Research Topics

Global vessel-source maritime pollution governance—technical innovation and policy orientation

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Global vessel-source maritime pollution governance—technical innovation and policy orientation

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Editorial: Global vessel-source maritime pollution governance—technical innovation and policy orientation

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Editorial on the Research Topic

Global vessel-source maritime pollution governance—technical innovation and policy orientation

As we sail into an era of heightened awareness and responsibility toward our planet, the need for sustainable practices and rigorous governance in the maritime industry has never been more crucial. This Research Topic unites 13 papers from Chinese scholars that explore the landscape of global vessel-source maritime pollution governance, presenting valuable insights into technical innovation and policy orientation.

The opening salvo is from Dong et al., who critically examine decarbonization laws and policies on international, regional, and national scales. They underscore the importance of striking the right balance between unilateral and uniform regulation while identifying areas for improvement in the shipping industry's ongoing decarbonization efforts. Their work sets the stage for the issue, providing a comprehensive analysis of global maritime decarbonization governance.

The following papers concentrate on China, a pivotal player in maritime activities. Sun et al. challenge the notion that shore power universally reduces carbon emissions, pointing to the limitations of China's coal-heavy energy structure. Their work calls on the government to develop shore power initiatives in tune with local conditions and to significantly increase clean energy's share in the power structure. Their research underlines the importance of context-specific strategies in reducing carbon emissions.

Continuing this focus on China, a new method of assessing ocean ecological security is introduced by Wang et al., which uses the concept of the energy ecological footprint as a means of assessing marine ecological security. Through a case study of Guangxi's marine ecosystem, they offer actionable guidelines for the sustainable development and utilization of marine ecosystems using this method as a novel tool for marine ecological security evaluation.

Several papers then delve into the operational and policy challenges confronting shipping decarbonization. Zheng et al. introduce a method for optimizing speed in real time with the goal of maintaining a balance between schedule reliability and energy efficiency. Their approach involves dynamically modifying sailing speeds to counterbalance the disruptions brought about by unpredictable changes in port handling efficiency. This could play a significant role in achieving a balance between reliability and energy efficiency, particularly in light of diverse policies aimed at reducing carbon emissions.

In a similar vein, Zhang et al. conduct a numerical assessment of China's policies aimed at reducing carbon emissions in the shipping industry using the policy modeling consistency index method. Their findings suggest that although the policies are largely consistent, there are areas in each that could be enhanced. The research highlights the necessity of promoting and utilizing clean energy, fostering cooperation between the shipping and port sectors, and setting up a strong governance structure to address issues related to decarbonization in the shipping industry.

Li et al. shift the focus to the environmental efficiency of ports, specifically examining eight ports within China's Bohai rim port group. They discovered a lack of environmental efficiency and proposed potential solutions such as technological advancements, optimization of input–output processes, and increased management supervision. This perspective aligns with the assessment by Yang et al. of China's regulatory framework for reducing carbon emissions in shipping. They argue that strengthening compulsory regulations and broadening the scope of policy norms are crucial measures toward achieving decarbonization in the shipping industry.

Yao et al. introduce a two-dimensional assessment framework for evaluating policy synergy in Coastal Ocean Pollution Prevention and Control Programs (COPPCP) in China. They highlight the importance of interdepartmental collaboration and suggest that the nature of such collaboration varies across different provinces. This perspective is complemented by the analysis of the evolving cruise industry from Tong et al. They identify five policy areas requiring further attention, signaling the need for an active and supportive government attitude toward the industry.

The issue of port pollutant emissions in the United States is brought into sharp focus by Xiao et al. They analyze the spatial distribution of port pollutant emissions and the factors affecting them, finding that NOx emissions were the highest, followed by SO_2 and CO. They emphasize the urgent need for effective control measures for NOx emissions. According to the authors, coastal expansion and population growth tend to increase pollution emissions in ports, while container traffic has the opposite effect. This analysis provides crucial insights for port managers and regulatory departments to curb pollution.

Alongside this, Xiao and Cui employ an evolutionary game model to explore the intricate relationship between the government and shipping companies, particularly in relation to shipping cycles and carbon quotas. They deduce that the government's carbon quota policy is heavily impacted by demand in the shipping market. As a result, they advise the government to predict shipping market demand and modify regulations as needed. Their research highlights the fluid interaction between policy and market dynamics in the pursuit of decarbonization in the shipping industry.

Meanwhile, Meng et al. provide a systematic visual analysis of the cruise research literature. The authors acknowledge the challenges faced by the cruise industry, including environmental sustainability issues. The authors also suggest that future research should focus on the optimization of energy systems and the impact of climate change on the cruise industry. This indicates a recognition of the environmental impact of the industry and the need for sustainable practices.

Finally, Tang et al. put forward three optimization models for repositioning empty containers in a low-carbon manner across multiple ports under uncertain conditions. Their research indicates that strategies that include the repositioning of empty containers can decrease storage and leasing expenses, in addition to reducing carbon emissions. This makes maritime operations both more economical and more eco-friendly.

In essence, this Research Topic illuminates the intricate tapestry of maritime pollution governance. It emphasizes the importance of embracing both technical innovations and policy reforms to navigate the shipping industry toward a more sustainable future. The voyage toward this future will undoubtedly be challenging, but as these papers clearly demonstrate, it is not only necessary but achievable. The contributions of these researchers collectively provide a compass for the industry, policy-makers, and researchers alike, guiding us toward a cleaner, greener future in maritime activities.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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A review of law and policy on decarbonization of shipping

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The carbon emission of shipping industry accounts for about 3% of the global total. With the continuous growth of international trade, the decarbonization and carbon neutralization of shipping industry has become an important direction for future development. New technologies, fuels and operational measures can help reduce the industry's greenhouse gas emissions, but without appropriate laws and policies, it will be difficult to achieve the targets set by the industry. Therefore, this paper reviews the decarbonization laws and policies introduced by International Maritime Organization, the European Union and the national levels. Then, this paper reviews the literature from two aspects: applicability and evaluation of laws and policies, improvement of laws and policies. On this basis, we summarize the challenges of shipping in formulating laws and policies and suggestions for improving them. Among them, the most important problem is the coordination between unilateral regulation and uniform regulation. Finally, this paper proposes the development principles based on shipping decarbonization laws and policies, that is, to comply with the principle of "common but differentiated responsibilities", to coordinate the relationship between international trade and international environmental protection, and to guarantee technical assistance to developing countries.

KEYWORDS

shipping, decarbonization, law and policy, emissions, review

1 Introduction

Economic and population growth has become important factors driving global energy demand. They have led to the significant development of international maritime trade and the increase in the number of global shipping ships (Elgohary et al., 2014). In terms of total volume, more than 80% of goods are transported by sea, which accounts for 70% of the total international trade (Yang and Liu, 2022). In the process of consuming fuel oil, the main engine, auxiliary engine and boiler of a ship will produce carbon dioxide (CO_2), nitrogen oxides (NOx), sulphur oxides (SO_x), carbon monoxide (CO), Unburned coals (HC), and particulate matter (PM2.5, PM10). These gases are major sources of air pollution and greenhouse gases(GHG) that contribute to climate change (Richter et al., 2004; Traut et al., 2018). It has been found that the air pollution near the port is particularly serious (Saxe and Larsen, 2004). Among them, NO_x, SO_2 and inhalable particulates (PM2.5) will harm human health (Pandolfi et al., 2011; Anderson and Bows, 2012; Marelle et al., 2016). CO_2 is the main GHG, which has promoted global warming to a certain extent.

The International Maritime Organization (IMO) Fourth GHG Study estimated the current carbon footprint of the shipping industry and projected GHG emissions from shipping. The study calculated total GHG emissions (including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions, in terms of carbon dioxide equivalents) of the entire ocean sector. GHG emissions from marine sector totaled 977 Mt in 2012 and 1,076 Mt in 2018, an increase of 9.6% compared to 2012. Carbon dioxide accounts for the largest share of GHG emitted. In 2012, 962 Mt of GHG were carbon dioxide, while in 2018, this figure increased by 9.3% to 1056 Mt. Compared with other industries, the share of CO_2 emissions from shipping is still relatively low, accounting for 2.89% of the total anthropogenic CO_2 emissions in 2018. The expected growth rate of the industry shows that decarburization and carbon neutralization of the shipping industry are urgent.

IMO developed a series of scenarios of socioeconomic (GDP and population) and energy-related input variables to estimate the impact on transportation and finally predict the CO_2 emissions from shipping under Business As Usual (BAU). BAU refers to how emissions from shipping develop when other industries follow a certain economic and climate path but shipping does not. Different scenarios were referred to in the forecast. SSP2 and SSP4 refer to the framework of Shared Socioeconomic Pathways, where SSP2 represents A middle-of-the-road scenario (Fricko et al., 2017), SSP4 stands for Inequality - A Road Divided (Calvin et al., 2017). The scenario 'RCP2.6' refers to the framework of Representative Concentration Pathways (Moss et al., 2010; Van Vuuren et al., 2011). The letters 'L' and 'G' refer to the method of estimation used for establishing the relationship between transport work and the socioeconomic input variables, where letter 'L' represents the method used for logistics regression and letter 'G' represents the method used for gravity model.

Figure 1 shows the forecast of CO_2 emissions from shipping under BAU. With the continuous growth of maritime transport demand, this will eventually lead to the CO_2 emissions from 10 million tons in 2018 to 10 - 15 million tons in 2050, an increase of 0 - 50% over the level in 2018, equivalent to 90 - 130% of the level in 2008. The difference of the forecast of CO_2 emissions is due to the fact that the predicted values of traffic work and GDP are not identical under various scenarios. In addition to the impact of scenario setting, the methods of logistics regression and gravity model make differences in the predicted values of traffic work.

IMO's emission reduction target is to reduce the total GHG emissions of the international shipping industry by at least 50% by 2050 compared with 2008 (IMO, 2020a). At present, it is in the initial stage of strategy implementation and adjustment. At the beginning of 2023, EEXI, CII and other environmental new policies will be implemented. Numerous studies have shown that new corporate, technical and regulatory measures are needed to decarbonize the shipping industry (Bouman et al., 2017; Traut et al., 2018; Psaraftis, 2019a; Balcombe et al., 2019). Researchers have proposed several alternative fuels, including biofuels (Bengtsson et al., 2012), batteries (Lindstad et al., 2017), wind propulsion (Rehmatulla et al., 2017; Gilbert et al., 2018), and nuclear power (Schøyen and Steger-Jensen, 2017), and they have begun to investigate the drivers of energy conversion in the shipping environment (Geels, 2012; Mander, 2017). The new regulatory measures have also been intensively discussed by the maritime research community. These measures include market-based measures, such as the global fuel tax and emissions trading plan (Van Leeuwen and van Koppen, 2016; Kosmas and Acciaro, 2017), and command and control measures, such as the mandatory ship energy efficiency management plan (Poulsen and Johnson, 2016), more stringent energy efficiency design index (Devanney, 2011) and speed limit (Psaraftis, 2019b). In terms of environmental governance, the new mechanism of combining the public and private sectors in international shipping in a novel way to promote decarbonization has also begun to attract people's attention (Wuisan et al., 2012; Poulsen et al., 2018). These measures will contribute to decarbonization.

