the total

simulation horizon is set to 9000 h, consisting of a 240-h warm-up period and an 8760-h effective simulation period. Only the results from the latter period are used for analysis to ensure that the reported outputs reflect the steady-state behaviour of the terminal system.

The combined verification and validation results demonstrate that the proposed DES-based OEPP model is logically sound, empirically grounded, and operationally realistic. The model is therefore suitable for evaluating the impacts of SP and its berthing-priority policy on ship-in-port performance.

5.2. Results and discussion

5.2.1. Baseline performance analysis

5.2.1.1. S1: Baseline arrivals with 0% SP utilisation. In S1, ships arrive at an average inter-arrival time of 2.66 h, with no vessels utilising SP.

Simulation results indicate that an annual average of 3383 vessels complete terminal operations and depart from the terminal. This figure is approximately 2.5% higher than the observed annual average of about 3300 vessel calls. The simulated vessel size distribution (Fig. 7) aligns with the empirical distribution specified in Table 11. Meanwhile, key operational parameters, including handling volume per ship, berth assignment, and the ranges of L_{ME} , L_{AE} , and L_{AB} reported in Table 14, remain within the expected bounds defined by the input data. The simulated annual container handling volume reaches 5.31 million TEUs, compared with the observed throughput of 6.15 million TEUs in 2022, corresponding to a deviation of approximately 13.7%. This difference can be attributed to three main factors. First, the simulation model adopts a simplified representation of terminal operations, capturing key processes while abstracting from certain real-world complexities, such as operational disruptions, stochastic delays, and external constraints (e.g., weather conditions and hinterland constraints). Second, the comparison involves two different indicators: quayside container handling volume and container throughput. While throughput represents the total container flow through the terminal, handling volume reflects the number of operational moves, which may differ due to transshipment and rehandling activities. As highlighted in Stahlbock and Voß (2008), there is no fixed one-to-one quantitative relationship between these two indicators, and their difference depends on terminal-specific operational characteristics and cargo flow structures. Third, the handling volume in the simulation is estimated based on relevant statistical standards for container terminal operations, which may differ from the actual throughput statistics reported by the terminal. In addition, container flows are inherently uncertain and influenced by complex operational factors, including cargo mix, transshipment demand, and temporal

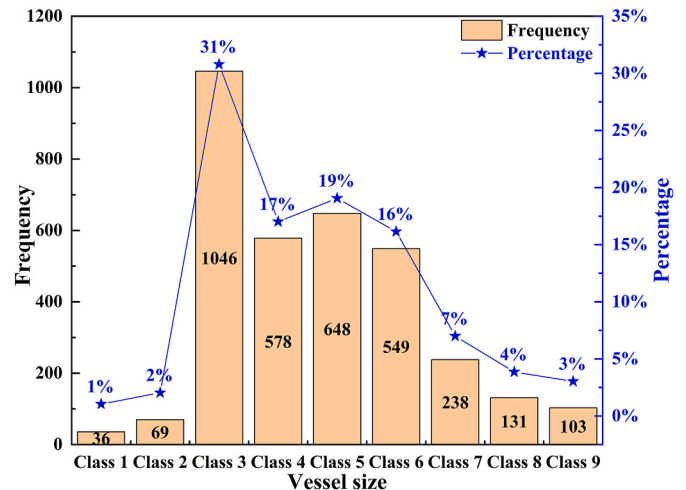


Fig. 7. Histogram distributions of ship sizes in the simulation.

Table 14
Simulated vessel characteristics and associated operational parameters.

Class	DWT (k ton)	Percentage	Handling volume per ship (TEU)	Berths	Range of L_{ME} (kW)	Range of L_{AE} (kW)	Range of L_{AB} (kW)
Class 1	5 (4.5-7.5)	1.0%	200-999	1-9.	41-1197	429	273
Class 2	10 (7.5-12.5)	2.0%	301-1199	1-9.	66-1848	429	273
Class 3	20 (12.5-27.5)	30.8%	300-1200	1-9.	84-3976	966	352
Class 4	30 (27.5-45)	17.0%	600-1500	1-9.	140-6946	516-916	352-420
Class 5	50 (45-65)	19.1%	800-2500	1-9.	287-8698	945-1148	420-597
Class 6	70 (65-85)	16.1%	2000-3000	3-9.	1094-10868	945-1225	597-678
Class 7	100 (85-115)	7.0%	2000-3000	3-9.	838-13018	980-1225	511-678
Class 8	120 (115-135)	3.9%	3000-3998	8, 9.	1162-13725	1163-1341	511-694
Class 9	150 (135-175)	3.0%	3000-4000	8, 9.	972-13725	1148-1780	354-694

variations in vessel arrivals. These factors introduce unavoidable discrepancies between simulated and observed values. Therefore, the observed deviation does not materially affect the study objectives, which focus on comparative scenario analysis and policy evaluation rather than exact throughput prediction. Similar levels of deviation have also been reported in previous port simulation studies (Wan et al., 2021). Hence, the comparison between empirical inputs and simulation outputs suggests that the model adequately reproduces key operational characteristics of SCT and provides a reliable basis for further analysis.

Under this baseline scenario, the average handling volume per vessel is 1571 TEU. The mean handling time is 18.68 h, with an average anchorage waiting time of 3.18 h, resulting in a total port time of 21.86 h. The corresponding average berth and quay crane utilisation rates are 80.39% and 63.58%, respectively.

Regarding emissions, total annual emissions from ships at SCT range from approximately 89 to 104 thousand tons. Table 15 lists the percentage contributions of different emissions. CO₂ overwhelmingly dominates total emissions, accounting for 98% to 99%. Owing to the sensitivity of NO_x to low-load MEs, the share of NO_x emissions exhibits greater variability, ranging from 0.29% to 1.02%. The remaining pollutants, SO₂, PM, and CO, each contribute less than 1% of total emissions. From a spatial perspective, ship-at-berth emissions constitute the majority of in-port emissions, representing 83% to 85% of the total, thereby identifying berthing operations as the dominant emission stage. In terms of emission sources, AEs and ABs are the primary contributors, accounting for 52.71%-53.56% and 37.02%-39% of total emissions, respectively. Emissions from low-load MEs during berthing range from 8.29% to 9.42%, driven mainly by substantial and variable NO_x and CO emissions under low-load operating conditions. On a per-ship basis, average emissions during a port stay range from 26 to 31 tons. The results clearly indicate that ship-at-berth emissions dominate total in-port emissions, suggesting that targeted mitigation measures during berthing, such as SP, can deliver substantial emission reductions at the port level.

5.2.1.2. S2: Baseline arrivals with 20% SP utilisation. S2 examines conditions under which vessels arrive at the terminal following baseline arrival patterns, with 20% of ships utilising SP. The simulation results are analysed under two policy settings: S2 (SP-only) and S2' (SP with Berthing-priority). For analytical clarity, the simulation indicators are classified into three groups: (1) Indicators marked with “•”, which

Table 15
Percentage contribution of ship emissions by category.

Category	Lower-bound contribution (%)	Upper-bound contribution (%)
By emissions	CO ₂ (98.93%), SO ₂ (0.62%), NO _x (0.29%), PM (0.11%), and CO (0.06%).	CO ₂ (98.14%), NO _x (1.02%), SO ₂ (0.62%), PM (0.12%), and CO (0.11%).
By emission locations	Berth (83.31%) and anchor (14.69%).	Berth (85.49%) and anchor (14.51%).
By emission sources	AEs (52.71%), ABs (39.00%), and low-load MEs (8.29%).	AEs (53.56%), ABs (37.02%), and low-load MEs (9.42%).

exhibit negligible absolute and relative changes and are therefore considered insensitive to scenario variation; (2) Indicators marked with “♦”, which vary in line with overall scenario trends; and (3) Indicators marked with “>”, which display significantly large changes, indicating high sensitivity to policy intervention. The results of port operational performance in S2 are illustrated in Fig. 8.

From the perspective of port operational performance, S2 (SP-only) shows no statistically significant impact on terminal port operations relative to S1. In contrast, the introduction of berthing-priority in S2' for SP-equipped vessels leads to pronounced operational effects. Compared with S1, the average ship-at-anchor time and ship-in-port time for SP-equipped vessels decrease by 61.09% and 9.29%, respectively, whereas non-SP vessels experience increases of 40.86% and 5.65%, respectively. Consequently, the system-wide average anchorage waiting time rises to 3.83 h, while the average ship-in-port time reaches 22.44 h, corresponding to increases of 20.2% and 2.62%, respectively.

Relative to S2 (SP-only), berthing-priority further reduces anchorage waiting time for SP-equipped vessels by 63.96%, while the impact on non-SP vessels and system averages remains moderate. However, due to the relatively low share of SP-equipped vessels and the limited contribution of ship-at-anchor time to ship-in-port time, the average increase remains modest, at 14.82% for anchorage time and 2.29% for port time. These findings indicate that berthing-priority policies may significantly improve operational efficiency for SP-equipped vessels and provide a strong incentive for SP adoption, while imposing moderate performance losses on non-SP vessels, thereby revealing an inherent trade-off between targeted incentives and system-wide operational efficiency.

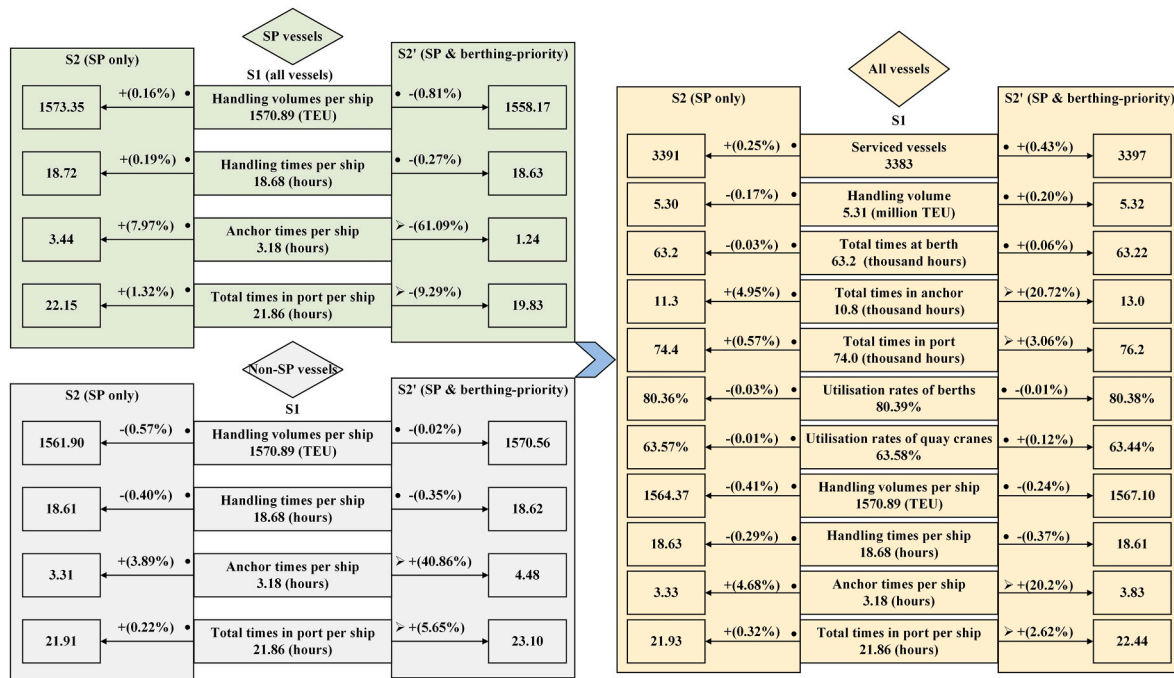
With respect to emissions, Fig. 9 shows distinct effects of SP adoption and berthing-priority policies across vessel types and system levels.

Under S2 (SP-only), average ship-at-berth emissions for SP vessels decline from 22.58-26.60 tons to 11.07-12.86 tons (approximately 51%), while average ship-in-port emissions decrease by approximately 43%. Consequently, aggregate ship-at-berth and ship-in-port emissions across all vessels are reduced by approximately 10% and 8%, respectively.

When berthing-priority is introduced (S2'), the effects become more differentiated. Although reductions in ship-at-berth emissions remain similar to those observed under S2, the berthing-priority policy further lowers average ship-at-anchor emissions for SP-equipped vessels by approximately 61.0%. In contrast, non-SP vessels experience a roughly 40% increase in anchorage emissions due to longer waiting times. As a result, average ship-in-port emissions decrease by over 53% for SP-equipped vessels but increase by approximately 5.3% for non-SP vessels.

At the system level, S2' continues to reduce total ship-at-berth emissions by about 10%; however, total ship-at-anchor emissions increase by 12.8%-22.1%, offsetting part of the environmental gains and limiting the reduction in total ship-in-port emissions to only 5.8%-7.2%. Accordingly, total ship-in-port emissions under S2' ([83.46, 96.60] kton) are about 0.9%-2.3% higher than those under S2 ([81.42, 95.55] kton). This outcome is primarily attributable to the extended anchorage time experienced by non-SP vessels, with the 80th percentile anchorage waiting time increasing from 3.34 h to 4.48 h.