Figure 2 illustrates the overall GHG reduction pathway to achieve IMO's ambitious goals, i.e. the absolute level of GHG emission reduction identified in the IMO GHG Strategy (at least 50% reduction by 2050 expressed in the illustrative chart in solid colors and green stripes). The progress of shipping carbon emissions is affected by the unknown "innovative measures, fuels and technologies". At present, the known design, technical and operational measures are reducing the emissions of the industry at the level suggested by IMO, but it is still unclear how unknown innovations, legislation, policies can contribute to decarbonization, especially when the degree of emission reduction is increasing year by year.

The shipping industry will certainly continue to increase its carbon intensity, but energy-saving technologies and reduced speed will not be enough to meet the targets set for the industry. To facilitate this, appropriate laws and policies are needed to regulate. IMO is an international regulatory authority for the shipping industry. In 1997, it revised the International Convention for the Prevention of Pollution From Ships 73/78 (MARPOL for short). The important result of this revision is the birth of supplementary VI Regulations for the Prevention of Air Pollution from Ships, MARPOL Annex VI for short). However, MARPOL Annex VI initially only covered emission control of

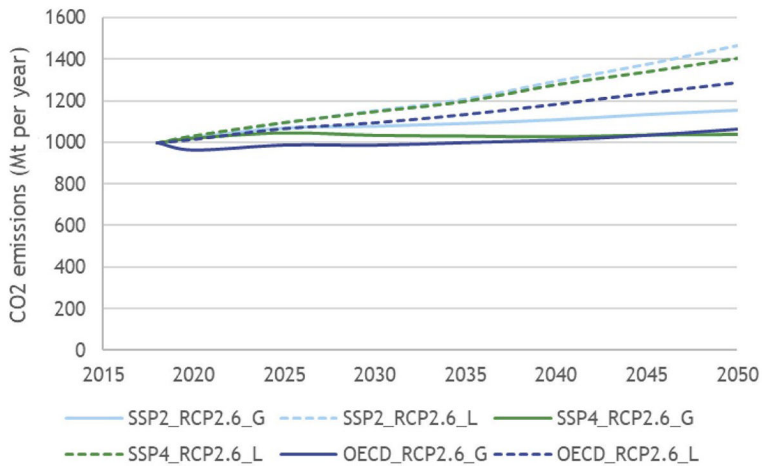

FIGURE 1
BAU forecasts of CO_2 emissions from ships under different scenarios. Source: IMO Fourth GHG Study (IMO, 2020).

air pollutants such as ozone-depleting substances, nitrogen oxides, sulfur oxides and volatile organic compounds, as well as standards and procedures for designating nitrogen oxides and sulfur oxides emission control areas, etc. It was not until 2011 that the IMO included marine GHG emission reduction in its regulatory framework. The GHG emitted by ship engines are regulated through the Ship Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). However, due to the high dispersion of ships in the shipping industry and the different sizes and types of ships, ships can be owned by a company in one country, and the owner of the company is a citizen of another country; It can be registered in another country (its flag country) and operated by a company in another country, which makes it difficult to reach consensus on decarbonization laws and policies (Shaffer and Bodansky, 2012). Appropriate laws and policies are conducive to the regulation of shipping decarbonization. However, there are some obstacles in the implementation of these laws and policies. For example, under the shipping decarbonization laws and policies, the cost of international maritime transport may increase. However, this will have an unequal impact on developing countries, which is also a major obstacle to the promotion of carbon reduction.

Therefore, this paper firstly introduces the legal and policy process of shipping decarbonization from IMO, EU level and national level. Then, based on the research of academic literature

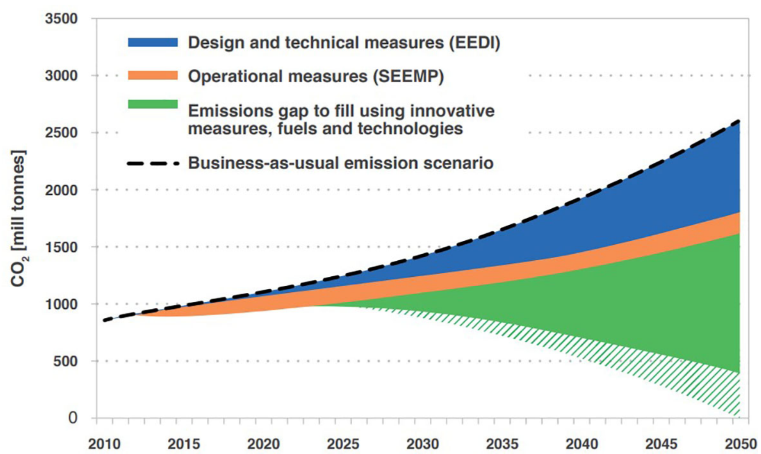

FIGURE 2
IMO GHG reduction pathway. Source: IMO (2020a).

on shipping decarbonization laws and policies, this paper reviews the literature from two aspects: applicability and evaluation of laws and policies, improvement of laws and policies. Next, this paper summarizes the challenges of shipping in formulating laws and policies and suggestions for improving them. Finally, the paper puts forward some suggestions for future development.

2 Development history of laws and policies on shipping decarbonization

2.1 IMO level

In the 1970s, the IMO discussed the problem of controlling air pollution from ships, especially toxic gases from ship exhausts. Air pollution received more attention in 1988 when the Marine Environment Protection Committee (MEPC) agreed to include the issue in its work programme. In 1991, the IMO adopted resolution A.719(17) on the International Convention for the Prevention of Pollution from Ships (MARPOL) Convention. The resolution calls on MEPC to prepare a new draft of the Annex to the MARPOL Convention on reducing air pollution from ships.

In 1995, the United Nations Framework Convention on Climate Change began to address GHG emissions from international shipping, recognizing that such emissions are increasing in volume and have an impact on climate change and the marine environment. The Kyoto Protocol, adopted in December 1997, is an important step in addressing climate change. Article 2 (2) states that the IMO is entrusted with the management of GHG emissions from international shipping. In the same year, the conference of MARPOL adopted Resolution 8 on "Carbon Dioxide Emissions from Ships", which asked the IMO to conduct study on GHG emissions and consider strategies to reduce carbon dioxide.

At the meetings held from 1998 to 2003, IMO mainly discussed the possibility of developing an IMO Strategy for Greenhouse Gas Emissions from Ships through MEPC. It was not until 2003 that the IMO adopted a resolution on "IMO Policies and Practices for Reducing Greenhouse gas Emissions from Ships", urging the IMO to develop mechanisms to address the issue.

Subsequently, IMO continued to actively work on designing regulatory tools to reduce GHG emissions from ships. On July 15, 2011, the IMO made a breakthrough in regulation. Since then, GHG emissions from international shipping will be regulated by revising Annex VI of MARPOL 73/78. The regulatory phases of MARPOL 73/78 are as follows. Step 1: According to MARPOL 73/78, from July 1, 2010, new building regulations on NOx will be applied to ships equipped with 130 kW or above diesel engines. Step 2: Secondary regulation, starting in 2011, aims to reduce NOx emissions by a further 15% to 20%. Step 3: The three-level regulation, which was implemented in 2016, aims to reduce current emissions in the ECA region by 80%. MARPOL 73/78 also added a new Chapter 4 in Appendix VI, introducing the mandatory Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships.

EEDI is a measure of the inherent CO_2 emission level of a ship in the design and construction stages, representing the CO_2 emissions per ton/mile of the ship. EEDI aims to establish a minimum energy efficiency standard for ships in the future (Ren et al., 2019). The emission baseline is established through statistical analysis of existing ships of various types and tonnage, and the energy efficiency of new shipbuilding is controlled on the basis of the baseline. After the implementation of EEDI, the energy efficiency design index of newly built commercial ships of various ship types and different tonnage must be less than the specified baseline ship energy efficiency design index. The smaller the EEDI, the more energy-efficient the design of ships (Attah and Bucknall, 2015).

EEDI reference levels for specific ship type/size combinations are gradually tightened every five years, which is expected to promote technological innovation early in the design process to improve fuel efficiency (Lindstad and Bo, 2018; Ancic et al., 2018). The ship's EEDI has been implemented in three stages since 2015. The first stage is 2015-2020. The ship's EEDI needs to be 10% lower than the baseline, which is calculated based on the reference line of the average efficiency of ships built between 2000 and 2010. The second stage of ship's EEDI is 2020-2024, and the ship's EEDI needs to be 20% lower than the baseline. The third stage of ship's EEDI will start in 2025, and the required reduction of ship's EEDI is set as 30%. At MEPC 74, the implementation of the third stage of EEDI for 12 ship types, including container ships, general cargo ships, LNG carriers, non-traditional cruise ships and 15000 DWT and above gas carriers, has been advanced to 2022, where the EEDI reduction rate of container ships has been improved on the original basis according to different tonnage.

The core of SEEMP is to formulate and effectively implement energy efficiency measures applicable to specific ships, which is divided into four steps: planning, implementation, monitoring, self-evaluation and improvement. Measures include improving voyage plan, weather navigation, speed optimization, optimal trim, optimal ballast, hull maintenance, propulsion system maintenance, etc. (Perera and Mo, 2016a; Hansen et al., 2020). The SEEMP incorporates best practice guidelines for energy efficient operation of ships and promotes the management of efficiency performance of individual ships and fleets over time. This is mainly achieved by the energy efficiency operation index (EEOI), which is a tool for monitoring the ship operation status, enabling the ship operator to measure the fuel efficiency in the ship operation and measure the impact of any change in the operation (Perera and Mo, 2016b).

In 2016, IMO Maritime Environment Protection Committee Resolution 278(70) adopted Amendment VI to MARPOL 73/78, requiring ships subject to the Convention to prepare and implement the Ship Fuel Consumption Data Collection Plan (DCS) (which is part II of SEEMP). It is used to collect and report fuel consumption data of ships over 5000 gross tons. The first calendaryear data collection was completed in 2019.

In April 2018, IMO adopted a preliminary strategy for reducing GHG emissions from ships. This policy framework sets key goals to reduce the carbon intensity of a single ship by implementing the further stage of EEDI for new ships. It is also proposed that by 2050, the annual GHG emissions of ships engaged in international navigation will be reduced by at least half compared with the level in 2008. In addition, in the 21st century, efforts should be made to gradually achieve zero GHG emissions from ships as soon as possible. By 2030, the carbon emission intensity of ships engaged in international navigation should be reduced by at least 40% on average, and efforts should be made to reduce the carbon emission intensity by 70% compared with the level in 2008. The strategy will be revised in 2023 and assess the impact of all proposed measures on countries.

In June 2021, IMO adopted key short-term measures aimed at reducing the carbon intensity of all ships by at least 40% by 2030, which is in line with the IMO's initial strategic objectives. These measures combine technical methods with operational methods to improve ship's energy efficiency. All ships must calculate their EEXI, and ships with more than 5000 gross tons will establish their annual operational carbon intensity index (CII) and carbon intensity rating mechanism. According to the regulations, CII is applicable to ship types above 5000GT (international voyage). According to the CII reached, a ship will be rated from A to E every year, where A is the best and C is the lowest rating requirement (Reusser and Perez, 2020; Daniel et al., 2022). This is the first time that IMO has established a formal rating mechanism for ships. It also sends a strong signal to the market that government departments, port authorities and other stakeholders are encouraged to provide incentives for ships rated A or B. For ships rated as Class D or Class E for three consecutive years, an improvement plan shall be submitted to clarify how to reach the required level (Class C or above).

2.2 EU level

In order to reduce GHG emissions, EU has been promoting the most active laws and policies. In March 2011, the European Commission issued a white paper on transportation as a guiding document of EU, which proposed that the carbon emissions in the field of transportation in 2050 would be reduced by 60% compared with 2008, of which the carbon emissions in maritime transport would be reduced by 40% - 50% compared with 2008. In June 2013, the European Commission proposed a draft regulation on "Monitoring, Reporting, Verification" of GHG emissions from shipping, referred to as "MRV Regulation" (Christodoulou et al., 2021). According to the draft regulation, ships will monitor and calculate fuel consumption, carbon dioxide emissions and related information during their own operations, and the submitted data will be verified by a certified third-party institution and reported within a specified period.

In July 2021, the EU released a package of reform plans called "Fit for 55", which is intended to fully integrate the shipping industry into the existing carbon market by 2026, so as to ensure that the EU's GHG emissions in 2030 will be reduced by at least 55% compared with the 1990 level. The proposal requires that the carbon market covers all emissions from shipping within the European Economic Area, all emissions from ships berthing at European ports, 50% of the carbon emissions from ships sailing from European ports to European ports and 50% of the carbon emissions from ships sailing from European ports to European ports (Council of the European Union, 2021; Sikora, 2021).

CO_2 emissions from shipping account for about a quarter of all transport related emissions in the EU. The EU's "Fit for 55" package proposes to adopt various regulatory policies, including EU Emission Trading System (EU ETS), FuelEU Maritime Initiative, Energy Taxation Directive and Renewable Energy Directive.

2.2.1 EU Emission Trading System (EU ETS)

The EU ETS has been in operation since 2005 and is the earliest carbon market in the world. In 2020, the EU Green Agreement promised to include shipping in the EU ETS. In July 2021, the EU's "fit for 55" package (European Commission, 2021) reaffirmed this point.

In this proposal, the EU emissions trading plan is applicable to ships with 5000 gross tons and above that strictly navigate within the EU will pay for all carbon dioxide emissions, while ships entering and leaving the EU will pay for 50% of their carbon dioxide emissions (no matter how much of the voyage is located inside or outside the EU) (Shi, 2016; Christodoulou et al., 2021).

Shipping enterprises need to purchase emission quotas, and one quota can emit one ton of carbon dioxide. According to the requirements of ETS, each shipping enterprise will be assigned a specific EU member state agency to supervise its compliance. If the quota exceeds the needs of the shipping enterprise, it can be sold to other companies in need, or it can be reserved for use in the next year.

Historically, the new industries that joined ETS were gradually included in the first few years through some free quotas. Unfortunately, free quotas have proved counterproductive, so the European Commission has decided that shipping should not benefit from them. However, the

European Commission proposed a phased approach requiring shipping companies to submit quotas corresponding to their percentage emissions. This phase means that shipping companies will be required to submit quotas according to the following schedule (Cullinane and Yang, 2022).
20% of verified emissions reported in 2023;
45% of verified emissions reported in 2024;
70% of verified emissions reported in 2025;
100% of verified emissions reported in 2026 and every year thereafter.

The phased implementation means that by 2026, the carbon price of each ton of carbon dioxide used for shipping will gradually rise.

On 22 June 2022, the European Parliament passed its version of legislation. In the text, the assembly made significant changes to the Commission's proposal. The most noteworthy is shipping, which proposes to change the number of voyages between EU's and non EU's ports and increase the percentage to 100%. This significantly expanded the influence of the EU ETS outside Europe. Its purpose is to seek to reduce more GHG emissions, but with the increase of compliance costs, this will certainly have a financial impact on shipping. In addition, the version of the European Parliament cancels the phased implementation period, but applies ETS to 100% emissions from 2024.

On 29 June 2022, the Council of EU adopted its version of ETS legislation. In its text, the Council recommended that the Commission retain the quota requirements implemented progressively by the Commission, thereby gradually increasing the number of allowances required and thereby increasing the carbon price.

Both the European Parliament and the Council have taken positions on the ETS proposal, but there are some issues on which the two bodies and the Commission need to agree before the proposal becomes law in the subsequent legislative process.

2.2.2 FuelEU Maritime Initiative

The FuelEU Maritime Initiative will set a maximum limit on the GHG content of the fuel used by ships to stimulate ships calling at European ports to adopt sustainable marine fuel and zero emission technology. Starting from 2025, the EU will impose more and more strict restrictions on the GHG intensity used in marine fuels, and set specific targets for GHG emission reduction, namely, 2% by 2025, 6% by 2030, 13% by 2035, 26% by 2040, 59% by 2045, and 75% by 2050 (Cullinane and Yang, 2022).

The reference value for calculating the onboard energy intensity corresponds to the fleet's average onboard energy GHG intensity in 2020, which is determined in 2015/757 according to the data monitored and reported within the framework of EU MRV regulations. This regulation is a necessary precursor to reduce CO_2 emissions at sea in Europe, because it has established the EU MRV database, which provides valuable information about ship energy efficiency, fuel consumption and CO_2 emissions once a year.

From the perspective of impact, the FuelEU Maritime Initiative will stimulate the development of sustainable marine fuels and zero emission technologies, including liquid biofuels, electronic liquids, decarbonized gases (including biological LNG and electronic gases), dehydrocarbon and dehydrocarbon derived fuels.

2.2.3 Energy Taxation Directive

In terms of the scope of energy tax collection, the EU's fossil fuel tax exemption policy in the shipping industry will be phased out, and the fossil fuel used in shipping will be retaxed, and the minimum tax rate will be set. According to the previous provisions of the Directive, marine fuels are tax exempt within the EU. All marine fuels sold in and used within the EU will be taxed from January 2023. In this way, marine fuels with serious pollution will be taxed the most. For example, when traditional fossil fuels are used as fuels, they will be taxed at a higher rate (i.e. 10.75 euro/GJ). When advanced sustainable biomass fuels and non-biomass renewable fuels (e.g. green hydrogen) are used, they can be taxed at the lowest rate (i.e. 0.15 euro/GJ) (Duscha and del Rio, 2017; Voulis et al., 2019).

2.2.4 Renewable Energy Directive

Renewable Energy Directive has set a higher target of 40% renewable energy in 2030. Among them, the intensity of GHG emissions in the transport sector is required to be reduced by 13%. These new goals will strengthen the demand for green hydrogen in the transport sector (Kohl et al., 2021). The plan also aims to promote renewable fuels to achieve the maximum emission reduction of GHG, and sets a target of 13% to reduce the carbon emission intensity in the transport sector, including international aviation and marine fuels. The target level of advanced biofuels has been raised to 2.2% of energy consumption in the transportation sector, and the target of 2.6% has been set for hydrogen and hydrogen based synthetic fuels in this industry. The Directive only sets targets, and more specific and directly related measures such as the EU ETS, FuelEU Maritime Initiative and Energy Taxation Directive are intended to help achieve them.

2.3 National level

As a global leader in the green transformation of shipping, Norwegian government aims to reduce the carbon emissions of domestic shipping and fishing vessels by 50% by 2030, and continue to promote the green development of the shipping industry through legislation, planning, financial support and other means. The Norwegian government also plays an important role in shipping carbon emission reduction. It has formulated a long-term subsidy and tax preference plan for the purchase of environment-friendly ships. In 2019, Norway's national budget set up a special fund to support the introduction of low emission and zero emission schemes for high-speed passenger ships, and used it as a subsidy for local governments to purchase environment-friendly high-speed ships. In July 2020, the Norwegian government required that all ships sailing in the Norwegian fjord area, which is listed as a world heritage site, must achieve zero emissions before 2026, becoming the first zero emissions area for ships in the world. In November 2020, IMO and the Norwegian government launched the GreenVoyage-2050 project, and the Norwegian government donated an additional 4.3 million dollars to IMO for this project. The project aims to support the decarbonization of the shipping industry according to IMO's initial strategy on reducing GHG emissions from shipping.

On April 20, 2021, the sixth carbon budget released by the UK government announced its latest emission reduction target, that is, by 2035, the carbon dioxide emissions will be reduced by 78% compared with the 1990 level. The UK became the first country in the world to include international shipping and aviation in its national carbon budget. In addition, the UK government has committed to provide 206 million pounds for research, which will be provided by the UK Ministry of Transport to the UK Shipping Office for Reducing Emissions. The purpose is to fund British companies to research and develop shipping emission reduction technologies, and support innovative enterprises.

In January 2022, the Danish Shipping Association introduced a strategy, which aims to accelerate the green transformation of global shipping by overcoming the regulatory, financial and political barriers that hinder the shipping neutralization. The strategy proposes to make good use of the potential of Denmark's shipping industry in offshore wind power and carbon capture and storage (CCS), and sets the goal of Denmark's shipping industry to achieve climate neutrality by 2050 without compensation, and to enable at least 5% of Denmark's operating fleet to use clean zero emission fuels such as green hydrogen, green ammonia, green methanol and advanced biofuels by 2030. All new ships ordered by Danish shipowners from 2030 will use net zero emission fuel or other zero emission propulsion methods.

Singapore Maritime and Port Authority (MPA) is the main body promoting the decarbonizing reform of Singapore's shipping industry. In 2011, MPA launched the Singapore Maritime Green Initiative (MSGI), aiming to reduce the environmental impact of shipping and related activities, and committed to investing up to 100 million Singapore dollars in MSGI within five years. The MSGI was updated in 2016, and the initiative was further extended to December 31, 2024 in 2019. In order to formulate a long-term strategy for the sustainable development of the marine industry, in March 2022, MPA released the Singapore Maritime Decarbonization Blueprint 2050, which will focus on supporting seven key areas of the maritime industry's decarbonization, and will add more than 300 million dollars to guarantee the implementation of the blueprint.