These findings indicate that, at a 20% SP utilisation rate, an SP-only



Scenario comparison of port operational performance (%)

Vessel type	Time type	S2 vs. S1	S2' vs. S1	S2' vs. S2
All-vessels	Ship-at-berth time per ship	-0.29%	-0.37%	0.09%
	Ship-at-anchor time per ship	4.68%	20.20%	14.82%
	Ship-in-port time per ship	0.32%	2.62%	2.29%
SP-vessels	Ship-at-berth time per ship	/	/	-0.46%
	Ship-at-anchor time per ship	/	/	-63.96%
	Ship-in-port time per ship	/	/	-10.48%
Non-SP vessels	Ship-at-berth time per ship	0.40%	-0.35%	0.06%
	Ship-at-anchor time per ship	3.89%	40.86%	35.59%
	Ship-in-port time per ship	0.22%	5.65%	5.42%

Fig. 8. Comparison of port operational performance indicators between S1 and S2.

strategy achieves greater overall emission reductions, whereas the berthing-priority policy redistributes emissions across vessel groups. Although the policy strengthens incentives for SP adoption and further reduces emissions from SP-equipped vessels, it may increase aggregate emissions by exacerbating congestion-related anchorage delays for non-SP vessels. Importantly, the additional emissions originate predominantly from anchorage operations rather than berth activities, suggesting that improvements in berth-side air quality achieved through SP deployment may be accompanied by higher system-level emissions arising from congestion-induced anchorage delays.

5.2.2. Sensitivity analysis

To further explore the impacts of SP and its berthing-priority policy on ship-in-port performance, this paper conducts a sensitivity analysis focusing on variations in SP utilisation rates and ship arrival volumes. Scenarios 1 to 6 are used to assess the multiple effects of different SP utilisation levels under a fixed ship arrival pattern. Additionally, S1, S2, S7, and S8 are designed to investigate the influence of increased ship arrivals on key performance indicators, both with and without SP and the associated berthing-priority policy.

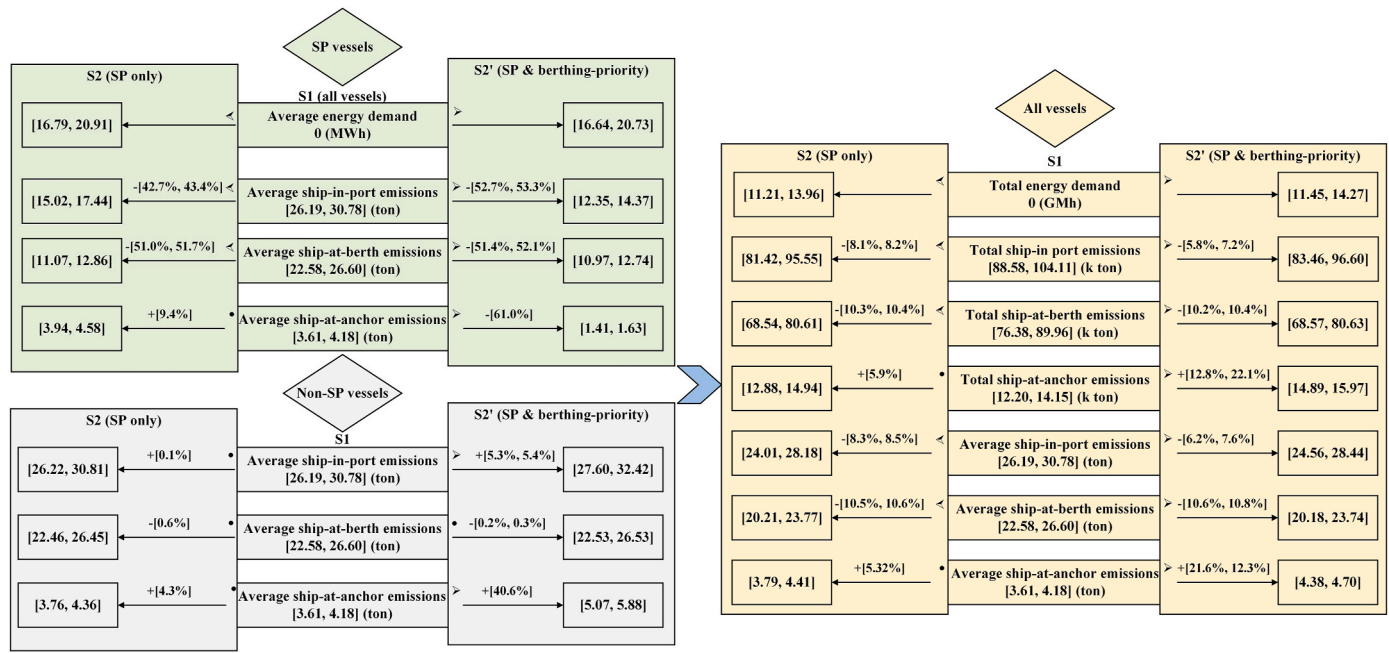
5.2.2.1. Effects of varying SP utilisation rates. In Scenarios 1 to 6, ships arrive at an average inter-arrival time of 2.66 h, while SP utilisation rates are set at 0, 20%, 40%, 60%, 80%, and 100%, respectively. These scenarios are designed to evaluate the effects of increasing SP adoption on ship-in-port performance before and after the implementation of

berthing-priority measures.

(1) Effects of varying SP utilisation rates without berthing-priority

Simulation results for Scenarios 1 to 6 (SP-only) indicate that the realised SP utilisation rates closely match the predefined scenario levels (20%, 40%, 60%, 80%, and 100%). Building on the results from S2, Scenarios 2 to 6 further analyse the relationship between SP utilisation and emissions outcomes, as shown in Fig. 10.

As the SP utilisation rate increases from 0% to 100%, average ship-at-berth and ship-in-port emissions for SP-equipped vessels remain consistently low, reflecting the substantial reductions observed under S2. Compared with S1, these emissions are reduced by approximately 51% (ship-at-berth) and 43% (ship-in-port), and remain relatively stable across higher utilisation levels (Fig. 10(3) and (4)). In contrast, increasing SP utilisation leads to a progressive and near-linear decline in average emissions across all vessels (Fig. 10. (5) and (6)). Specifically, average ship-at-berth emissions decrease from 22.5–26.6 tonnes to 11.0–12.8 tonnes, while average ship-in-port emissions fall from 26.2–30.8 tonnes to 14.9–17.3 tonnes. At SP utilisation rates of 20%, 40%, 60%, 80% and 100%, the reductions in average ship-at-berth emissions and ship-in-port emissions per vessel reach 11%, 21%, 31%, 42%, and 51%, and 8%, 17%, 26%, 37%, and 43%, respectively (Fig. 10. (2)). These results demonstrate that higher SP utilisation rates lead to substantial and systematic reductions in ship-in-port emissions, confirming the effectiveness of SP as a key measure for improving port air



Scenario comparison of port environmental indicators (%)

Vessel type	Emission type	S2 vs. S1	S2' vs. S1	S2' vs. S2
All-vessels	Ship-in-port emissions per ship	-[8.3%, 8.5%]	-[6.2%, 7.6%]	+ [0.9%, 2.3%]
	Ship-at-berth emissions per ship	-[10.4%, 10.6%]	-[10.6%, 10.8%]	-[0.1%, 0.2%]
	Ship-at-anchor emissions per ship	+5.32%	+ [12.3%, 21.57%]	+ [6.7%, 15.4%]
SP-vessels	Ship-in-port emissions per ship	/	/	- 17.60%
	Ship-at-berth emissions per ship	/	/	- 0.90%
	Ship-at-anchor emissions per ship	/	/	- 64.3%
Non-SP vessels	Ship-in-port emissions per ship	+0.1%	+ [5.3%, 5.4%]	+ [5.2%, 5.3%]
	Ship-at-berth emissions per ship	-0.6%	- [0.2%, 0.3%]	+0.3%
	Ship-at-anchor emissions per ship	+4.3%	+40.6%	+34.8%

Fig. 9. Comparison of port environmental indicators between S1 and S2.

quality.

In addition to the overall emission reductions, Table 16 further reveals the changes in emission composition and pollutant-specific mitigation effects under different SP utilisation levels. Despite the substantial reductions in total emissions, the relative composition of pollutants remains largely stable across scenarios. CO₂ consistently dominates the emission profile, accounting for approximately 98.6%–98.8% of total emissions, while SO₂, PM, NO_x, and CO contribute only marginal shares. A slight downward trend is observed for NO_x and CO, indicating a modest shift in emission structure as SP utilisation increases. In terms of pollutant-specific reductions, all emission categories exhibit monotonic and progressive declines with increasing SP utilisation, consistent with the system-level trends shown in Fig. 10. However, the magnitude of reduction varies across pollutants. Notably, CO and NO_x show the highest sensitivity to SP utilisation, with reductions reaching up to 66.18% and 54.62%, respectively, under S6. By comparison, CO₂ reductions are relatively lower in percentage terms (up to 43.04%), but remain dominant in absolute emission reduction due to its overwhelming share in total emissions. These results indicate that increasing SP utilisation not only reduces total emissions but also delivers disproportionate mitigation benefits for air pollutants such as CO and NO_x. This suggests that SP adoption plays a particularly important role in improving local air quality, even though the overall emission structure remains largely unchanged.

(2) Effects of varying SP utilisation rates with berthing-priority

The results for S2'–S6 under the SP with berthing-priority setting are presented in Fig. 11 and reveal pronounced changes in operational indicators. As shown in Fig. 11(1), the proportion of SP-equipped vessels increases progressively from 0% in S1 to 100% in S6', while the total number of serviced vessels remains relatively stable across scenarios. Fig. 11(2)–(4) further reveals differentiated operational impacts across vessel types. For SP-equipped vessels, average ship-at-anchor time remains relatively low at moderate utilisation levels, increasing only slightly from 1.2 h in S2' to 1.9 h in S5', before rising to 3.4 h under full SP utilisation (S6). Correspondingly, average ship-in-port time remains broadly stable at approximately 20 h, with a moderate increase observed only at the highest utilisation level. In contrast, non-SP vessels experience progressively deteriorating operational performance as SP utilisation increases. Average anchorage waiting time rises continuously from 3.2 h in S1' to 10.1 h in S5', while average ship-in-port time increases from 21.9 h to 28.7 h. This pattern suggests that increasing SP utilisation intensifies competition for berth resources and disproportionately affects non-SP vessels through extended waiting times. Under the full SP utilisation scenario (S6), no non-SP vessels remain in the simulated vessel population, leading to a corresponding reduction in their waiting and port times to zero. At the system level (Fig. 11(4)), average ship-in-port time remains relatively stable, fluctuating within a

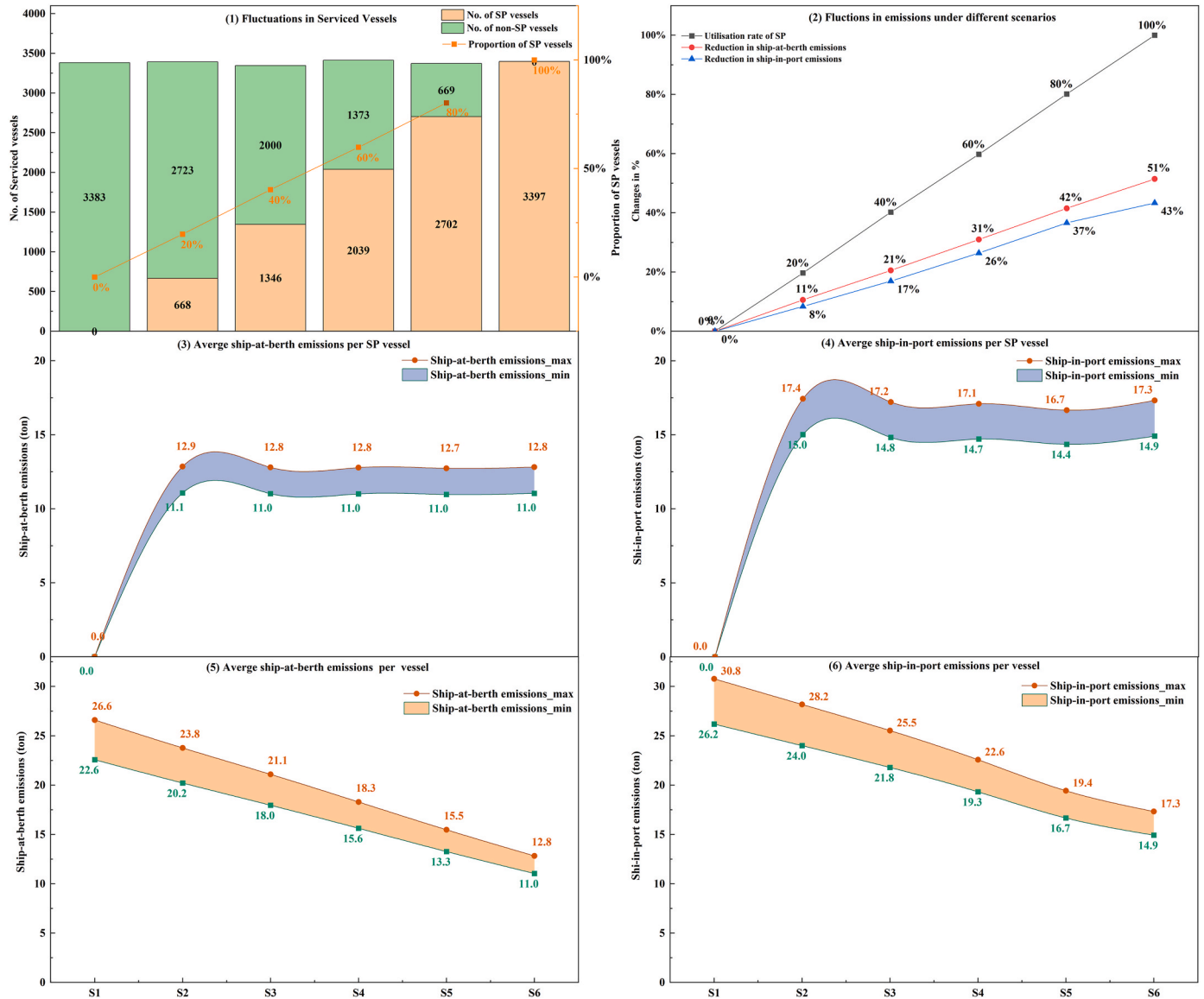


Fig. 10. Comparative analysis of ship-in-port performance indicators with significant changes across Scenarios 1 to 6 (SP-only).