California of the United States promotes the use of shore power by legislation. In 2010, California formally raised the "Control of Toxic Air Pollutants Emission from Auxiliary Diesel Engines of Ocean going Ships at Ports" to California law, mandating container ships, mail ships and refrigerated cargo carriers attached to California ports to improve the utilization of shore power as required during docking. According to the law, the number of times the shipping company uses shore power when it is affiliated to a California port accounts for 50% of the total number of times it is affiliated to the port from 2014 to 2016; 70% from 2017 to 2019; After 2020, it will reach 80%. If it fails to meet the requirements, it will be fined. With the promotion of this law, the utilization rate of shore power in California ports has significantly increased, exceeding 80% in 2020.

China actively integrates with international shipping emission reduction rules to promote green development of domestic shipping industry. Drawing on IMO's practice of improving the design level of ship energy conservation and emission reduction through EEDI, China issued the Limits and Verification Methods for Fuel Consumption of Operating Ships and the Limits and Verification Methods for CO2 Emission of Operating Ships in 2012. Drawing on the policy of "Ship Emission Control Area" (ECA) in MARPOL Convention, China began to set up ECA in coastal waters in 2015 in accordance with the Air Pollution Prevention Law. In 2016, China issued the Limits and Measurement Methods for Exhaust Pollutants from Ship Engines (China's first and second stages) to control the emission of atmospheric pollutants from ships with stricter standards. Since 2017, the scope of water areas for controlling sulfur content in fuel oil used by ships has been continuously increased. In 2018, the Maritime Safety Administration of the People's Republic of China issued the Measures for the Collection and Management of Energy Consumption Data of Ships, which requires ships with a gross tonnage of 400 tons or more or a main propulsion power unit of 750 kilowatts or more to collect data on fuel consumption, sailing time, mileage, cargo turnover and other data according to the prescribed methods and procedures, laying a foundation for building a monitoring, reporting and verification (MRV) system for ship carbon emissions.

As a major player in the global shipping and shipbuilding industry, Japan is investing capital and research efforts in the introduction of ultra-low emission or zero emission ships, from shipbuilding to fuel development. In August 2019, Japan established the "Ship Carbon Recovery Working Group" to discuss the feasibility of using methane technology for zero emission ship fuel. In March 2020, the Japanese government released the "Zero Emission Roadmap for International

Shipping", which aims to build a "Zero Emission Ecological Ship" by 2028.

The Ministry of Ocean and Fisheries and the Ministry of Trade, Industry and Energy of the Republic of Korea jointly announced the "2030 Green Ship-K Initiative" to seek to develop an environment-friendly and sound image of Korean ships. The initiative aims to reduce GHG by 40% in the next 25 years and by 70% in the next 30 years. Various departments announced that they would provide 960 billion Korean won to develop the application of liquefied natural gas (LNG), battery power and hybrid power systems in shipping.

3 Literature review on laws and policies of shipping decarbonization

With the proposal of laws and policies on shipping decarbonization, scholars have also carried out some research to promote the development of laws and policies on shipping decarbonization. Romano and Yang (2021) proposed that the research was also carried out according to some regulations issued at that time. In their analysis, it was found that only one paper studied the impact of shipping emissions on port areas in 2005-08. From 2009 to 2012, there were 5 papers in this field. This increase may be due to the regulation formulated in 2008, namely the ECA amendment formulated by IMO to limit SO_x and NO_x emissions, which came into effect in July 2010. This paper sorts out the existing literature and reviews it from two aspects: applicability and evaluation of laws and policies, improvement of laws and policies.

3.1 Applicability and evaluation of laws and policies

The concept of "common but differentiated responsibilities" means different treatment between developed countries and developing countries (Rajamani, 2000), which is the basis of climate change discussion in the United Nations Framework Convention on Climate Change (UNFCCC). The position of the IMO is that shipping industry regulation needs to be implemented at the global level, so it should be applied equally to all flag countries. Because of the international climate mitigation policy, the cost of international maritime transport may increase, and even if the cost increases slightly, it may also have a disproportionate impact on developing countries, especially small island countries and landlocked countries. The conflict between the two has always been a major obstacle to progress (Cullinane and Cullinane, 2013). Miola et al. (2011) proposed that if the sector is listed as a separate party to the post Kyoto Protocol, a fund should be set up to help developing countries cope with climate change. In this way, the global ceiling of marine fuel is in line with the principle of "equal treatment" of IMO, regardless of flag countries, while financial support is in line with the concept of "common but differentiated responsibilities" of international climate change negotiations.

Since the IMO Marine Environment Protection Committee reached an agreement on further considering the new work plan and guidelines for market-based measures (MBMs) in emission control, it has conducted some research on shipping carbon tax, and scholars have studied the feasibility and impact of this policy. Tseng and Pilcher (2016) proposed the port ship emission tax scheme, which they believe is feasible at the policy level. Han and Notteboom (2017) simulated the impact of the port emission tax plan on port competition, and believed that the collection of emission taxes would generally lead to the reduction of port cargo volume (due to the increase of related costs), which would damage the profitability of port operators and shipping companies. Zhu et al. (2018) proposed that the uncertainty of carbon tax policy would affect the fleet planning of shipping companies and increase costs. Under the uncertainty of policies, enterprises will lease more ships and invest more in fleet operation when facing the risk of high carbon tax. Ding et al. (2020) proposed two carbon tax schemes based on international reality: fixed tax rate scheme and progressive tax rate scheme. The study found that the unit cost under the progressive carbon tax is lower than that under the fixed carbon tax within a given route, so the company may be willing to comply with the progressive tax plan.

Niese et al. (2015) simulated the uncertainty of goods trade economy in the face of growing environmental problems and emission regulations. Results inform decisions about when, where, and how to incorporate the changeability that maximizes expected life cycle rewards. Balcombe et al. (2019) divided the shipping carbon reduction policies into three categories: Emissions price controls, Emissions quality controls, and Subsidies, and studied their main strengths and weaknesses. Emissions price controls, such as carbon taxes, represent high economic and environmental efficiency, but may lead to restrictions on development, and may lead to the transition from maritime transport to high carbon transport routes (air and road). Another disadvantage is the risk of carbon leakage. A quantity control mechanism like ETS has two main benefits. First, its flexible nature allows the upper limit to change, but can determine the emission reductions achieved. As the industry is highly cyclical, changes in demand for emissions will affect emission prices, so it is necessary to set an appropriate upper limit. Direct financial support through subsidies is very effective in other sectors, and can be acted upon quickly, and can be targeted at technology or interventions. Subsidies must be carefully implemented and monitored and revised when conditions change.

In addition, for some laws and policies that have been implemented, scholars have also studied the applicability of these policies and judged them. For example, Hansen et al.

(2020) discussed how to translate SEEMP legislation into practice, and how crew members can accept and use it in daily operations. It is found that many goals or requirements conflict with energy-saving operation. The implementation of SEEMP legislation is challenging to a certain extent, because multiple participants affecting ship operations need to cooperate and have the same priority in energy efficiency. Nikopolou et al. (2013) evaluated the increased cost of adopting different methods to comply with the strict emission requirements of the Nordic SECA. These cost increases are likely to directly translate into higher tax rates. This will have a significant impact on the field of competition, especially in arenas such as Northern Europe, where a large proportion of goods flow is relatively short (i.e. within Europe). However, the implementation of MBMs may bring benefits to the shipping industry, as these measures may help to partially reduce the additional cost burden of complying with atmospheric emission regulations. Xiao et al. (2022) evaluated the control effect of the ECA policies on pollutant emissions and found that the control effect of various ECA policies on pollutant emissions is not the same, that is, the impact of ECA policies on SO_2 and particulate matter is the largest, and that on NO_x is minimal. Touratier-Muller et al. (2019) studied the policy effectiveness of the French government on SMEs since the implementation of the two freight plans. Regarding the mandatory initiative to force all French carriers to use four computing technologies to calculate and transmit CO_2 information (Decree 2011-1336), they concluded that the government initiative was not successful. At Fedi's research (Fedi, 2017), he found that the EU MRV regulations are facing severe criticism from the European shipping industry, especially from the European Community Shipowners Association and the International Chamber of Shipping. The shipowner hopes to persuade the EU to align its unilateral MRV regulations with the DCS of the IMO, because the shipping industry is a global industry that needs global rules.

3.2 Improvement of laws and policies

The decarbonization of shipping needs the support of various laws or policies, including stricter energy efficiency targets, speed limits and low-carbon fuel standards. Halim et al. (2018) believed that these policies could be implemented by member states of IMO. Governments and ports can provide the necessary infrastructure, such as shore power facilities, charging systems and alternative fuel fuelling facilities. Governments can also encourage domestic green shipping, promote research and development of zero carbon technologies, and develop programs to improve the commercial feasibility of these technologies. Financial institutions can develop green financial programs to stimulate sustainable shipping. Kontovas and Psaraftis (2011) compared the emission standards and technical solutions of EU and IMO on climate change. It is found that from a political perspective, it is easier to require technical and operational measures through legislation, which may indeed have great potential to reduce emissions. Chircop (2019) proposed the need for new international standards, tools and best practices to supplement the existing energy efficiency management rules in the 1973/78 International Convention for the Prevention of Pollution from Ships. Miola et al. (2011) proposed that the international shipping sector should meet the following four points when formulating carbon reduction laws and policies: (1) policymakers should set binding and ambitious long-term emission reduction targets, (2) economic incentives to encourage flexible action, (3) knowledge and technology sharing of innovative mitigation practices, and (4) transparency, administrative feasibility and easy to implement monitoring and implementation mechanisms.

However, since major international strategies often do not produce immediate results, this means that IMO should take stronger measures and lay the foundation for stronger goals before 2023. IMO should seize the imminent opportunity to bring a set of revised objectives for COP26 and MEPC77 (Bullock et al., 2022). Shi and Gullett (2018) proposed The challenges of regulating GHG emissions from international shipping, including how to allocate emissions to individual states, how to determine the appropriate regulatory roles for the UNFCCC and the IMO, how to choose among different regulatory tools to achieve a unable reduction in shipping GHG emissions, and how to balance the interests of developed and developing states. The interest disputes between developed and developing states mainly lie in the "common but differentiated responsibilities" (CBDR) principle and "no more favorable treatment" (NMFT) principle. The CBDR principle requires both developed and developing countries to make contributions to solving environmental problems. However, because developed states have made great historical contributions to environmental problems and developing states have weak capabilities, developed states should bear the main responsibility. The NMFT principle refers to "the port country implements applicable standards for all ships in its ports in a unified way, regardless of the flag it flies". The NMFT principle seeks equal treatment for all countries, while the CBDR principle seeks to reduce the responsibilities of developing countries on the premise of fairness. This makes it difficult for shipping carbon emission reduction to form a global unified policy. Heitmann and Khalilian (2011) proposed the best way to allocate international shipping emissions within the UNFCCC system is to allocate them to all parties according to the nationality of the transport company, or the country where the ship is registered or the operator is located.