Table 16
Percentage contribution and reduction of ship emissions by pollutant under different scenarios (%).

Category	Pollutant	S1	S2	S3	S4	S5	S6
Percentage contribution (%)	CO ₂	98.63%	98.60%	98.64%	98.67%	98.70%	98.78%
	SO ₂	0.62%	0.62%	0.62%	0.62%	0.62%	0.62%
	PM	0.11%	0.11%	0.11%	0.11%	0.10%	0.10%
	NO _x	0.66%	0.64%	0.61%	0.58%	0.54%	0.48%
	CO	0.08%	0.08%	0.07%	0.07%	0.06%	0.05%
Reduction relative to S1 (%)	CO ₂	0.00%	8.18%	17.83%	25.75%	36.78%	43.04%
	SO ₂	0.00%	8.18%	17.83%	25.76%	36.79%	43.05%
	PM	0.00%	9.69%	20.83%	30.29%	42.75%	50.65%
	NO _x	0.00%	10.51%	22.41%	32.65%	45.80%	54.62%
	CO	0.00%	12.74%	26.94%	39.56%	55.04%	66.18%

narrow range of approximately 21.9–23 h across all scenarios. Average anchorage waiting time exhibits a modest increase at intermediate SP utilisation levels before declining slightly at higher utilisation rates. This indicates that, despite substantial redistribution effects between SP and non-SP vessels, the overall operational performance of the terminal remains broadly stable. Fig. 11(5) further compares average anchorage waiting time and total port time under SP-only and SP with berthing-

priority scenarios. The results show that berthing-priority consistently reduces ship-at-anchor time and ship-in-port time for SP-equipped vessels while increasing delays for non-SP vessels. These differences become more pronounced at intermediate SP utilisation levels, highlighting the transitional trade-offs introduced by priority-based operational policies during the early stages of SP adoption. These results indicate that the initial implementation of berthing-priority policies may

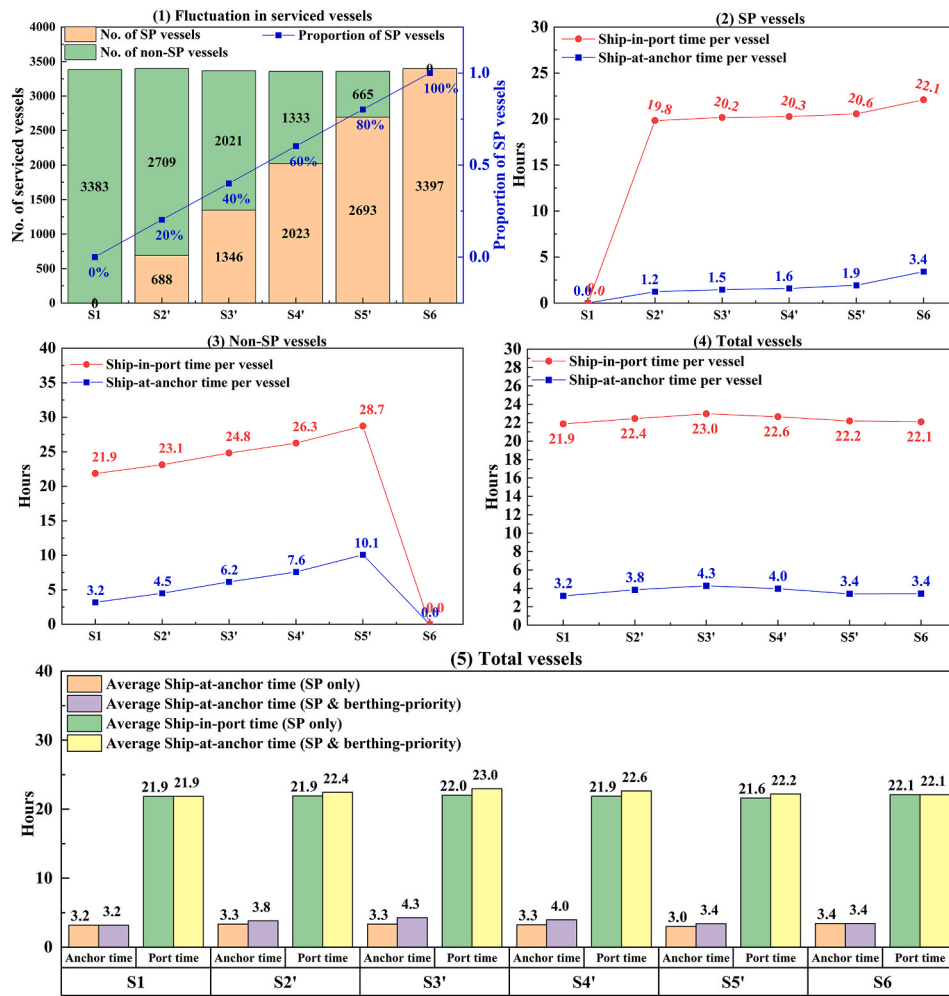


Fig. 11. Comparative analysis of operational indicators with significant changes across multiple scenarios.

increase anchorage congestion due to unequal service allocation. However, as SP adoption expands, this effect weakens and ultimately disappears as SP utilisation approaches full adoption.

Fig. 12 illustrates the evolution of environmental indicators for vessels under different SP utilisation rates with berthing priority. For SP-equipped vessels (Fig. 12(1-3)), the adoption of SP leads to a substantial reduction in berth-related and total in-port emissions relative to S1. Average ship-at-berth emissions decrease sharply from approximately 22.6–26.0 tons to 11.0–12.8 tons, representing a reduction of about 51%, while average ship-in-port emissions decline from 26.2 to 30.8 tons to approximately 14.9–17.3 tons, corresponding to a reduction of about 43% across Scenarios 1–6. By contrast, average ship-at-berth emissions remain relatively low under moderate SP utilisation levels but gradually increase as SP utilisation approaches 100%, reaching approximately 3.9–4.5 tons under S6. This trend suggests that SP adoption delivers substantial emission-reduction benefits for SP vessels, particularly during the early stages of policy implementation. For non-SP vessels (Fig. 12 (4–6)), average ship-at-berth emissions remain largely unchanged across Scenarios 1–5, indicating that SP adoption has limited direct effects on berth-related emissions for vessels without SP capability. However, average ship-at-berth emissions increase substantially with SP utilisation, rising from approximately 3.6–4.2 tons in S1 to 11.0–12.7 tons in S5'. Correspondingly, average ship-in-port emissions increase from 26.2–30.8 tons to 33.5–39.3 tons. These results indicate that non-SP vessels experience the greatest environmental disadvantages during the transitional stages of SP adoption, when SP-equipped and non-SP vessels coexist and compete for limited berth resources. At the system

level (Fig. 12(7-9)), average ship-at-berth emissions across all vessels decline almost linearly as SP utilisation increases, with each additional 20% increase in SP utilisation yielding an approximate 10% reduction in berth-related emissions. Correspondingly, average ship-in-port emissions decrease overall, with reductions of approximately 8%, 17%, 26%, 37%, and 43% across Scenarios 2'–6, respectively. In contrast, average ship-at-berth emissions exhibit a non-linear pattern, initially increasing during the intermediate stages of SP adoption, reaching a peak under S3' (40% SP utilisation), and subsequently declining as SP utilisation approaches full adoption. This wave-like trend indicates that anchorage-related emissions become most pronounced during the transitional phase of SP adoption, when SP-equipped vessels are preferentially allocated to berths while non-SP vessels experience longer anchorage delays. As SP utilisation approaches 100%, anchorage-related emissions gradually return to near-baseline levels due to the disappearance of non-SP vessels and the reduction in asymmetric berth competition.

Fig. 13 compares environmental indicators across scenarios 1–6 under SP-only and SP with berthing-priority settings. The results reveal that: (1) Average ship-at-berth emissions are highly similar under both policy settings and decline almost linearly with increasing SP utilisation. (2) Average ship-at-berth emissions are considerably more sensitive to berthing-priority and exhibit a pronounced non-linear pattern. Under the SP-only setting, anchorage-related emissions remain relatively stable across scenarios. By contrast, under the berthing-priority setting, anchorage emissions initially increase, with the effect being most pronounced at low SP utilisation levels (20%–

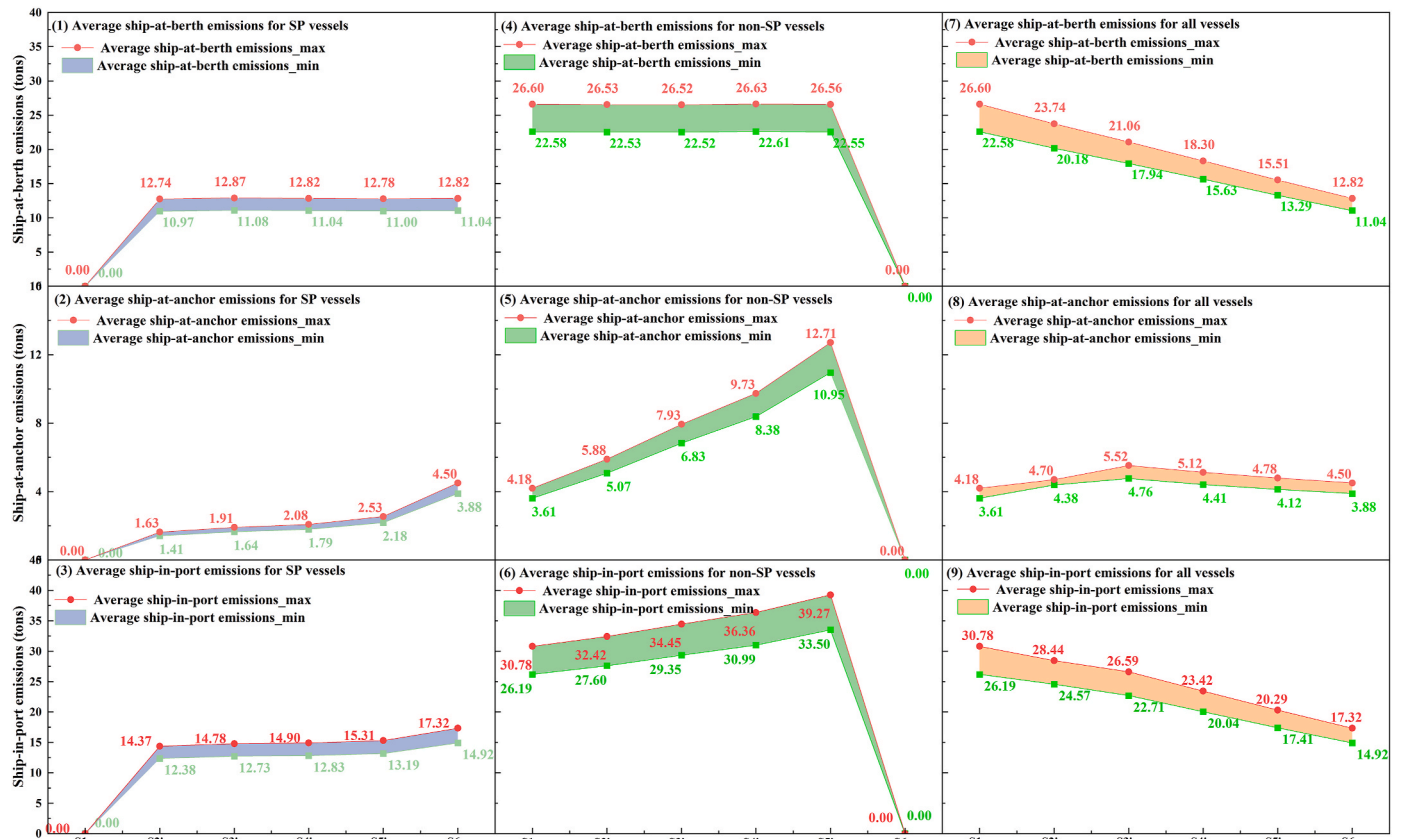


Fig. 12. Comparative analysis of environmental indicators with significant changes across multiple scenarios.

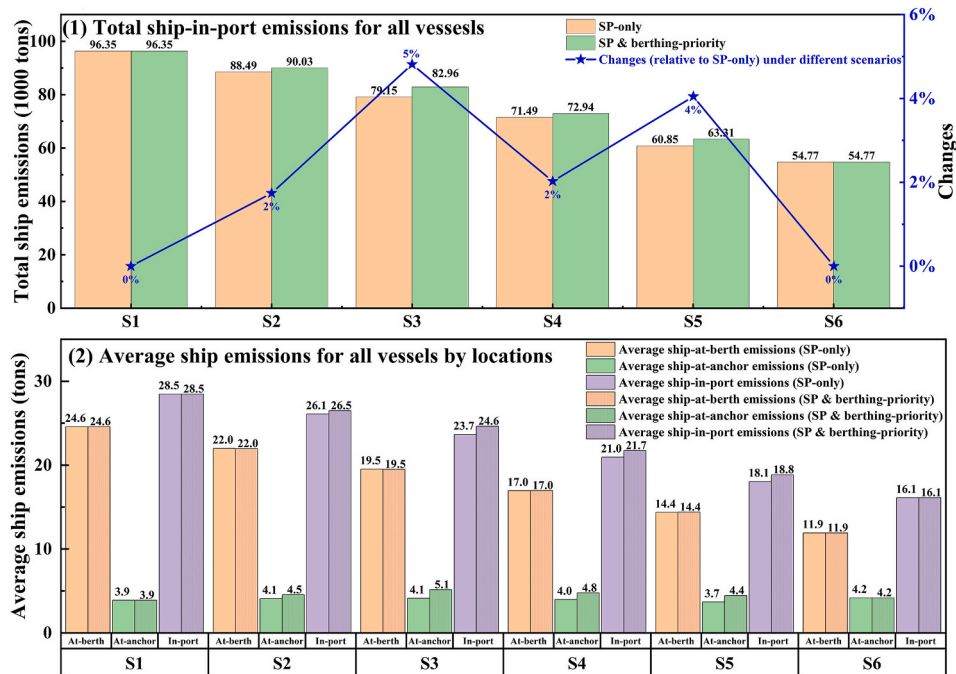


Fig. 13. Comparative analysis of environmental indicators under SP-only and SP with berthing-priority policies.