Regional or unilateral regulations such as emission control areas (ECAs) and regional speed limits were opposed by governments and regulators (Chang and Wang, 2012; Panagakos et al., 2014; Sys et al., 2016). Homsombat et al.

(2013) compared the unilateral and coordinated pollution tax policies of a region, and provided differentiated but alternative services for shipping companies in competing ports in the region. They found that ports that unilaterally levy local pollution taxes will not only push the shipping business to their competitors' ports, but also suffer more spill pollution. Sheng et al. (2017) developed a comprehensive model to investigate the economic and environmental impacts of the uniform marine emission regulation and uniform marine emission regulation. The results show that unilateral regulation may actually lead to an increase in total emissions, while unified regulation will always reduce total emissions. Under any kind of regulation, it may have an asymmetric impact on shipping companies and ports. Finally, it is recommended not to adopt unilateral regulations, and the importance of considering the impact of alternative emission policies on shipping companies and port operations is emphasized. Primorac's research (Primorac, 2018) has the same results. He studied Legal challenges of implementing the system of monitoring carbon dioxide emissions from maritime transport within ports of call under the jurisdiction of EU member states The European legal sources related to this issue were reviewed, and the impact of the application of relevant provisions on the reduction of CO_2 and emissions from ports was analyzed. Finally, it was considered that it was necessary to achieve international harmonization in laws and policies to reduce CO_2 emissions from global maritime transport.

Although unilateral laws and regulations have some shortcomings, there are different views in academic research and practice. Gilbert and Bows (2012) proposed that although the industry still prefers global emission reduction policies, the urgency of requiring emission reduction requires exploring complementary sub global measures. Wan et al. (2018) proposed that IMO should not only rely on universal or majority consensus (top-down approach) to regulate marine pollution, but should recognize and encourage constructive regional action (patchwork approach) to solve the problem of GHG emission reduction. Regional action should not be equated with illegitimate unilateralism; On the contrary, they can play an important catalytic role in promoting global policy action (Shaffer and Bodansky, 2012).

The concept of multi center climate governance proposed by Nobel Prize winner Elinor Ostrom believes that although no country can solve the problem of global climate change, it does not mean that only one global unified solution can solve it. Maritime supervision and governance scholars adopt the concept of multi center and emphasize the fragmented, multi-level and overlapping structure of shipping governance (Bloor et al., 2014; Van Leeuwen, 2015). The case of shipping sulfur and nitrogen emission reduction provides an example for policy experiment and learning how to occur in a multi center sequence. Since the early 2000s, some national or regional policies, such as Norway's voluntary agreement, different port taxes in Sweden, emission standard restrictions set by the EU and the introduction of the EU's emission control area (ECA), have not distorted the fair competition environment. Gritsenko (2017) put forward four principles that take into account the specificity of shipping to support polycentric marine government in his research, which are respectively promote institutional diversity, target shipping sectors, use subsidiarity as a criterion for policy implementation, demonization of information design

Yang et al. (2017) proposed that the establishment of China's MRV regulations is the basis for the introduction of carbon reduction regulations or policies. After quantifying CO_2 emissions, it is suggested that Chinese policymakers consider taking mitigation measures, such as a cap and trade program and carbon taxes. Policy formulation requires decision makers to conduct various deliberations and discussions to ensure that practices comply with international regulations. Walsh et al. (2017) proposed that it is necessary for the UK to adopt new strict policies, such as regulatory or financial incentives, to reduce the basic complexity of the shipping industry.

4 Conclusions

With the accelerated economic recovery and the increasing demand of the shipping market, more GHG emissions have also been caused. In order to promote the sustainable development of shipping and accelerate the process of carbon neutralization of shipping, IMO has also proposed the goal of reducing the total GHG emissions of the international shipping industry by at least 50% compared with 2008 by 2050. New technologies, fuels and operational measures will help reduce GHG emissions in the industry, but without appropriate laws and policies, it will be difficult to achieve the goals set by this industry.

IMO has been committed to promoting the emission reduction of GHG in the shipping industry, and listed reducing carbon emissions from ships as a key management measure. In order to promote the international shipping industry to achieve the emission reduction goal as soon as possible, the mandatory EEDI has been introduced for new ships, and the SEEMP has been introduced for all ships. It is required that ships to which the Convention applies should prepare and implement the Ship Fuel Consumption Data Collection Plan (DCS). In the latest regulations, all ships must calculate their existing EEXI. Ships with a gross tonnage of more than 5000 tons will establish their annual operational CII and carbon intensity rating mechanism. In the future, IMO will continue to strive to achieve the goals set in its "Preliminary Strategy". To this end, it has developed a work plan and timetable to consider candidate short-term and medium-term measures. In order to reduce GHG emissions, EU has been promoting the most active laws and policies, including the guidance document of the white paper on transportation, MRV regulations and the package reform plan of "Fit for 55". The shipping related items in "Fit for 55" are EU ETS, FuelEU Maritime Initiative, Energy Tax Directive and Renewable Energy Directive. In addition, the national level is also actively promoting shipping carbon reduction legislation and policies.

In view of the academic literature on the research of shipping decarbonization laws and policies, this paper reviews the literature from two aspects: applicability and evaluation of laws and policies, improvement of laws and policies. The existing literature has analyzed the applicability of existing laws and policies in different countries and different subjects from multiple perspectives, proposed obstacles to policy implementation, and put forward some countermeasures and suggestions from the IMO and national levels. Under the laws and policies of shipping decarbonization, the cost of international maritime transport may increase, but this will have an unequal impact on developing countries, which is also a major obstacle to the promotion of carbon reduction. In addition, more research has been done on the coordination between unilateral regulations and unified regulations. The study found that ports that unilaterally levy local pollution taxes will not only push the shipping business to their competitors' ports, but also suffer more spillover pollution. Unilateral regulations may lead to an increase in total emissions, while unified regulations will always reduce total emissions. But only global unified regulations cannot completely solve the problem of GHG emissions from shipping. Therefore, we should also recognize and encourage constructive unilateral or regional regulations to solve the problem of GHG emission reduction. It is worth noting that regional action should not be equated with illegitimate unilateralism. How to link unilateral laws and regulations with those of IMO is a problem worth studying in the future, and it is also a problem that each country or region must consider when formulating laws and regulations.

Now, facing the huge pressure of carbon emission targets and taking strict actions, IMO urgently needs more perfect laws and policies. This paper gives the following countermeasures and future research directions. First, it is suggested that CBDR principle in line with environmental justice should be placed in an overall position as the source of law in this field. Second, constructive regional laws and policies should be recognized and encouraged to solve the problem of GHG emission reduction, and regional laws and regulations should also be properly connected with the regulations of IMO. Third, it is very important to coordinate the relationship between international trade and international environmental protection. Fourth, it is necessary to introduce regulations on technology development and transfer under the WTO framework as soon as possible, so as to promote technical assistance from developed countries to developing countries at the legal level. Finally, it should be made clear that simply talking about principles cannot effectively promote decarbonization of shipping. In order to promote the construction of the carbon emission reduction mechanism of the maritime industry under the guidance of the principles, we should consider how to effectively implement it and how to avoid unilateralism and hegemonism in the implementation.

Author contributions

JD, JZ, YY, and HW conceived the manuscript. JD and YY wrote the manuscript and synthesized the data. JZ and HW helped write the manuscript and provided constructive feedback. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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Carbon emission reduction of shore power from power energy structure in China

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With the construction of China's ecological civilization and the proposal of carbon peaking and carbon neutrality goals, shore power has been vigorously developed as an important technology for the future green development of ports. However, China's electricity is still mostly coal-fired, which produces many carbon emissions. Coupled with regional differences, shore power is by no means certain to lower carbon emissions compared with fuel throughout China. Considering the power energy structure in different regions, this paper establishes a carbon emission correlation model between fuel and shore power during ship berthing, calculates the feasibility and actual emission reduction effect of shore power in coastal ports, and studies the restriction condition of starting time for the use of shore power for ships attached to ports according to the national policy of mandatory use of shore power. The results show that only a small part of coastal provinces and cities are suitable for using shore power, and it is limited by the berthing time of the ship. However, this condition is not related to the size of ships but related to the proportion of power generation. Therefore, the government should develop shore power according to local conditions, and vigorously increase the proportion of clean energy, so that the shore power truly achieve zero carbon emissions.

KEYWORDS

shore power, power source, carbon emissions, power energy structure, actual emission reduction effect

1 Introduction

With the continuous rise of global temperature, greenhouse gases, especially carbon emissions, have attracted much attention from all over the world. In 2020, China pledged to achieve peak carbon emissions before 2030 and to strive to achieve carbon neutrality before 2060 (Sun et al., 2022). The transportation sector has an important role to play in achieving carbon peaking and carbon neutrality goals. As one of the industries difficult to decarbonize (Sharmina et al., 2021), the shipping industry has been attempting to take various measures to reduce the carbon emissions of ships, such as a carbon tax (Ding et al., 2020), ship speed optimization (Cariou et al., 2019), low-carbon fuel and alternative power (Xing et al., 2020), etc. These measures are mainly to reduce the carbon emissions of ships during navigation, but ships also consume fuel and produce CO_2 in the process of berthing operations. Therefore, shore power, as one of the ways to reduce carbon emissions in port operations, has been widely studied and promoted in recent years (Lathwal et al., 2021).

Shore power refers to the power supply that connects to the power supply on the dock and turns off the ship's generator when the ship docks so that the power load on the ship can be transferred to the shore seamlessly. It consists of three parts: the shore power system and infrastructure, the cable management system and the ship-side power system (Chen et al., 2019; Peng et al., 2020). It can not only effectively reduce ship emissions by approximately 48-70% during the ship's stay in port (Zis et al., 2014) but also eliminate the noise and vibration caused by the operation of the ship's generator. It is especially suitable for vessels with relatively fixed routes, large power consumption and high air pollutant emission levels when docking, such as container ships, ferries, cruise ships and medium and large bulk carriers (Dai et al., 2020).