40%), then gradually decline at intermediate utilisation levels (40%–80%), and eventually converge towards the SP-only levels as SP utilisation approaches full adoption. This pattern indicates that anchorage-related spillover effects are most significant during the transitional phase of SP adoption. (3) Total ship-in-port emissions for all vessels

decrease monotonically as SP utilisation increases from 0% to 100% under both policy settings, confirming the overall effectiveness of SP adoption in reducing port-related emissions. (4) Relative to the SP-only case, both average and total ship-in-port emissions for all vessels remain consistently higher under the SP with berthing-priority setting across

Scenarios 2–5. These differences are most evident at low and intermediate SP utilisation levels and gradually diminish as SP penetration increases. These results suggest that the environmental consequences of berthing-priority exhibit clear stage-dependent characteristics and are strongly influenced by the coexistence ratio of SP-equipped and non-SP vessels.

Table 17 presents the emission composition by pollutant under berthing-priority settings. The percentage contributions of different pollutants are highly similar to those reported in Table 16 under the SP-only setting, with CO₂ consistently accounting for the overwhelming majority of total emissions, while SO₂, PM, NO_x, and CO contribute relatively small shares. However, compared with the SP-only case, the emission reduction rates are consistently higher under berthing-priority settings. Specifically, the differences in total emission reductions between the two policy settings are approximately 2.2%, 4.8%, 2.0%, 3.7%, and 0% across Scenarios 2–6, respectively. This further confirms that berthing-priority policies may increase overall pollutant emissions during the transitional stages of SP adoption. These findings indicate that operational benefits for SP-equipped vessels may come at the expense of higher anchorage emissions from non-SP vessels, thereby reducing the net environmental benefits of SP deployment. As SP utilisation approaches full adoption, the differences between the two policy settings gradually diminish, suggesting that the additional environmental impacts of berthing-priority become negligible under high SP penetration levels.

5.2.2.2. Effects of varying ship arrival intervals.

(1) Effects of varying ship arrival intervals without SP

Under the no-SP setting, Scenarios S1, S7, and S8 are used to examine the effects of baseline, 10%, and 20% increases in vessel arrival rates, respectively, with Fig. 14 presenting the corresponding ship-in-port performance across different traffic conditions. As shown in Fig. 14 (1), increases in vessel arrivals have a limited influence on handling-related indicators. Average handling volume per vessel and handling time per vessel remain broadly stable across scenarios, indicating that terminal handling efficiency is largely maintained under higher traffic intensity. Meanwhile, the number of serviced vessels rises from 3283 in S1 to 3713 and 4042 in S7 and S8, respectively. Fig. 14(2) and (3) show that congestion-related indicators are considerably more sensitive to traffic growth. Average ship-at-anchor time increases sharply from 3.18 h in S1 to 6.42 h in S7 and 25.82 h in S8, leading to corresponding increases of 14% and 103% in average ship-in-port time. A similar amplification effect is observed for environmental indicators. While average ship-at-berth emissions remain relatively stable, average ship-at-anchor emissions increase by 123% and 871%, and average ship-in-port emissions rise by 135% and 150% in S7 and S8, respectively

(Fig. 14(3)). These results indicate that increasing vessel arrival rates primarily affects anchorage-related performance and generates pronounced non-linear congestion effects as traffic demand approaches terminal capacity limits.

(2) Effects of varying ship arrival intervals with SP-only

Based on the no-SP analysis, Table 18 and Fig. 15 further examine the effects of SP deployment on ship-in-port operational and environmental performance under varying vessel arrival intensities with SP utilisation rates of 20% and 40% in the absence of berthing-priority measures. The operational indicators show trends similar to those observed under the no-SP setting, whereas the primary differences are reflected in the environmental indicators owing to the emission-reduction benefits of SP deployment.

Environmental impacts exhibit a pronounced amplification pattern as vessel arrival intensity increases. Under SP-utilisation settings, ship-at-anchor emissions grow non-linearly with rising traffic demand, substantially outpacing the increase in ship-at-berth emissions and becoming the dominant source of incremental emissions. In Scenario S8, anchorage-related emissions account for approximately 58% and 69% of total ship-in-port emissions under the 20% and 40% SP-utilisation settings, respectively. Consequently, total ship-in-port emissions increase sharply as traffic intensity rises. Relative to the corresponding baseline scenarios, a 20% increase in vessel arrivals increases total ship-in-port emissions by approximately 141% and 168% under the 20% and 40% SP-utilisation settings, respectively, largely driven by congestion-induced growth in anchorage emissions.

At the vessel level, average ship-at-anchor and ship-in-port emissions increase substantially for both SP-equipped and non-SP vessels, whereas average ship-at-berth emissions remain largely unchanged across scenarios. This finding confirms that the deterioration in environmental performance is driven primarily by prolonged anchorage delays rather than berth operations.

Despite these adverse congestion effects, higher SP utilisation continues to reduce berth-related emissions under elevated traffic conditions. When vessel arrivals increase by 10%, each additional 20% increase in SP utilisation reduces total ship-at-berth emissions by approximately 10%, while total ship-in-port emissions increase by 1%–13%, suggesting that part of the environmental benefits of SP are offset by increased anchorage emissions. Under a 20% increase in vessel arrivals, berth-related emissions continue to decline by around 10%; however, total ship-in-port emissions initially decrease by approximately 6% before increasing by about 13% as anchorage congestion intensifies.

These findings indicate that, although increasing SP utilisation remains effective in reducing berth-side emissions, overall environmental performance under high-traffic conditions is increasingly constrained by

Table 17
Percentage contribution and reduction of ship emissions by pollutant across scenarios with berthing-priority.

Category	Pollutant	S1	S2'	S3'	S4'	S5'	S6
Percentage contribution	CO ₂	98.59%	99.05%	98.60%	98.65%	98.34%	98.76%
	SO ₂	0.62%	0.62%	0.62%	0.62%	0.62%	0.62%
	PM	0.11%	0.11%	0.11%	0.11%	0.10%	0.10%
	NO _x	0.69%	0.67%	0.64%	0.60%	0.56%	0.50%
	CO	0.08%	0.08%	0.07%	0.07%	0.06%	0.05%
Reduction relative to S1	CO ₂	0.00%	6.13%	13.89%	24.26%	34.46%	43.06%
	SO ₂	0.00%	6.13%	13.89%	24.26%	34.46%	43.07%
	PM	0.00%	7.60%	16.79%	28.50%	40.06%	50.12%
	NO _x	0.00%	9.49%	20.52%	33.78%	46.94%	58.75%
	CO	0.00%	10.56%	22.70%	37.26%	51.67%	64.82%
Increase relative to SP-only	CO ₂	0.00%	2.24%	4.80%	2.03%	3.70%	0.00%
	SO ₂	0.00%	2.24%	4.80%	2.03%	3.70%	0.00%
	PM	0.00%	2.21%	4.83%	2.10%	3.95%	0.00%
	NO _x	0.00%	2.08%	4.63%	2.05%	4.12%	0.00%
	CO	0.00%	2.21%	5.05%	2.43%	4.86%	0.00%

(1) Comparison of indicators between S1, S7, and S8 (without SP)

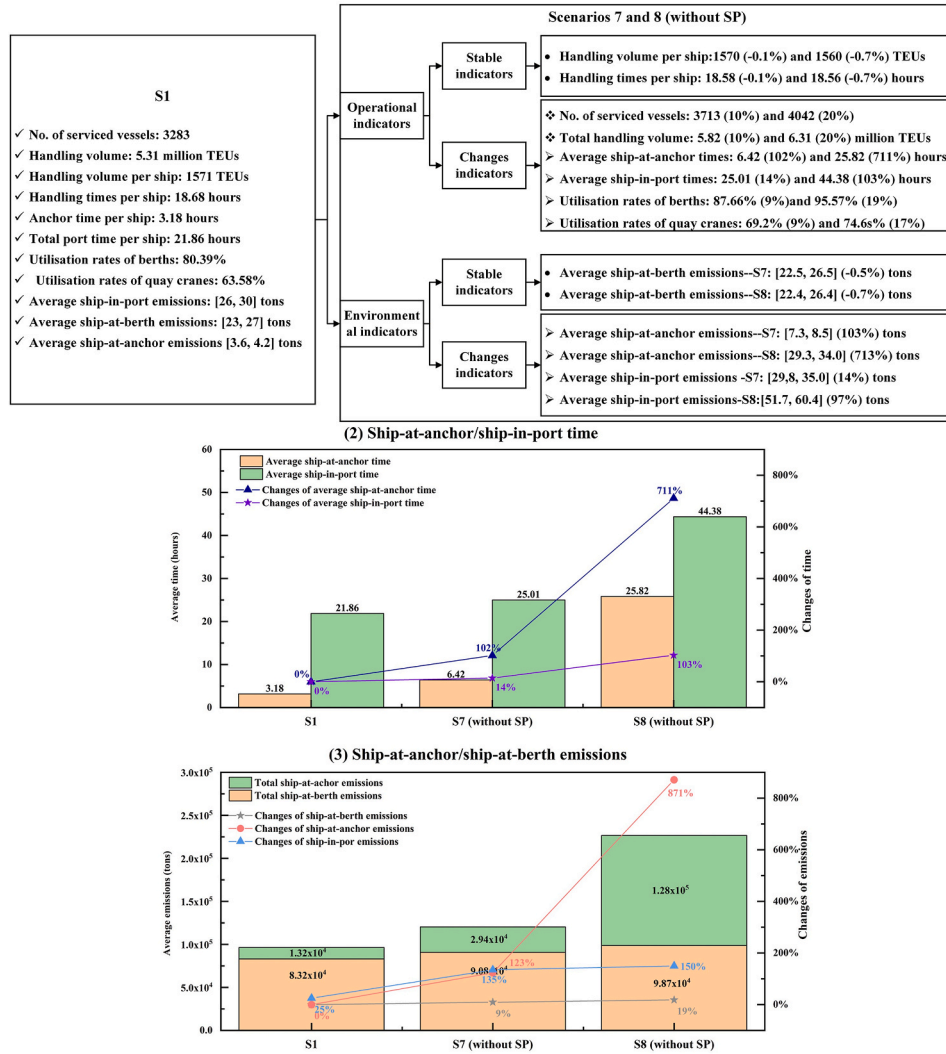


Fig. 14. Comparative analysis of ship-in-port performance with varying ship arrivals without SP.

Table 18

Ship-in-port operational indicators under varying vessel arrival rates with 20% and 40 SP utilisation under SP-only settings.

Metric	Units	SP-only (20%)			SP-only (40%)		
		S2	S7'	S8'	S3	S7'	S8'
Serviced vessels	/	3391	3738	4041	3346	3703	4058
SP-equipped vessels	/	688	759	815	1346	1494	1615
Non-SP vessels	/	2709	2980	3225	2021	2209	2444
Total handling volume	mTEU	5.30	5.85	6.32	5.26	5.81	6.36
Average handling volume	TEU	1564	1565	1564	1571	1569	1568
Average ship-at-berth time	Hour	18.63	18.61	18.61	18.69	18.62	18.62
Average ship-at-anchor time	Hour	3.33	8.17	25.07	3.34	7.04	35.62
Average ship-in-port time	Hour	21.93	26.63	43.67	22.03	25.67	54.23

anchorage congestion. As vessel arrival intensity approaches or exceeds terminal capacity limits, the environmental benefits of SP deployment may be substantially eroded by congestion-related emissions. These results highlight the need to integrate SP deployment with traffic management strategies, capacity enhancements, and complementary operational measures to mitigate anchorage congestion and preserve system-wide environmental benefits.

(3) Effects of varying ship arrival rates under SP with berthing-priority

Table 19 presents terminal operational performance under varying vessel arrival rates with 20% and 40% SP utilisation levels with the berthing-priority policy in place. The results exhibit patterns broadly similar to those observed under the no-SP and SP-only scenarios, with the principal differences arising from the differentiated impacts of the priority mechanism on SP-equipped and non-SP vessels. SP-equipped vessels experience shorter anchorage and ship-in-port times than non-SP vessels, and the differences become more pronounced as traffic intensity increases. Under the 40% SP-utilisation setting, for example, the average ship-in-port time of non-SP vessels reaches 75.46 h in S8''',

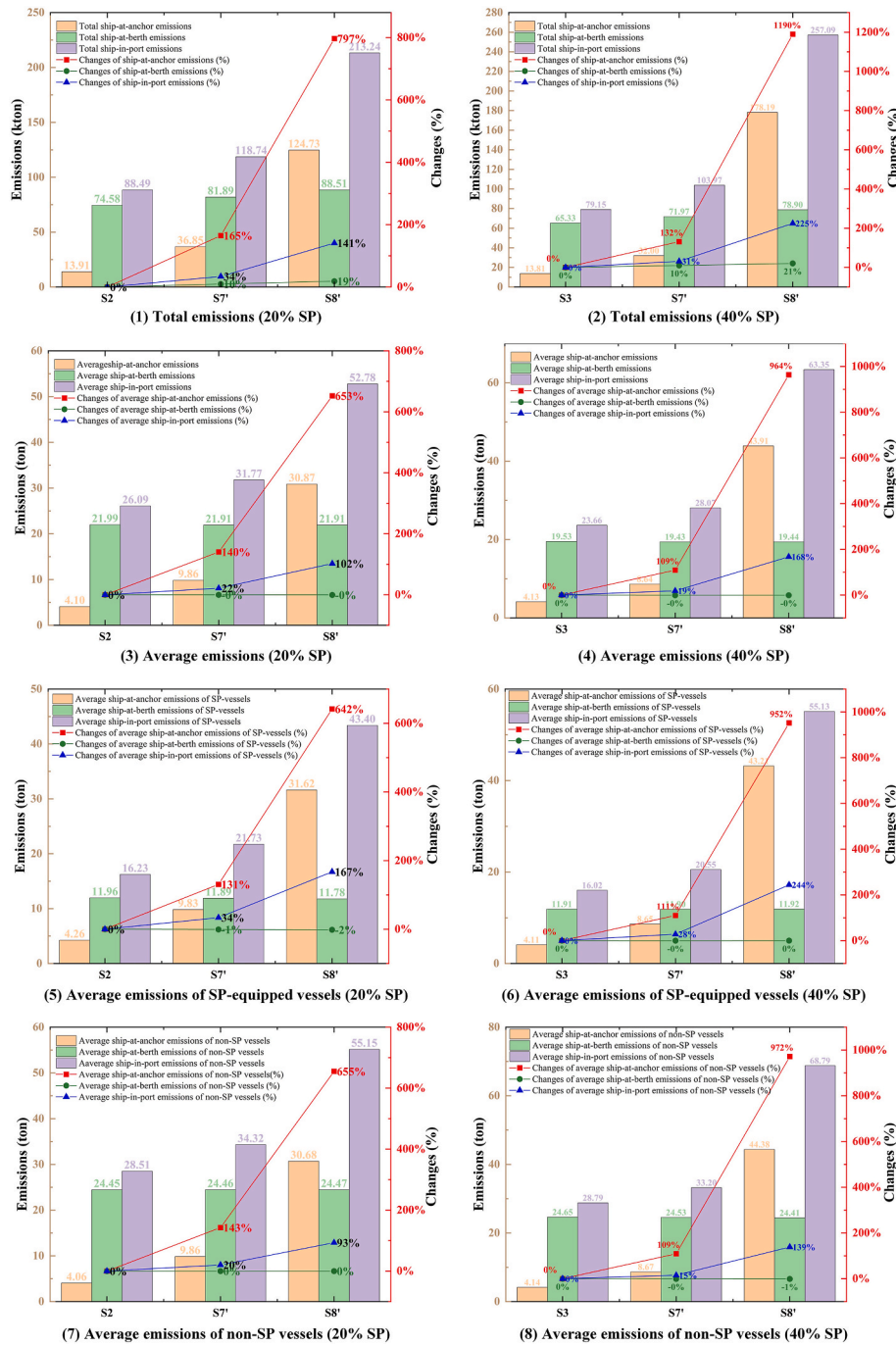


Fig. 15. Ship-in-port environmental indicators under varying vessel arrival rates with 20% and 40% utilisation under SP-only settings.

compared with only 21.38 h for SP-equipped vessels. This divergence indicates that berthing-priority policies can shift congestion burdens towards non-SP vessels under heavily congested operating conditions. Accordingly, at the 20% SP-utilisation level, average ship-at-anchor time increases from 3.83 h in S2' to 8.17 h in S7'' and further to 31.29 h in S8'', while average ship-in-port time rises from 22.44 to 26.84 and 49.85 h, respectively. A similar but more pronounced pattern is observed at the 40% SP-utilisation level, where average ship-at-anchor time increases from 4.28 h in S3' to 35.16 h in S8''', accompanied by an increase in average ship-in-port time from 22.96 to 53.73 h. These findings suggest that even moderate increases in vessel arrivals can trigger disproportionate growth in anchorage congestion as terminal operations approach capacity limits.

Compared with the corresponding SP-only scenarios, the effects of

berthing-priority are mixed and highly dependent on traffic conditions. At the 20% SP-utilisation level, average ship-at-anchor time increases by 14.8% in S2' and by 24.8% in S8'' relative to the corresponding SP-only cases, with average ship-in-port time increasing by 2.3% and 14.2%, respectively. At the 40% SP-utilisation level, ship-at-anchor time increases by 28.0% in S3' and 31.9% in S7''', while average ship-in-port time rises by 4.2% and 8.7%, respectively. However, under the most congested scenario (S8'''), both ship-at-anchor time and ship-in-port time decline marginally by 1.3% and 0.9%, respectively. Overall, the berthing-priority policy improves turnaround performance for SP-equipped vessels but extends anchorage delays for non-SP vessels, resulting in complex trade-offs between vessel-level benefits and system-wide operational performance.

Environmental impacts broadly mirror the operational patterns

Table 19

Ship-in-port operational indicators under varying vessel arrival rates with 20% and 40 SP utilisation under SP with berthing-priority settings.

Metric	Units	SP with berthing-priority (20%)			SP with berthing-priority (40%)		
		S2'	S7''	S8''	S3'	S7'''	S8'''
Serviced vessels	/	3397	3719	4059	3366	3707	4038
SP-equipped vessels	/	688	745	818	1346	1480	1614
Non-SP vessels	/	2709	2974	3241	2020	2227	2424
Total handling volume	mTEU	5.32	5.85	6.32	5.28	5.79	6.27
Average handling volume	TEU	1567	1574	1558	1567	1562	1554
Average ship-at-berth time	Hour	18.61	18.66	18.56	18.68	18.60	18.57
Average ship-at-anchor time	Hour	3.83	8.17	31.29	4.28	9.29	35.16
SP-equipped vessels	Hour	1.24	1.87	2.47	1.46	2.03	2.81
Non-SP vessels	Hour	4.48	9.76	38.55	6.16	14.11	56.89
Average ship-in-port time	Hour	22.44	26.84	49.85	22.96	27.89	53.73
SP vessels	Hour	19.83	20.53	21.06	20.17	20.59	21.38
Non-SP vessels	Hour	23.10	28.42	57.11	24.81	32.74	75.46
*Changes of ship-at-anchor time	%	14.8%	0.0%	24.8%	28.0%	31.9%	-1.3%
*Changes of ship-in-port time	%	2.3%	0.8%	14.2%	4.2%	8.7%	-0.9%

Note: *Changes in average ship-at-anchor time and average ship-in-port time are calculated relative to the SP-only scenarios under the same SP utilisation level and vessel arrival rate.

observed in Fig. 16, with the main difference concentrated in congestion-related indicators. In particular, both total and average ship-at-anchor emissions exhibit strong non-linear growth as vessel arrival intensity increases. Under the same SP utilisation setting, ship-at-anchor emissions increase by approximately 118%–142% in S7 and more than 729%–909% in S8 relative to corresponding baseline scenarios (S2' or S3') (Fig. 16 (1)–(4)). Correspondingly, ship-in-port emissions rise by 21%–33% in S7 and 127%–202% in S8. The amplification effect is more pronounced at the 40% SP-utilisation level, indicating that environmental performance deteriorates rapidly as traffic demand approaches terminal capacity limits.

The environmental consequences of congestion are distributed unevenly across vessel groups. For SP-equipped vessels, average ship-at-anchor emissions increase from 1.54 tons in S2' to 2.27 tons in S7'' and 2.95 tons in S8'' under the 20% SP utilisation setting, representing increases of 50% and 94%, respectively. Similar patterns are observed under the 40% SP-utilisation setting, where average ship-at-anchor emissions increase from 1.78 tons in S3' to 2.46 tons in S7''' and 3.36 tons in S8'''. However, the increase is substantially greater for non-SP vessels. Under the most congested scenarios, anchorage-related emissions for non-SP vessels exceed berth-related emissions and become the dominant contributor to ship-in-port emissions. This finding suggests that congestion spillovers generated by berthing-priority operations are transferred disproportionately to non-SP vessels.

Compared with the corresponding SP-only scenarios, the environmental effects of berthing-priority policies depend strongly on both SP utilisation and traffic intensity. In most cases, berthing-priority settings result in higher overall emissions, particularly under moderate SP-utilisation levels and elevated traffic demand. This occurs because the operational benefits gained by SP-equipped vessels are partly offset by increased anchorage delays and associated emissions among non-SP vessels. Nevertheless, the adverse environmental impacts of berthing-priority diminish as SP utilisation increases, indicating that the policy becomes more effective when a larger share of vessels can benefit from preferential berth access.

The results suggest that increases in vessel arrival intensity can substantially amplify congestion-related emissions, potentially offsetting the environmental gains from SP deployment. These findings highlight the need to coordinate SP deployment with traffic management, capacity planning, and complementary operational measures to mitigate congestion spillovers and preserve system-wide environmental benefits.

5.2.3. Equipment utilisation analysis

Fig. 17 presents the effects of SP utilisation, vessel arrival intensity, and berthing-priority policies on berth and quay crane utilisation. The

two indicators follow closely aligned trends across all scenarios, reflecting the strong operational linkage between berth occupancy and quay crane deployment.

The results show that equipment utilisation is driven primarily by vessel arrival intensity rather than by SP utilisation or berthing-priority policies. Under baseline traffic conditions (S1–S6 and corresponding scenarios), berth and quay crane utilisation remain relatively stable at approximately 79%–81% and 63%–64%, respectively. When vessel arrivals increase by 10% (S7 and corresponding scenarios), utilisation rises to around 88%–89% for berths and 69%–70% for quay cranes. Under a 20% increase in vessel arrivals (S8 and corresponding scenarios), berth utilisation approaches 96%, while quay crane utilisation reaches approximately 74%–75%. On average, every 10% increase in vessel arrivals raises berth utilisation by approximately 7.8 percentage points and quay crane utilisation by 5.6 percentage points.

These findings suggest that traffic growth, rather than SP deployment or berthing-priority policies, is the principal driver of capacity pressure and congestion formation. Because all berths are assumed to be SP-compatible, changes in SP utilisation do not materially affect berth availability or resource allocation. Instead, increasing traffic demand pushes terminal operations progressively closer to their practical capacity limits.

The implications become particularly evident under the high-demand scenarios (S8 and corresponding scenarios), where berth utilisation approaches saturation. Under such conditions, additional traffic cannot be accommodated efficiently, resulting in a rapid escalation of anchorage waiting times and associated emissions. Consequently, anchorage operations rather than berth activities become the primary source of system-wide delays and environmental impacts. These results highlight the importance of considering terminal capacity constraints when promoting SP adoption. While SP deployment can improve environmental performance at berth, its effectiveness may be limited if traffic growth generates severe congestion outside the terminal. Therefore, SP policies should be coordinated with capacity planning, traffic management measures, and infrastructure investment to ensure that environmental gains are not undermined by congestion-related operational inefficiencies. It should be noted that these findings are based on the assumption that all berth are SP-compatible. In ports where SP-compatible and conventional berths coexist, competition for limited SP-capable infrastructure may create more complex utilisation patterns and congestion dynamics, potentially altering both operational and environmental outcomes.