With the attention of environmental protection in China, shore power as an effective way of saving energy and reducing emissions, has been vigorously promoted. By the end of 2021, port power facilities had covered approximately 7,500 berths across the country, with 75 percent coverage of five specialized berths, including container, passenger rolling, cruise, and passenger transport of over 3,000 tons and dry bulk cargo of over 50,000 tons (Zhang, 2022). However, due to the time-consuming connection of shore power and the lack of standardization in various countries (Yin et al., 2020) its utilization rate is less than 20% (Wang, 2022), In this regard, the Ministry of Transport proposed mandatory measures (MOT of the PRC, 2021): "If a ship with power-receiving facilities berths in a coastal port with shore power facilities for more than 3 hours and berths in an inland river for more than 2 hours, it shall use shore power. Otherwise, it will be punished based on the total power of the ship's generator set, combined with the power of the ship's generator set and the length of berthing." However, from the perspective of shore power sources, the power source will also produce carbon emissions in the process of power generation; therefore, whether it is truly low carbon compared with fuel is controversial. At present, thermal power generation accounts for 71.13% of the total in China; hydropower and other new energy sources account for 28.87% (NBS of the PRC, 2021). It can be seen that thermal power generation is still the main source of carbon emissions. In addition, there are certain differences in the power consumption of different areas: hydropower has dominated the central part, the coastal areas have good nuclear power generation, and northwestern and northern China have good resources for wind power and solar power generation, but there is almost no clean energy power generation in the northeastern inland areas. Different provinces with ports also have different proportions of electricity and energy; therefore, mandatory measures may not be applicable to all areas, and the mandatory berthing time also needs to be verified.

Therefore, to further study the emission reduction effect of shore power compared with fuel, we verify the feasibility of shore power in different provinces and cities from the perspective of power sources, obtain specific conditions for using shore power, such as berthing time, and propose suggestions on the response strategies of each province and city according to the current shore power policy. This paper establishes a carbon emission correlation model between fuel and shore power during ship berthing and compares the carbon emissions generated using fuel and shore power to provide a reference for the promotion of shore power in different areas. The rest of this paper is organized as follows: Section 2 presents a literature review of shore power sources, emission reduction effects, and promotion optimization. Section 3 describes the methodology, including problem definition, symbolic terminology and mathematical models. Section 4 conducts a case study on the feasibility and conditions of using shore power in coastal port provinces and cities. Finally, Section 5 summarizes the conclusions and policy implications.

2 Literature review

Shore power is one of the important measures to reduce carbon emissions in ports. Current research has mainly focused on the emission reduction effect of shore power and how to promote and optimize shore power in terms of environmental issues.

2.1 Traceability of shore power

The carbon emissions of shore power are closely related to the method of electricity generation; that is, the actual energy mix of the grid, such as coal, nuclear energy, photovoltaic energy, etc., should be considered (Peng et al., 2019). For a cleaner and greener environment, the development of renewable energy is very important to reduce air pollution by using shore power (Kotrikla et al., 2017). Studies have shown that the source of electricity has gradually shifted from thermal combustion to wind energy, tidal energy, and solar energy (Kalikatzarakis et al., 2018). Among them, wind energy, as a clean, natural and abundant renewable energy source, has high global potential. However, according to Kumar et al. (2016), while offshore wind resources are more promising than onshore resources and can compete with fossil-fuel power plants in terms of efficiency and output, there is no advanced technology to fully utilize them. There are also scholars studying wave-power generation for sustainable coastal development, but there are challenges such as high costs (Xu and Huang, 2018). Solar energy is not conducive to the stable operation of the power grid because of its large randomness, intermittency and volatility (Gao et al., 2022). Therefore, renewable energy is still unable to meet the power demand of ships in the short term.

According to the CEC data of the PRC (2020), China's electricity energy is still dominated by fossil-fuel thermal power generation. Although the development of hydropower resources in clean energy has been very high, tidal power generation has long been established as a demonstration project, but it has not been promoted. In the future, China's power generation method will gradually change to new energy sources such as wind energy and solar energy as the core sources and hydropower as the auxiliary source, thereby gradually reducing the proportion of thermal power in the overall power system (Zhang et al., 2015). Therefore, from the perspective of shore power traceability, the widespread use of shore power is an inevitable trend, but it is currently affected by the cleanliness of the power generation energy. The emission reduction effect of shore power needs to be improved.

2.2 Emission reduction effect of shore power

Shipping is increasingly recognized as an important source of air pollutants such as NO_x, SO_2, CO, particulate matter (PM) and the main greenhouse gas, CO_2. Most CO_2 emissions from shipping occur during the time ships spend in port (Styhre et al., 2017). Some scholars taking Guangzhou Port as an example compared the environmental benefits of two emission reduction measures using low-sulfur oil and shore power technology. The results showed that shore power has significant advantages in reducing NO_x emissions (He et al., 2020). In addition, quantitative calculations for Kaohsiung Port have shown the long-term potential of shore power to improve environmental and socioeconomic conditions by reducing port emissions (Tseng and Pilcher, 2015). To reduce air pollution, the Italian government has considered using shore power to reduce air pollution caused by ships and has conducted an economic analysis (Adamo et al., 2014).

However, some scholars are skeptical about the emission reduction effect of shore power. The European Commission has been hoping for a shift to an energy-efficient model for shipping, but research has shown that the implementation of shore power can be challenging. For most EU member states, shore power will help reduce CO_2 emissions, but the proportion of power generation energy varies from country to country; therefore, not all maritime countries can use shore power to reduce CO_2 emissions (William, 2010). In countries with a high carbon content in the electricity supply, the use of shore power from the national grid can lead to increased carbon emissions compared to the use of standard diesel generators (Winkel et al., 2016). In addition, according to the requirement of "connecting shore power first, then loading and unloading operations", it takes time for ships to connect to shore power, which may cause delays. If the carbon reduction effect of shore power is considered from the perspective of the entire voyage, the increase in carbon emissions due to delays caused by shore power can almost be offset by the reduction in shore power (Dai et al., 2020). Therefore, the actual emission reduction effect of shore power needs to be considered and studied in various aspects according to the characteristics of different areas.

2.3 Promotion and optimization of shore power

The research of Chen et al. (2019) shows that the promotion of shore power is subject to 12 constraints in four aspects: technological application, economic cost, operation management, and policy system. The most critical among them are the policy support system, the construction standards for shore power, and the laws and regulations. From the perspective of technical application, Tang et al., (2018) proposed a hybrid energy system including shore power, offshore photovoltaics, batteries, and diesel, considering different shore power prices and emission policies and optimizing them. There have also been discussions on the challenges of shore power technology to the voltage, frequency, power and other technical requirements of ships and onshore ships. By comparing various shore power technologies, it has been recommended to adopt new shore power technologies compatible with TN and IT standards (Kumar et al., 2019; Wu et al., 2013). In response to the high initial investment and operating costs of shore power and the lack of attractiveness, Dai et al. (2019) proposed an environmental and technical–economic analysis framework combined with an emissions trading scheme (ETS) to evaluate the economic feasibility of shore power, because shore power investment in the port is only economically feasible if the port can profit from the sale of electricity. Tan et al. (2021) established a ship selection behavior model for the economics of shore power to assist shipowners in making decisions about using shore power or fuel. The inland river shore power service evaluation system was established to realize an evaluation of the environmental benefits of a shore power system in a designated area.

In addition, the optimization of shore power can mainly be considered from the perspectives of shipowners, ports and governments (Qi et al., 2020). From these three perspectives, economic problems and management defects are the main obstacles to the wider application of shore power. In addition, government subsidies play an important role in the deployment of shore power (Wu and Wang, 2020). Therefore, it is necessary to strengthen the cooperation among shipowners, ports and governments.

At present, the research on shore power has mainly focused on the development and overall promotion and optimization of shore power. Few scholars have considered the inconsistency of the power energy structure in different areas of China from the perspective of shore power sources and the actual emission reduction effect of shore power relative to fuel. There is a lack of research on shore power construction strategies according to local conditions. Therefore, this paper traces the source of shore power, mainly considering thermal power, hydropower, nuclear power, wind power, solar power and other power generation methods. Combined with the power energy structure in different areas, the carbon emission correlation model between fuel and shore power during ship berthing is established, and the calculation of the actual emission reduction effect is completed. Finally, the necessary conditions for the berthing time for ships to use shore power to achieve carbon emission reduction are determined, and pertinent suggestions for realizing the construction of shore power in Chinese ports according to local conditions are proposed.

3 Methodologies

3.1 Problem definition

The purpose of this paper is to study the real emission reduction effect by using shore power instead of auxiliary engine fuel for ships calling at Chinese ports, considering the power traceability of the shore power system. The main issues can be divided into the following two parts:

(1) Under the current power energy structure of coastal provinces and cities in China, how can we determine whether the ports of each province or city are suitable for using the shore power system?

(2) What is the specific emission reduction effect of different ships using shore power? What are the basic conditions for determining that a ship is suitable for using shore power?

This paper solves the above problems by establishing a mathematical model. The main parameters involved in the model are given below:

where Y_i is the amount of carbon emissions reduced o from ship i using shore power instead of fuel during the berthing operation, g;

Δ is the marginal carbon emission reduction benefit from a ship using shore power, g/kWh;

CE_{Fi} is the carbon emissions from fuel used by ship i at berth, g;

CE_{Ei} is the carbon emissions from the whole process of shore power usage from ship i at berth, g;

CE_{EFi} is the carbon emissions from preparing the shore power for ship i, g;

CE_{EEi} is the carbon emissions from using the shore power by ship i, g;

$FC_i$is the fuel consumption of ship i at berth, g;

EC_i is the total electricity consumption using the shore power by ship i at berth, kW;

EC_{Gi} is the electricity required by ship i when using shore power, kW;

EC_{Ti} is the power loss when ship i uses shore power, kW;

FC_{Ei} is the fuel consumption for preparing the shore power for ship i, g;

P_i is the auxiliary rated power of ship i, kW;

LF is the auxiliary engine load factor of the ships at berth;

SFC is the amount of fuel required per unit of electricity, g/kWh;

T_i is the dwell time during loading and discharging of ship i at berth, h;

t is the time for preparing shore power, h;

$T^*$is the basic berthing time of a ship for carbon emission reduction by using shore power, h;

GT_i is the gross tonnage of ship i, GT or TEU;

DT_i is the deadweight of ship i, t or TEU;

v is the handling efficiency of the port of call, t/h or TEU/h;

Y_{F} is the carbon emission factor of the fuel used by marine auxiliary engines;

Y_{EJ} is the average carbon emission factor of energy j;

η_j is the proportion of power generation of energy j in an area; and

μ is the average power loss factor.

3.2 Mathematical model

In this section, a shore power–fuel carbon emission correlation model is established. It calculates the actual emission reduction effect of ships using shore power instead of fuel. Then, we determine whether the port is suitable for using shore power systems. Finally, we determine the basic conditions for carbon emission reduction by using shore power. The model is described as follows:

$$Y_i = CE_{Ei} - CE_{Fi} \tag{1}$$

The correlation model can be divided into two parts: the calculation of the carbon emissions of ships using shore power and auxiliary engine fuel.