5.2.4. Port energy demand and power characteristics of SP

Fig. 18 shows the distribution of SP energy demand across vessel classes and simulation scenarios. As shown in Fig. 18 (1), SP energy

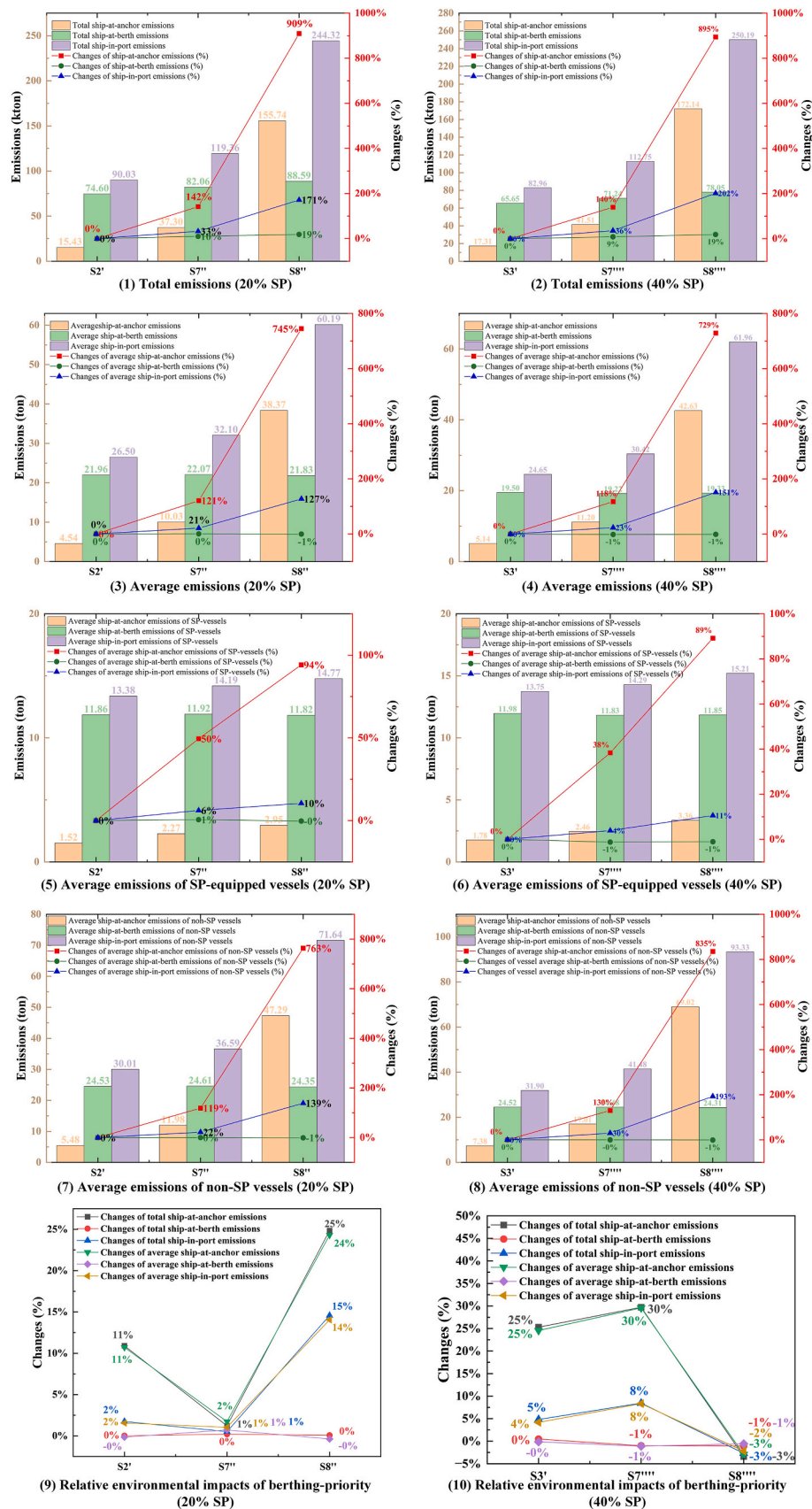


Fig. 16. Comparative analysis of ship-in-port performance indicators with varying ship arrivals, with 20% and 40% utilisation rates, and berthing-priority.

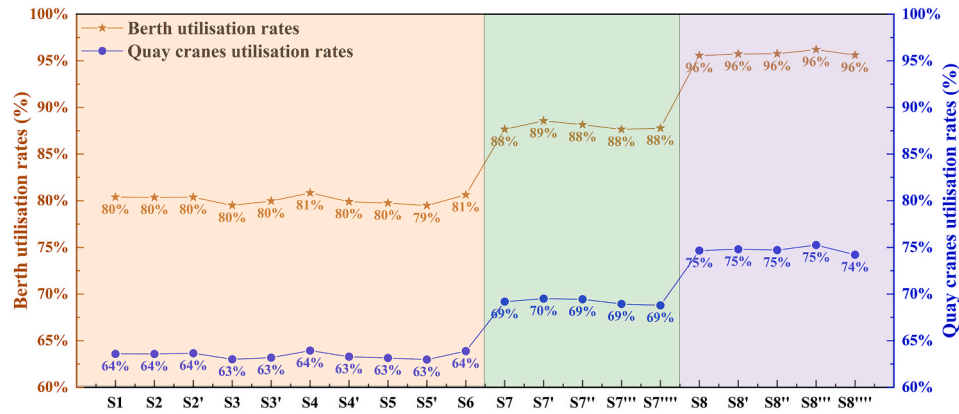


Fig. 17. Effects of SP utilisation and vessel arrival intensity on berth and quay crane utilisation rates.

consumption increases markedly with vessel size. Per-call SP energy consumption ranges from 4.47 MWh for Class 1 vessels to 45.22 MWh for Class 9 vessels, with an overall average of 19.5 MWh per vessel, reflecting the larger auxiliary power requirements and more complex onboard systems of larger vessels. While smaller vessels exhibit relatively low and concentrated demand levels, medium and large vessels account for a disproportionately large share of SP electricity consumption and display greater variability in energy use.

Fig. 18 (2) illustrates the evolution of aggregate SP energy consumption across scenarios. Under baseline traffic conditions (Scenarios S2–S6), average SP energy consumption rises from 12.59 GWh at 20% SP utilisation (S2) to 63.79 GWh under full SP adoption (S6), representing a 407% increase relative to S2. The near-linear relationship between SP utilisation and electricity demand indicates that aggregate SP consumption is primarily determined by the proportion of vessels connected to SP. At a given SP utilisation level, the introduction of berthing-priority policies has only a negligible influence on total SP energy consumption. For example, SP energy consumption changes from

12.59 GWh in S2 to 12.86 GWh in S2', from 25.26 GWh in S3 to 25.35 GWh in S3', and from 50.48 GWh in S5 to 50.07 GWh in S5'. In all cases, the differences remain below 3%, indicating that berthing-priority affects the timing of berth allocation rather than the total amount of electricity consumed. Higher vessel arrival rates further increase SP demand across all utilisation levels. Under the 10% higher arrival-rates' scenarios (S7 series), SP energy consumption rises to 14.24 GWh at 20% SP utilisation and 27.99 GWh at 40% SP utilisation, corresponding to increases of 13% and 122% relative to S2, respectively. Similar patterns are observed under the 20% higher arrival-rate scenarios (S8 series).

These results demonstrate that both SP utilisation and vessel arrival intensity influence electricity demand; however, SP utilisation remains the dominant driver, while the impact of berthing-priority policies on aggregate energy consumption is marginal. Consequently, large-scale SP adoption is expected to substantially increase port electricity demand, highlighting the importance of long-term power supply planning, grid capacity expansion, and integrated energy management strategies to ensure reliable and efficient operation under high-utilisation conditions.

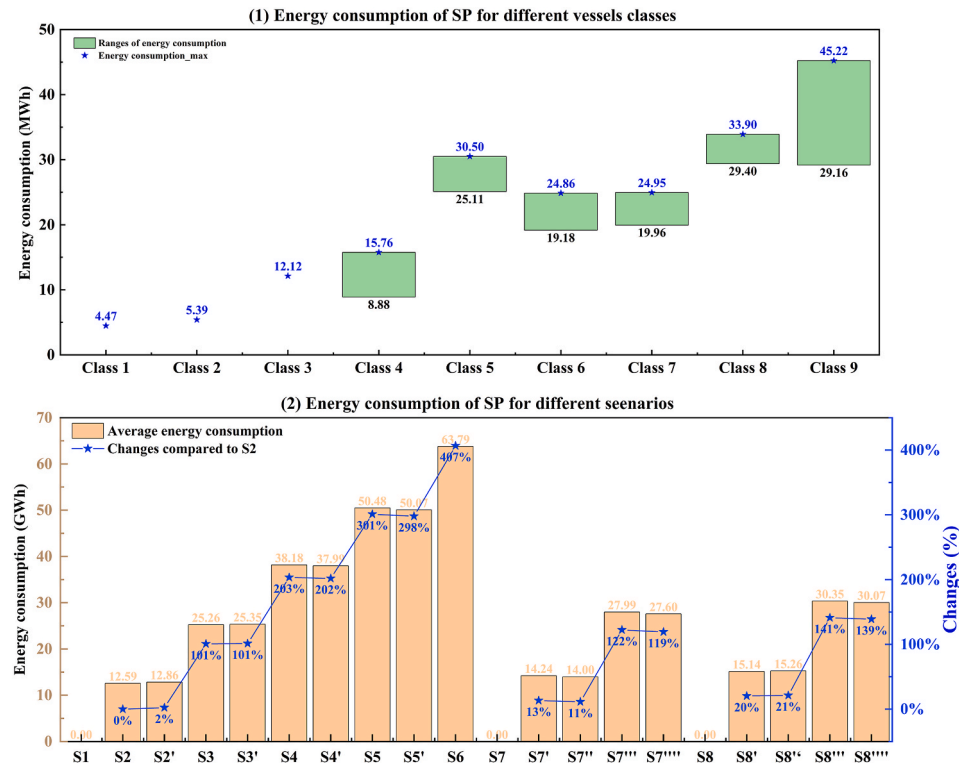


Fig. 18. Energy demand of SP for different vessel classes and scenarios.

Fig. 19 and Table 20 jointly illustrate the characteristics of port-wide real-time power demand of SP demand under different SP utilisation levels, vessel arrival intensities, and berth allocation policies.

The results show that SP utilisation is the principal determinant of both average and peak electricity demand. Under baseline traffic conditions, mean power demand increases from 1.44 MW at 20% SP utilisation (S2) to 7.31 MW under full SP adoption (S6), while peak demand rises from 5.67 MW to 10.37 MW. These results indicate that large-scale SP deployment will substantially increase port electricity requirements and place greater demands on supporting energy infrastructure.

Beyond increasing demand levels, higher SP utilisation also alters load characteristics. Although the standard deviation of power demand increases from 1.16 MW in S2 to 1.91 MW in S6, the coefficient of variation declines from 0.81 to 0.26. This suggests that, despite larger

absolute fluctuations, electricity demand becomes relatively more stable and predictable as SP adoption expands, reflecting an aggregation effect associated with multiple connected vessels.

Vessel arrival intensity further elevates both average and peak demand across all SP-utilisation levels. However, its influence is primarily reflected in higher load levels rather than fundamental changes in load patterns. By contrast, berthing-priority policies have little effect on aggregate electricity consumption, with differences in mean demand generally remaining below 5% across comparable scenarios. Nevertheless, berthing-priority tends to increase short-term load variability by concentrating vessel connections within narrower time windows, leading to slightly higher coefficients of variation.

The results indicate that SP utilisation governs the scale and predictability of port electricity demand, whereas vessel arrival intensity

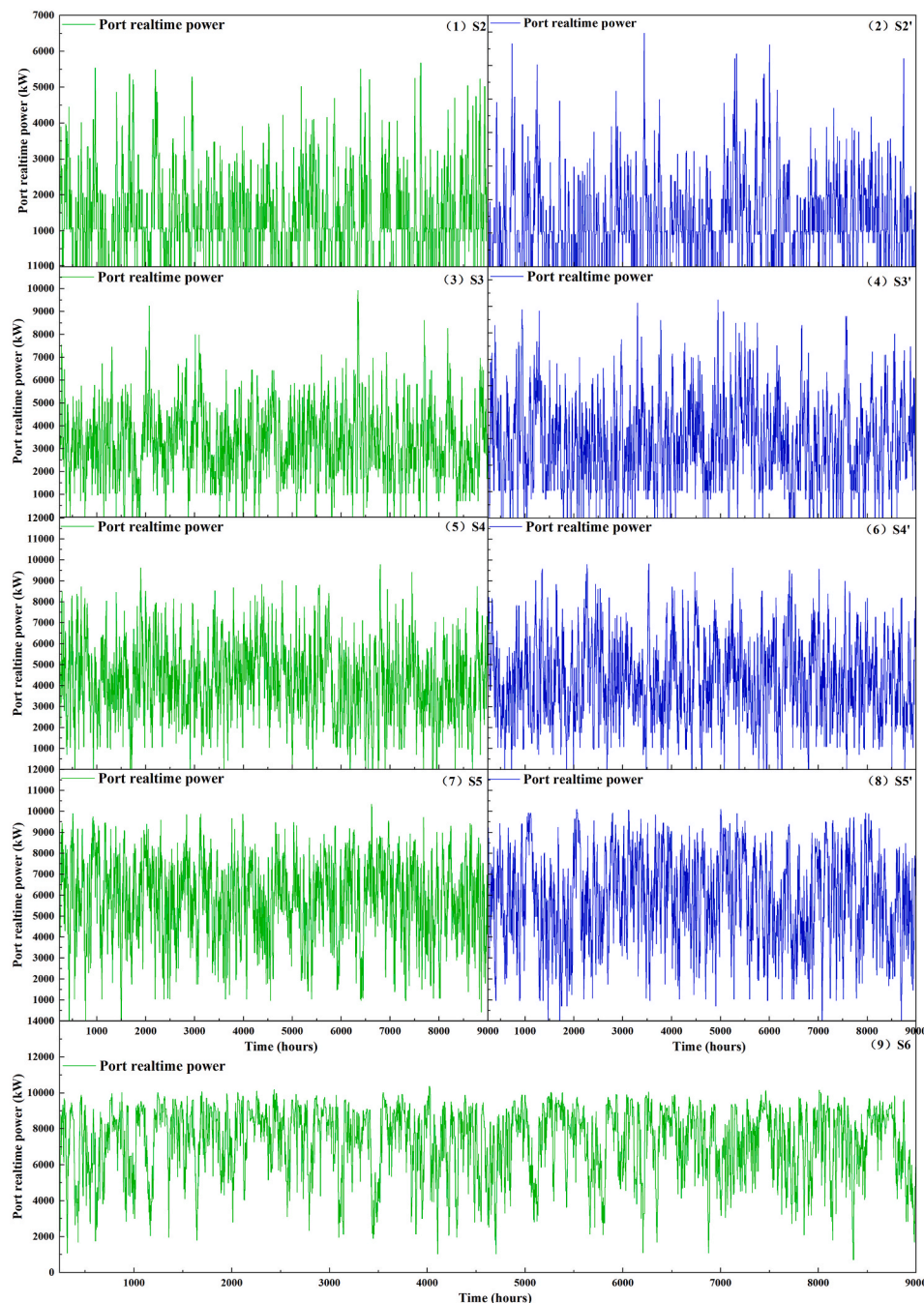


Fig. 19. Port real-time power.

Table 20

Statistical characteristics of port-wide real-time power demand of SP under different scenarios.

Scenarios	Maximum (kW)	Minimum (kW)	Range (kW)	Mean (kW)	Variance	Standard Deviation (kW)	Coefficient of Variation	Peak-to-valley difference rate
S2	5674.0	0	5674.0	1438.46	1353525	1163.41	0.8088	394.5%
S2'	6967.0	0	6967.0	1394.73	1421961	1192.46	0.8550	499.5%
S3	10050.5	0	10050.5	2877.43	2236208	1495.40	0.5197	349.3%
S3'	8858.5	0	8858.5	2896.70	2771549	1664.80	0.5747	305.8%
S4	9771.0	0	9771.0	4274.85	3125324	1767.86	0.4135	228.6%
S4'	9805.5	0	9805.5	4263.72	3583199	1892.93	0.4440	230.0%
S5	10344.5	0	10344.5	5817.36	3611250	1900.33	0.3267	177.8%
S5'	10097.5	0	10097.5	5808.78	4567442	2137.16	0.3679	173.8%
S6	10369.0	716	9653.0	7311.41	3650295	1910.57	0.2613	132.0%
S7'	6455.0	0	6455.0	1504.04	1339797	1157.50	0.7696	429.2%
S7''	7280.0	0	7280.0	1683.78	1736265	1317.67	0.7826	432.4%
S7'''	9919.5	0	9919.5	3230.57	2383937	1544.00	0.4779	307.1%
S7''''	9856.0	0	9856.0	3284.56	2784671	1668.73	0.5081	300.1%
S8'	7047.5	0	7047.5	1771.45	1540042	1240.98	0.7005	397.8%
S8''	7265.0	0	7265.0	1714.86	1706678	1306.40	0.7618	423.6%
S8'''	8484.5	0	8484.5	3382.87	2373646	1540.66	0.4554	250.8%
S8''''	10442.5	0	10442.5	3431.29	3432127	1852.60	0.5399	304.3%

and berthing-priority policies mainly influence its temporal distribution. These findings provide important insights for power-supply planning, peak-load management, demand-response strategies, and the design of integrated port energy systems under large-scale SP deployment.

5.3. Summary of key findings

Based on the simulation analysis in Section 5, the results are consistent with the qualitative expectations and offer a rigorous quantitative evaluation of the impact of SP and its berthing-priority policy. The proposed OEPP simulation framework is shown to effectively capture the operational, environmental, and energy-related interactions of vessels in port. The key findings are summarised as follows:

- (1) SP utilisation is an effective strategy for reducing ship-at-berth-related emissions.

Under the SP-only setting, emissions decrease almost linearly with increasing SP utilisation. Relative to the no-SP scenario, SP utilisation rates of 20%, 40%, 60%, 80%, and 100% SP reduce total ship-at-berth emissions by approximately 11%, 21%, 31%, 42%, and 51%, respectively, while total ship-in-port emissions decline by 8%, 17%, 26%, 37%, and 43%. The largest reductions are observed for local pollutants, reaching 66.18% for CO and 54.62% for NO_x. These results confirm that expanding SP adoption is an effective and scalable pathway for simultaneously achieving emission mitigation and air-quality improvement in port areas.

- (2) Berthing-priority policies generate transitional trade-offs between operational efficiency and environmental performance, and their effectiveness depends strongly on SP utilisation levels and traffic conditions.

Berthing-priority substantially improves operational performance for SP-equipped vessels but increases anchorage delays and emissions for non-SP vessels. Consequently, both average and total ship-in-port emissions under the berthing-priority setting remain approximately 2%–5% higher than those under the corresponding SP-only scenarios during the transitional stages of SP adoption, with the additional emissions primarily originating from anchorage congestion rather than berth operations. These adverse effects become more pronounced as vessel arrival intensity increases. Under several high-traffic scenarios, anchorage-related emissions exceed berth-related emissions and become the dominant source of total ship-in-port emissions. The results further reveal clear stage-dependent characteristics. Congestion-induced spill-overs are most evident at low SP utilisation levels, gradually diminished

at intermediate utilisation levels, and become negligible as SP utilisation approaches full adoption. These findings are derived from the case terminal considered in this study and may vary under different port operating conditions.

- (3) Vessel arrival intensity has a stronger influence on port performance than SP utilisation.

While berth-side handling efficiency remains relatively stable across all scenarios, increases in vessel arrivals lead to severe anchorage congestion and strong non-linear deterioration in operational and environmental performance. A 20% increase in vessel arrivals causes average anchorage waiting time to increase by more than eightfold and total ship-in-port emissions to increase by more than 140% under several scenarios. These results indicate that congestion effects associated with traffic growth can substantially outweigh the emission-reduction benefits of SP deployment.

- (4) Anchorage-related emissions become the dominant source of environmental deterioration under high-traffic conditions.

Although SP effectively reduces berth-related emissions, increasing traffic intensity results in rapid growth of anchorage-related emissions. Under severe congestion scenarios, anchorage emissions account for up to 58%–69% of total ship-in-port emissions, exceeding berth-related emissions and becoming the primary contributor to overall environmental impacts. This finding highlights the importance of incorporating congestion effects into evaluations of port decarbonisation measures.

- (5) Equipment utilisation is primarily determined by vessel arrival intensity rather than SP utilisation or berthing-priority policies. Berth and quay crane utilisation remain relatively stable across different SP utilisation levels, reflecting the full SP coverage of the terminal. In contrast, higher vessel arrival rates significantly increase equipment utilisation and push the terminal toward its practical capacity limits. Under the highest traffic scenario, berth utilisation approaches 96%, resulting in substantial increases in anchorage waiting time and associated emissions.
- (6) Large-scale SP deployment substantially increases port electricity demand while improving load regularity.

SP utilisation is the dominant determinant of port-wide electricity demand. As SP utilisation increases from 20% to 100%, mean real-time power demand rises from 1.44 MW to 7.31 MW, while peak demand increases from 5.67 MW to 10.37 MW. Although the standard deviation of power demand increases from 1.16 MW to 1.91 MW, the coefficient of

variation declines markedly from 0.81 to 0.26, indicating that the load profile becomes more stable and predictable as SP adoption expands. This reflects the aggregation effect of multiple SP-connected vessels, whereby individual demand fluctuations are smoothed at the system level. Vessel arrival intensity further increases both average demand and peak load, whereas berthing-priority policies have only marginal effects on aggregate electricity consumption and mainly influence short-term load variability. These findings reveal the dynamic characteristics of port-wide SP demand under different operational conditions and provide a quantitative basis for future research on ship scheduling under power constraints, real-time energy management, SP capacity allocation, and the coordinated optimisation of port operations and energy systems.

6. Implications

The findings of this work provide several important implications for the design of SP deployment strategies, supporting operational policies, and port decarbonisation planning.

First, the results reinforce the role of SP as a key instrument for reducing ship-related emissions in ports. The substantial emission reductions achieved under increasing SP utilisation confirm that accelerating SP adoption should remain a central objective of port decarbonisation strategies. However, the results also demonstrate that the environmental effectiveness of SP cannot be assessed solely on the basis of berth-side emission reductions. Congestion-induced emissions generated during anchorage waiting may partially offset the environmental gains achieved through SP deployment. Consequently, policy evaluation and planning should adopt a ship-in-port perspective that captures the entire vessel turnaround process rather than focusing exclusively on berth operations.

Second, the results suggest that berthing-priority policies should be implemented in a phased and adaptive manner. While priority allocation improves operational performance for SP-equipped vessels and strengthens incentives for SP adoption, it may simultaneously increase anchorage waiting times and emissions for non-SP vessels across different stages of the transition process. Importantly, these adverse environmental impacts are concentrated mainly at the anchorage rather than at the berth. Consequently, berth-side air quality can continue to improve through SP utilisation, while congestion-induced anchorage emissions may weaken overall system-level decarbonisation benefits. When SP utilisation remains relatively low (approximately $\leq 40\%$), priority allocation may generate congestion spillovers that increase delays and emissions among non-SP vessels. At intermediate SP utilisation levels (approximately 40%–80%), berthing-priority can be introduced in a conditional and congestion-responsive manner to balance operational efficiency and environmental performance. Once SP utilisation exceeds approximately 80%, the adverse spillover effects become relatively small, supporting broader implementation of berthing-priority policies. These findings suggest that port authorities should avoid applying a uniform policy throughout the transition period. Instead, congestion-responsive and utilisation-dependent priority schemes should be adopted to balance operational efficiency and environmental objectives.

Third, the findings highlight the importance of integrating SP deployment with broader congestion-management and capacity-planning strategies. Vessel arrival intensity exerts a substantially stronger influence on overall port performance than SP utilisation alone and can rapidly erode environmental gains through increased anchorage delays and associated emissions. In several high-traffic scenarios, anchorage-related emissions become the dominant contributor to total ship-in-port emissions. This suggests that SP deployment should be coordinated with berth-capacity planning, vessel-arrival management, and operational-efficiency improvements to prevent the transfer of environmental burdens from berth operations to anchorage areas.

Fourth, large-scale SP deployment will have significant implications

for port energy systems. Although higher SP utilisation substantially increases average and peak electricity demand, it also improves the predictability of the load profile through aggregation effects. These findings highlight the importance of integrating SP planning with power-system development, including SP capacity allocation, grid reinforcement, energy storage deployment, and renewable energy integration. The real-time power-demand characteristics identified in this study further provide a quantitative basis for future research on coordinated ship scheduling and port energy management under power constraints.

Finally, the proposed OEPP simulation framework demonstrates the value of integrating operational, environmental, and energy-system perspectives within a unified modelling environment. By capturing the interactions among vessel arrivals, berth allocation policies, emissions, and electricity demand, the framework provides a practical tool for evaluating policy–operation–environment–energy trade-offs. The approach is transferable to different port contexts and offers a foundation for future research on the coordinated optimisation of port operations, decarbonisation measures, and energy systems.

7. Concluding remarks

From both port and vessel perspectives, this study systematically investigates the multiple effects of SP and its berthing-priority policy on ship-in-port performance. In a structured and multi-stage research framework, this paper first reviews SP applications, related policies and regulations, and the existing literature to identify research gaps to fill up. Next, discrete-event simulation and ship emission estimation methods are justified as suitable analytical tools for this research. The third step involves integrating the real-world characteristics of container terminal operations into an integrated OEPP simulation model that explicitly accounts for SP adoption and berthing-priority mechanisms. The model is subsequently validated using data from SCT and relevant literature, supported by expert consultation, scenario analysis, and sensitivity analysis. A series of scenarios with varying SP utilisation rates and ship arrival frequencies is then simulated to evaluate the combined operational, environmental, and energy-related impacts of SP-related policies.

The findings and implications of this work are presented to summarise the characteristics of ship-in-port emissions under different scenarios, ranging from no SP to a series of SP utilisation rates, with and without berthing-priority. These findings provide a scientific and reasonable assessment of the multiple effects of SP on ship-in-port performance.

- (1) Without SP, ship-in-port emissions are substantial, with approximately 80% of total emissions generated during berthing, primarily from AEs. However, this emission structure changes significantly as traffic intensity increases. While berth-related emissions remain relatively stable, congestion-induced anchorage emissions grow nonlinearly and account for an increasingly large proportion of total ship-in-port emissions. Under severe congestion conditions, anchorage emissions may become the dominant source of ship-in-port emissions, demonstrating that traffic growth can substantially alter both the magnitude and composition of port-related emissions.
- (2) SP utilisation is confirmed as an effective and scalable emission-reduction strategy. Increasing SP utilisation from 0% to 100% results in an approximately linear reduction in emissions, with total ship-at-berth emissions decreasing by up to 51% and total ship-in-port emissions falling down by up to 43%. The largest reductions are achieved for local air pollutants, particularly CO and NO_x, demonstrating the significant contribution of SP to both port decarbonisation and local air-quality improvement.
- (3) Berthing-priority policies create transitional trade-offs between operational efficiency and environmental performance. While

priority allocation benefits SP-equipped vessels, its overall effectiveness depends on SP utilisation levels and traffic conditions. The results indicate that adaptive and phased implementation strategies are required to balance operational efficiency with environmental objectives during the transition towards large-scale SP adoption.

- (4) Vessel arrival intensity is the dominant driver of congestion and environmental performance. Moderate increases in traffic demand generate disproportionate increases in anchorage waiting time and emissions due to strong non-linear congestion effects. While a 10% increase in vessel arrivals raises total ship-in-port emissions by 14%–36%, a 20% increase results in emission increases of 97%–225%, depending on the SP policy setting. As traffic intensity approaches terminal capacity limits, anchorage-related emissions become the dominant contributor to total ship-in-port emissions, demonstrating that congestion can substantially erode the environmental benefits of SP deployment. Therefore, traffic management and capacity planning are essential complements to SP-based decarbonisation strategies.
- (5) Large-scale SP deployment has significant implications for port energy systems. Mean real-time power demand increases from 1.44 MW under 20% SP utilisation to 7.31 MW under full adoption, while peak demand rises from 5.67 MW to 10.37 MW. Although absolute load fluctuations increase, the coefficient of variation decreases from 0.81 to 0.26, indicating improved load regularity due to aggregation effects. These findings reveal the dynamic characteristics of port-wide SP demand and provide a quantitative basis for future studies on ship scheduling under power constraints, SP capacity allocation, and coordinated port-energy management.

The numerical results from the OEPP simulation framework may vary across ports, but the identified trends remain robust. The findings underscore the importance of accelerating SP adoption, implementing adaptive and context-sensitive berthing-priority policies, and coordinating SP deployment with traffic management and energy system planning. From a methodological perspective, integrating economic indicators and optimisation techniques into future extensions of the model would further support investment evaluation, policy calibration, and risk mitigation.