3.2.1 Fuel-carbon emission model

When ships are berthing, only auxiliary engines are used to power the ship; therefore, the ship fuel-carbon emission model can be established based on the ship's auxiliary fuel consumption formula (Moreno-Gutierrez et al., 2018).

$$CE_{Fi} = \gamma_F \times FC_i \tag{2}$$

$$FC_i = P_i \times LF \times SFC \times T_i \tag{3}$$

$$T_i = \frac{DT_i}{v} \tag{4}$$

3.2.2 Shore power–carbon emission model

When a ship uses shore power, its carbon emission sources can be divided into two parts:

(1) The carbon emissions from auxiliary fuel consumption when the ship is waiting to connect to and disconnect from the shore power;
(2) The carbon emissions from the traceability process of power consumption.

Its calculation formula is as follows:

$$CE_{Ei} = CE_{EFi} + CE_{EEi} \tag{5}$$

Among them, the carbon emission calculation formula of the fuel part is basically the same as that of the fuel-carbon emission model, but the berthing time becomes the waiting time for the ship to connect and disconnect the shore power.

$$CE_{EFi} = \gamma_F \times FC_{AEi} \tag{6}$$

$$FC_{AEi} = P_i \times LF \times SFC \times t \tag{7}$$

The carbon emissions of the shore power part need to consider the loss of electric energy in the transmission process. The calculation formula is as follows:

$$CE_{EEi} = \sum_j \gamma_{Ej} \times \eta_j \times EC_i \tag{8}$$

$$EC_i = EC_{Gi} + EC_{Ti} \tag{9}$$

According to the China Energy Statistical Yearbook (Department of Energy Statistics. National Bureau of Statistics, 2013), the average CO_2 emission coefficient γ_{Ej} of each power source is shown in Table 1.

The total power consumed by ships at berth using shore power includes the power required for the ships' operation and the power loss in the power grid. Therefore, the calculation is divided into two parts: the power consumption process and the power transmission and transformation process.

3.2.2.1 Power consumption

$$EC_{Gi} = P_i \times LF \times T_i \tag{10}$$

$$P_i = f(GT_i) \tag{11}$$

The rated power of the ship's auxiliary engine is a key parameter to calculate the ship's electricity consumption. The relationship function between the auxiliary engine rated power of different types of ships and the gross tonnage of the ship obtained by the study has a good fitting effect (Gutierrez et al., 2019). It can be useful for the calculation of P_i , as shown in Table 2.

3.2.2.2 Power loss

In the process of power supply, the power system will inevitably have some power loss, including the energy loss caused by transmission lines and the power loss caused by transformers and other power(Sundaram, 2022). In addition, there is also the loss of transmission from the grid to the onshore power supply. The power consumption formula in the power consumption process is as follows:

$$EC_{Ti} = \frac{EC_{Gi}}{1-\mu} \times \mu \tag{12}$$

3.3 Judgment rules based on the correlation model

By analyzing the constructed correlation model, the criteria for determining whether the ship calling at a port is suitable for using shore power can be obtained. When Y_i <0, the ship is suitable for using shore power at this port; otherwise, it cannot achieve carbon emission reduction by using shore power. In addition, the correlation model can determine the cleanliness of shore power from two perspectives: port and ship.

TABLE 1 Average carbon emission coefficient of each power source.

Power source type	γ_{Ej} (g/kWh)	Power source type	γ_{Ej} (g/kWh)
Coal power	1001	Hydroelectric power	4
Fuel power	840	Nuclear power	16
Gas power	469	Photovoltaics power	48
Wind power	12	Photothermal power	22

(Source: Department of Energy Statistics, 2013).

TABLE 2 Relation function of auxiliary engine-rated power and gross tonnage of various types of marine auxiliary engines.

Types of ship	f(GT)	R^2
General cargo ship	$1.328(GT)^{0.7321}$	0.7986
Cruise	$-1.119\times10^{-6}(GT)^2+0.3692(GT)$	0.8488
Reefer ship	0.2073(GT)+587.4	0.5953
LNG ship	$2.597\times10^{-11}(GT)^3-4.131\times10^{-6}(GT)^2+0.2040(GT)+422.6$	0.9005
Bulk Carrier (Grain)	$2.786\times10^{-11}(GT)^3-3.609\times10^{-6}(GT)^2+0.1506(GT)+99.97$	0.8662
Bulk Carriers	0.06610(GT)+335.2	0.8937
Oil tanker	$70.86(GT)^{0.3317}$	0.6467
Container ship	$4.217\times10^{-6}(GT)^2+0.1331(GT)$	0.7697
Container ship (TEU)	0.0003(TEU)2+1.562(TEU)	0.7494
Chemical tanker	$108.6(GT)^{0.3062}$	0.8441

(Source: Gutierrez-Romero et al., 2019).

By deforming the judgment rule (Y_i <0), the marginal carbon emission reduction benefit of port shore power can be obtained, and the cleanliness of shore power can be determined from the perspective of the port.

$$T \times P_i \times \left(\frac{\sum_j \gamma_{Ej}\times\eta_j}{1-\mu} - \gamma_F \times SFC\right) + P_i \times \gamma_F \times SFC \times t < 0 \tag{13}$$

$$\Delta = \gamma_F \times SFC - \frac{\sum_j \gamma_{Ej}\times\eta_j}{1-\mu} \tag{14}$$

According to the above judgment rules, when the proportion of thermal power generation in the area is low, $\Delta>0$, then the marginal carbon emission reduction benefit of using shore power at the port is positive, and the shore power system can achieve carbon emission reduction; and when the proportion of thermal power generation in the area is high, $\Delta\leq0$, then the port is not suitable for using shore power.

Determining from the perspective of the ship, when $\Delta>0$, Y_i =0; then, the solution equation for the basic berthing time is as follows:

$$T^* = \frac{f(GT_i)\times\gamma_F\times SFC\times t}{f(GT_i)\times\gamma_F\times SFC - f(GT_i)\times\frac{\sum_j \gamma_{Ej}\times\eta_j}{1-\mu}} \tag{15}$$

For a port with positive marginal carbon emission reduction benefits of shore power, the port is suitable for using shore power systems; when the berthing time of the ship exceeds the basic berthing time, the ship is suitable for using shore power at this port.

4 Case analysis

4.1 The power energy structure of coastal ports

According to the shore power–fuel carbon emission correlation model, the power energy structure has a significant impact on whether the ports are suitable for using shore power. This section first collects data from various provinces and cities in China in 2021 (see Appendix A for detailed data). Among them, the provinces and cities where Chinese coastal ports are located are currently dominated by thermal power generation, but there are certain differences in the power energy structure in different provinces and cities.

In addition, the power grid is usually used between the provinces in China for power transmission. At present, the six regional power grids belonging to the State Grid in China have basically achieved interconnection and interoperability. Therefore, the Chinese power distribution and transmission network can be divided into two parts: the State Grid and Southern Power Grid (Abhyankar et al., 2020). According to an assumption (Chen et al., 2022), the power generation of each province or city first meets its own electricity demand. If there is surplus electricity, it will be transmitted to other provinces and cities through the grid market, as shown in Table 3.

The remaining electricity consumption in Guangdong, Guangxi, and Hainan is provided by the Southern Power Grid, and that in the other eight provinces and cities is provided by the State Grid (Abhyankar et al., 2020). According to each area's own power generation and grid distribution (this study ignores the loss rate of cross-provincial distribution), the actual power energy structure of 11 coastal port provinces and cities is shown in Figure 1 (see Appendix A for detailed data):

4.2 Model Input

The important parameters of the model are set, as shown in Table 4.

In addition to the above parameters, the dock-loading efficiency is affected by the operation efficiency of the quay crane and the number of quay cranes, and the number of quay cranes is related to the length of the ship. Therefore, the dock-loading efficiency needs to consider the actual terminal

TABLE 3 Grid power energy structure.

Grid name	Proportion of thermal power generation (%)	Proportion of hydroelectric power generation (%)	Proportion of wind power generation (%)	Proportion of nuclear power generation (%)	Proportion of solar power generation (%)
The State Grid	69.88	17.23	9.78	0	3.11
Southern Power Grid	27.38	64.93	6.09	0	1.60

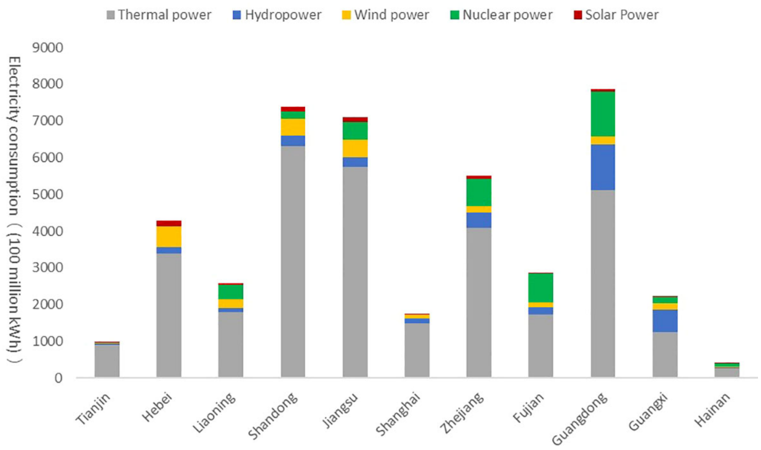

FIGURE 1
The actual power energy structure of 11 coastal port provinces and cities. (Source: NBS of the PRC, 2021).

equipment and ship conditions. In addition, to set the loading efficiency, the study determines the revised content of the container ship design ship size in the "Code for General Plane Design of Seaports" issued by the Ministry of Communications and the actual situation of Xiamen Port's container terminal, as shown in Table 5.

4.3 Feasibility analysis of port shore power

Solving the relational model, if Δ>0, for some ships that meet certain conditions, the use of shore power can achieve carbon emission reduction, and the larger the value of Δ is, the better the carbon emission reduction effect of using shore power. Therefore, regarding Δ as an indicator for determining the cleanliness of port shore power, combined with the current situation of the actual power energy structure in China, a reasonable assumption is made for the case.

Chinese statistics in 2021 show that coal power accounts for nearly 90% of thermal power generation, oil power accounts for a very low proportion, and photovoltaic power generation accounts for more than 99% of solar power generation. Therefore, in this case study, assuming that coal power and gas power account for 90% and 10% of thermal power

TABLE 4 Model parameter value.

Parameter name	Value	Unit	Sources and remarks
γ_F	3.114	g CO_2/g	(Ji and El-Halwagi, 2021)
LF	0.19	–	(Nguyen et al., 2022)
SFC	213.7	g/kWh	(Moreno-Gutierrez et al., 2018)
t	1	h	(Tseng and Pilcher, 2015)
μ	6.6	%	(CPNN, 2022)

TABLE 5 Loading efficiency value.