This work faces several limitations, which also implies future research directions. First, the model assumes fixed berth allocation and dedicated quay-crane assignment, whereas ports may adopt more flexible operational practices. Although sensitivity analyses indicate that the main behavioural patterns remain robust, alternative operational arrangements may affect the magnitude of the reported outcomes. Second, the scenario settings are intended to represent plausible SP-adoption pathways and traffic conditions. Consequently, the policy thresholds identified in this study should be interpreted as indicative rather than universally applicable and may vary across port contexts. Third, the analysis focuses on operational performance, electricity demand, and tank-to-wake emissions associated with ship-in-port activities. It does not explicitly consider electricity-system constraints, life-cycle environmental impacts, or the carbon intensity of electricity generation. As a result, the results primarily reflect the local environmental benefits of SP deployment rather than its overall decarbonisation impacts. In regions where the electricity is supplied primarily from relatively clean sources, SP is more likely to deliver substantial net environmental benefits. By contrast, in regions with carbon-intensive power systems, particularly those heavily reliant on coal-fired generation, part of the emissions burden may shift from sea to land. Other techniques such as carbon capture shall be jointly investigated to enable the benefits.

Future research may adopt a more integrated perspective by combining operational modelling with power-system analysis, life-cycle assessment, and techno-economic evaluation. An immediate piece of

follow-up work is to examine how infrastructure investment, regulatory instruments, economic incentives, and operational policies can jointly influence SP adoption under different institutional and market conditions. Extending the analysis to multiple terminals, ports, and regional port networks would enrich our understanding of how SP deployment interacts with broader transport, energy, and decarbonisation strategies. New advancements would continue to enhance effective and context-sensitive policy frameworks for accelerating the transition towards low-emission port operations.

CRedit authorship contribution statement

Jinggai Wang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ying En Ge:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Visualization, Writing – review & editing. **Zaili Yang:** Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **Huanhuan Li:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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Data availability

Data will be made available on request.

References

- Altiok, T., Melamed, B., 2007. Simulation modeling and analysis with ARENA. *Interfaces* 38, 485–487.
- Anylogic, 2022. Process modeling Library blocks. The AnyLogic Company. <https://anylogic.help/library-reference-guides/process-modeling-library/pml-blocks.html> [Accessed].
- Anylogic Simulation Software, 2023. What is discrete-event simulation modeling. The AnyLogic Company: The AnyLogic Company. Available: <https://www.anylogic.com/use-of-simulation/discrete-event-simulation/>, 2023.
- Bullock, S., Hoolohan, C., Larkin, A., 2023. Accelerating shipping decarbonisation: a case study on UK shore power. *Heliyon* 9, e17475. <https://doi.org/10.1016/j.heliyon.2023.e17475>.
- Chen, J.H., Chen, H., Shi, J., Shi, M.Y., Xu, J.Y., Jiang, H.Q., Xiang, Y., Liu, Y.N., Chen, H. Z.Y., 2025. AIS data-driven assessment of shore side electricity's emission reduction potential in China. *Transp. Policy* 167, 130–144. <https://doi.org/10.1016/j.tranpol.2025.03.027>.
- China Merchants Group, 2018. Shekou container terminals. China Merchants Group: China Merchants Group. <https://www.cmport.com.hk/enTouch/business/Infor.aspx?id=10005254>, 2018.
- China Ports and Harbors Association Container Branch 2023. Results of the 2022 annual single-category evaluation of China's port container terminals announced. *Containerization*, 34, 23–25.
- Clarksons Research, 2025. Green Technology Tracker. Clarkson Research: Clarkson Research. <https://sin.clarksons.net/>. March 2026.
- Daniel, H., Antunes, C.H., Trovao, J.P.F., Williams, D., 2023. Shore operations enhancement of bulk carriers based on a multi-objective sizing approach. *Energy Convers. Manag.* 276, 116497. <https://doi.org/10.1016/j.enconman.2022.116497>.
- Daniel, H., Trovão, J.P.F., Boulon, L., Williams, D., 2025. Shore power deployment strategies and policies including alternative fuels. *Transpn. Res. Part D: Transp. Env.* 148, 104999. <https://doi.org/10.1016/j.trd.2025.104999>.
- European Commission, 2023. European Green Deal: Ambitious New Law Agreed to Deploy Sufficient Alternative Fuels Infrastructure. European Commission, European Commission. https://ec.europa.eu/commission/presscorner/detail/en/IP_23_1867. (Accessed 28 March 2023).
- Gligor, D.M., Davis-Sramek, B., Tan, A., Vitale, A., Russo, I., Golgeci, I., Wan, X., 2021. Utilizing blockchain technology for supply chain transparency: a resource

- orchestration perspective. *J. Bus. Logist.* 43, 12287. <https://doi.org/10.1111/jbl.12287>.
- Liang, X.R., Fan, S.Q., Li, H.H., Goerlandt, F., Yang, Z.L., 2026. Freeports under the lens: securing container supply chains with a risk-based inspection framework. *Transpn Res. Part E Logist. Transport. Rev.* 208, 104658. <https://doi.org/10.1016/j.tre.2025.104658>.
- Merkel, A., Nyberg, E., Ek, K., Sjöstrand, H., 2023. Economics of shore power under different access pricing. *Res. Transport. Econ.* 101, 101330. <https://doi.org/10.1016/j.retrec.2023.101330>.
- MoT of the PRC, 2013. Design code of general layout for Sea ports. Ministry of Transport of the People's Republic of China: Ministry of Transport of the People's Republic of China. Available: https://xxgk.mot.gov.cn/2020/jigou/syj/202006/t20200623_3314130.html, 12 2013.
- Mot of the PRC, 2022. Green transportation development for 14th five-year plan. MOT of the PRC: MOT of the PRC. https://xxgk.mot.gov.cn/2020/jigou/zhghs/202201/t20220121_3637584.html. (Accessed 21 January 2022).
- MoT of the PRC, 2023. Official Interpretation of the Action Plan for the Demonstration and Promotion of Shore Power Use by International Container Ships and Cruise Ships at Port (2023–2025). Mot of the PRC. <https://gd.msa.gov.cn/html/gdmsa/xxgk/article/2023/ee8cf6a09a19b0f2389817f7b3508a17.html?hav=6RxbIVw1Mci4uCi>. (Accessed 4 September 2023).
- MoT of the PRC, 2025. Ministry of transport decision on amending the measures for the administration of port and vessel shore power. <https://gd.msa.gov.cn/html/gdmsa/xxgk/article/2025/066a548d0f08425fb2a2ba8f5fd5ac80.html>. (Accessed 13 May 2025).
- Neagoe, M., Hvolby, H.H., Taskhiri, M.S., Turner, P., 2021. Using discrete-event simulation to compare congestion management initiatives at a port terminal. *Simulat. Model. Pract. Theor.* 112, 102362. <https://doi.org/10.1016/j.simpat.2021.102362>.
- Nguyen, D.H., Lin, C., Cheruiyot, N.K., Hsu, J.Y., Cho, M.Y., Hsu, S.H., Yeh, C.K., 2021. Reduction of NOx and SO2 emissions by shore power adoption. *Aerosol Air Qual. Res.* 21, 210100. <https://doi.org/10.4209/aaqr.210100>.
- Peng, Y.T., Wang, Y.D., Li, Z.C., Sheng, D., 2023. Subsidy policy selection for shore power promotion: subsidizing facility investment or price of shore power? *Transp. Policy* 140, 128–147. <https://doi.org/10.1016/j.tranpol.2023.07.004>.
- Port of Los Angeles, 2024. Alternative maritime power. [https://www.portoflosangeles.org/environment/air-quality/alternative-maritime-power\(amp\)](https://www.portoflosangeles.org/environment/air-quality/alternative-maritime-power(amp)).
- Qi, J.W., Wang, S.A., Peng, C.S., 2020. Shore power management for maritime transportation: status and perspectives. *Maritime Transport Res.* 1, 100004. <https://doi.org/10.1016/j.martra.2020.100004>.
- Radwan, M.E., Chen, J.H., Wan, Z., Zheng, T.X., Hua, C.Y., Huang, X.L., 2019. Critical barriers to the introduction of shore power supply for green port development: case of Djibouti container terminals. *Clean Technol. Environ. Policy* 21, 1293–1306. <https://doi.org/10.1007/s10098-019-01706-z>.
- Rockwell, A., 2024. Discrete event modeling | arena simulation software. Rockwell Automation: Rockwell Automation. <https://www.rockwellautomation.com/en-us/products/software/arena-simulation/discrete-event-modeling.html>, 2024.
- Rossetti, M.D., 2015. *Simulation Modeling and Arena*.
- Shenzhen Municipal Transportation Bureau, 2022. Notice on the Announcement of Shore Power Facility Information at Shenzhen Port. Shenzhen government online: Shenzhen Municipal Transportation Bureau. http://www.sz.gov.cn/cn/xxgk/zfxxgj/tzgg/content/post_10029789.html, 2022.
- Song, Z.Z., Tang, W.S., Zhao, R.Q., Zhang, G.Q., 2022. Implications of government subsidies on shipping companies' shore power usage strategies in port. *Transpn Res. Part E Logist. Transport. Rev.* 165, 102840. <https://doi.org/10.1016/j.tre.2022.102840>.
- Stahlbock, R., Voß, S., 2008. Operations research at container terminals: a literature update. *Spectrum* 30, 1–52. <https://doi.org/10.1007/s00291-007-0100-9>.
- Starcrest, 2023. Port of Los Angeles Inventory of Air Emissions CY 2022. Starcrest Consulting Group, LLC, Port of Los Angeles. https://kentico.portoflosangeles.org/getmedia/409590b5-0e6a-4c15-8d9b-fcd02624933/2022_Air_Emissions_Inventory_August_2023.
- Stolz, B., Held, M., Georges, G., Boulouchos, K., 2021. The CO2 reduction potential of shore-side electricity in Europe. *Appl. Energy* 285, 116425. <https://doi.org/10.1016/j.apenergy.2020.116425>.
- Un Trade & Development, 2025. Merchant Fleet by Flag of Registration and by Type of Ship, Annual. UN Trade & Development: UN Trade & Development. <https://unctadstat.unctad.org/datacentre/dataviewer/US.MerchantFleet>, 2026.
- Uzun, D., Okumus, D., Dogancan, U., Gunbeyaz, S.A., Karamperidis, S., Hudson, D., Turan, O., Allan, R., 2024. Port energy demand model for implementing onshore power supply and alternative fuels. *Transpn Res. Part D: Transp. Env.* 136, 104432. <https://doi.org/10.1016/j.trd.2024.104432>.
- Wan, Z., Zhang, T., Sha, M., Guo, W., Jin, Y., Guo, J.J., Liu, Y.T., 2021. Evaluation of emission reduction strategies for berthing container ships: a case study of the Shekou container terminal. *J. Clean. Prod.* 299, 126820. <https://doi.org/10.1016/j.jclepro.2021.126820>.
- Wang, J.G., Li, H.H., Yang, Z.L., Ge, Y.E., 2024a. A novel scheme for shore power data to enhance containership-at-berth emission estimation. *Transpn Res. Part D: Transp. Env.* 134, 104353. <https://doi.org/10.1016/j.trd.2024.104353>.
- Wang, J.G., Li, H.H., Yang, Z.L., Ge, Y.E., 2024b. Shore power for reduction of shipping emission in port: a bibliometric analysis. *Transpn Res. Part E Logist. Transport. Rev.* 188, 103639. <https://doi.org/10.1016/j.tre.2024.103639>.
- Wang, J.G., Zhong, M.S., Wang, T.N., Ge, Y.E., 2023. Identifying industry-related opinions on shore power from a survey in China. *Transp. Policy* 134, 65–81. <https://doi.org/10.1016/j.tranpol.2023.02.010>.
- Wang, Z., Hu, H.T., Zhen, L., 2024c. Berth and quay cranes allocation problem with on-shore power supply assignment in container terminals. *Comput. Ind. Eng.* 188, 109910. <https://doi.org/10.1016/j.cie.2024.109910>.
- Zhang, J.L., Xin, X.R., Liao, Z.G., Dubey, R., Nguyen, T.T., Li, N., Yang, Z.L., 2025. Analysis of the ripple effects of disruptions on multimodal container terminals operations: a system dynamics approach. *Transpn Res. Part E Logist. Transport. Rev.* 202, 104264. <https://doi.org/10.1016/j.tre.2025.104264>.
- Zhen, L., Wang, W.C., Lin, S.M., 2022. Analytical comparison on two incentive policies for shore power equipped ships in berthing activities. *Transport. Res. Part E Logist. Transport. Rev.* 161, 102686. <https://doi.org/10.1016/j.tre.2022.102686>.
- Zhen, L., Yuan, Y.Y., Dan, Z.G., Psaraftis, H.N., Wang, S.A., 2023. Subsidy strategy design for shore power utilization and promotion. *Marit. Pol. Manag.* 51 (8), 1606–1638. <https://doi.org/10.1080/03088839.2023.2263010>, 2263010.
- Zheng, T., Li, J.M., Zhao, M.R., Xiao, H.P., 2025. Research on Berth Scheduling Optimization of Container Terminal Considering Shore Power Distribution. *Navigation of China. Navigation of China*.
- Zhong, Z.Y., Jin, H., Sun, Y.Y., Zhou, Y.J., 2024. Two incentive policies for green shore power system considering multiple objectives. *Comput. Ind. Eng.* 194, 110338. <https://doi.org/10.1016/j.cie.2024.110338>.