Vessel size (TEU)	Length of ship (Meter)	Number of quay cranes used	Quay crane operation efficiency (TEU/h)	Loading efficiency (TEU/h)
≤200	≤80	1	30	30
201-1050	81-160	2	30	60
1051-3500	161-240	3	30	90
3501-6630	241-320	4	30	120
6631-12500	321-400	5	30	150

generation, respectively, and photovoltaic power generation is used for solar power generation, the correlation model solution results can be obtained (see Appendix A for detailed data). Through the analysis of the solution results, under the current power energy structure, the marginal carbon emission reduction benefits of Tianjin, Hebei, Liaoning, Shandong, Jiangsu, Shanghai and Zhejiang are all negative. Among the 11 coastal port provinces and cities in China, only the ports in Fujian, Guangdong, Guangxi and Hainan are suitable for using shore power.

Although China is still dominated by thermal power generation, with the development of clean energy, the proportion of coal power and even thermal power will gradually decrease in the future. Therefore, in the case of widespread use of clean energy in the future, it can be foreseen that the promotion of shore power is imperative. However, the current national policy of mandatory use of shore power is not applicable to provinces and cities whose current power energy structure is biased toward thermal power.

4.4 Carbon emission reduction effect and condition analysis of shore power

The feasibility analysis of shore power in provinces and cities with coastal ports shows that the power energy structure of Fujian, Guangdong, Guangxi and Hainan is suitable for the use of shore power. Therefore, this case study selects Haikou Port and Xiamen Port as cases, taking the container ship Taking as the object (assuming that the ship is fully loaded). Considering the relationship between the loading efficiency and ship size, the relationship between the specific carbon emission reduction effect of the shore power and the size of the ship is analyzed, and the results are shown in Figure 2.

In Figure 2, under the same loading efficiency, the reduction in carbon emissions of ships using shore power is positively correlated with the size of the ship. Overall, large ships are more suitable for using shore power than small ships. In addition, for ships of the same size, the cleaner the power energy structure at the port of call is, the better the carbon emission reduction effect of using shore power.

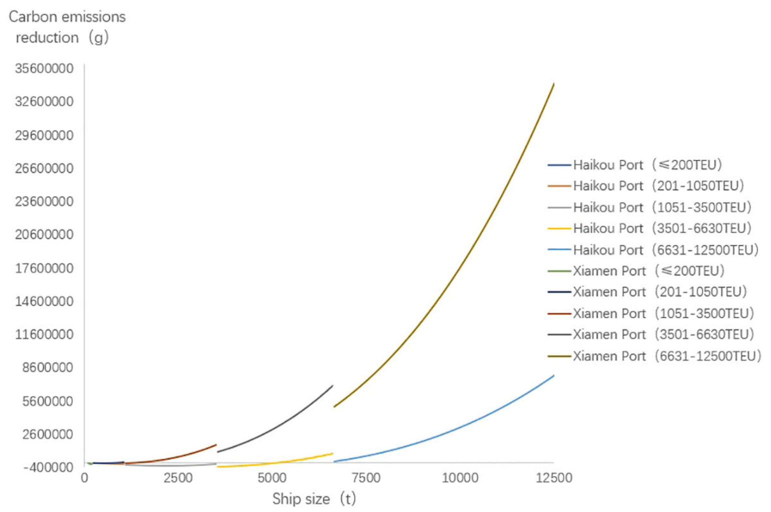

FIGURE 2
The relationship between carbon emission reduction and ship size.

According to the analysis of the carbon emission reduction effect, only ships that meet certain conditions are suitable for using shore power. For the policy of mandatory use of shore power, this case study also examines the basic berthing time (when the actual berthing time of the ship exceeds this value, the carbon emission of the ship using shore power begins to be lower than that of using fuel).

According to the calculation formula of T^* , the basic berthing time is not related to the size of the ship. Under the same power energy structure, the basic berthing time is a fixed value. In addition, ports in each area have different basic berthing times for shore power use due to their different power energy structures. The cleaner the power energy structure of a port is, the lower the requirements for its basic berthing time. In the case study, in Haikou Port, ships with a berthing time of more than 42.99 hours are suitable for using shore power; in Xiamen Port, ships with a berthing time of more than 16.41 hours can use shore power.

5 Conclusion and policy implications

5.1 Conclusion

This paper focuses on the emission reduction effect of shore power from the perspective of power traceability. Although shore power is an effective means to reduce ship-berthing carbon emissions, it is not applicable to all areas. The study establishes a shore power–fuel carbon emission correlation model and studies the feasibility of using shore power in the ports of coastal provinces and cities under the current traceability of power sources. In addition, we analyze the carbon emission reduction effect from shore power of specific ports. Finally, according to the national policy of compulsory use of shore power, the conditions and restrictions for ships calling at ports to use shore power are examined. The paper draws the main conclusion as follows: At present, most provinces and cities in coastal cities mainly rely on thermal power generation, but the proportion of clean energy varies. Among them, Guangxi accounts for almost half of the clean energy; Guangdong has a certain proportion of hydropower and nuclear power generation; Fujian and Hainan account for approximately 1/5 of nuclear power generation; and other coastal provinces and cities still have more than 70% thermal power generation. The feasibility calculation through the carbon emission correlation model shows that the marginal carbon emission reduction benefits of shore power in most ports are negative. Only four ports, Fujian, Guangdong, Guangxi and Hainan, are suitable for using shore power because of their relatively clean power energy structure. However, it is also related to the berthing time of the ship; that is, only when the berthing time of the ship exceeds the basic berthing time of using shore power at the port of call is the use of shore power related to lower net carbon emissions. Therefore, the basic berthing time of shore power use can be used as a condition for determining whether a ship is suitable for using shore power at the port of call, which has nothing to do with the size of the ship. In addition, the cleaner the power energy structure of the port area is, the higher the marginal carbon emission reduction benefit of the shore power system, and the lower the berthing time requirements for ships suitable for using shore power.

5.2 Policy implications

At present, most policies for shore power in China are methods of encouragement and support. Mandatory measures on berthing time ignore the differences in the power energy structure of ports in various areas. Therefore, this paper proposes suggestions for the promotion of shore power according to local conditions from the perspective of power traceability:

Different laws and policies should be formulated and implemented in accordance with the power energy structure, economic development level, port resources, etc., of different areas. Compulsory measures should be implemented for coastal ports in Fujian, Guangdong, Guangxi and Hainan. When the size of the ship and the loading and unloading time exceed a certain value, the responsible subject and reward and punishment measures for using shore power are clarified. Relevant laws and regulations should be formulated and improved according to the actual situation. At the same time, financial subsidies and support should be increased, the idle rate of shore power berths should be reduced, and the development of shore power should be ensured. For areas where the current use of shore power is still not clean enough, the use of shore power should not be mandatory for the time being.

Finally, there are some limitations in this paper. For example, the model does not fully consider the influence of practical factors and only studies the single ship type of coastal area and container. And to achieve China's carbon peaking and carbon neutrality goals, the promotion of shore power is the inevitable trend of port development in the future, the future can be from inland areas and other ship form further in-depth study, but also to realize the energy revolution is a long process, each region should fully consider its electricity clean degree to shore power promotion policy and planning, at the same time, our country should actively develop new energy technologies, gradually increase the proportion of clean energy, so as to fundamentally make the shore power to achieve zero emissions, create a green, safe, economical and new port environment.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

LS:Conceptualization, Writing - Review & Editing. PD: Conceptualization, Investigation, Writing - Original Draft. YX: Methodology, Formal analysis, Investigation. WL:Supervision. ZH: Resources. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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Supplementary material

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Marine ecological security assessment from the perspective of emergy ecological footprint

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Introduction: Marine ecological security assessments are considered as a basis for coordinating marine economic development and ecological protection.

Methods: We propose an assessment method based on the emergy ecological footprint which first measures the emergy of the natural and economic elements of the marine ecosystem. Considering the role of economic, social and waste discharge factors in the marine ecosystem, an ecological security evaluation index is constructed, and a dynamic evaluation is conducted based on long time series data to characterize the change trend of ecological security.

Results: The Guangxi marine ecosystem was selected as the case study, and the ecological security dynamic evaluation was conducted by collecting data from 2008 to 2020. The results show that Guangxi's marine ecosystem has always been in an ecologically secure state, but since 2010, the emergy ecological footprint intensity has been increasing, indicating ecosystem deterioration. Therefore, some targeted suggestions are put forward.

Discussion: This method provides a new assessment tool for marine ecological security evaluation and offers guidance for the sustainable development and utilization of marine ecosystems.

KEYWORDS

ecological security, emergy, ecological footprint, marine economy, assessment

1 Introduction

In recent years, the total output value of the global marine industry has been increasing, and emerging marine industries have developed rapidly (Yin et al., 2022; Ye et al., 2022). The marine economy has become an important part of many national economies and an important contributor to the sustainable development of human society. With the rapid development of marine economy, the contradiction between marine resource development and ecological environment protection has become increasingly prominent (Samhouri et al., 2012; Thushari and Senevirathna, 2020), with negative factors including ocean warming (Gomiero et al., 2018), biodiversity loss (Xu et al., 2017), water and air pollution (Xu et al., 2022), resource depletion (Bax et al., 2021; La Daana et al., 2022), and overfishing (Sumaila and Tai, 2020). The second global marine comprehensive assessment report released by the United Nations in 2021 pointed out that the global ocean surface pH decreased by approximately 0.1 on average, and the acidity increased by approximately 30%. The number of "dead water areas" with extremely low oxygen content in the world's oceans increased from more than 400 in 2008 to nearly 700 in 2019. The annual economic losses caused by overfishing are as high as 88.9 billion dollars. The development of the marine economy has exerted increasing pressure on marine ecosystems, leading to their deterioration as well as threatening and restricting high-quality economic development and the pace of ecological and social transformation (Liu C. et al., 2021).

Global sustainable development goals, such as "carbon peaking" and "carbon neutralization," have imposed new requirements on marine industries, accelerating the transformation and upgradation of the marine economy. Effective use of marine resources, reducing pressure on the environment while maintaining the rapid growth of the marine economy, and improving marine ecological security are significant challenges in the development of the marine economy. As a result, there is an increasingly urgent need to propose a marine ecological security assessment model to support coordinated development of the marine economy, and to offer a theoretical basis for rational and orderly marine development and research. However, the energy flow and material flow involved in the marine ecosystem are various and of different types. How to deal with different flows and construct evaluation indicators to evaluate the marine ecological security scientifically and reasonably is a big challenge.

Since the concept of ecological security was initially put forward (Brown, 1977), an increasing number of scholars have given it attention. During the late 1990s Costanza (1999) developed the eco-economic value system to assess true values of global marine ecosystem services, which focused attention on rational use and protection of marine resources. Marine ecology and industry face many problems. Effective measures must be taken to coordinate the development of marine resources and the protection of the ecological environment to promote the sustainable development of the marine ecological economic system (Koulouri et al, 2022). On the basis of analyzing the ecological, economic and social importance of global coastal areas, Martínez et al. (2007) proposed that to achieve sustainable development of coastal areas, marine ecosystem assessment should be strengthened.

Effectively measuring marine ecological security is challenging, and scholars have adopted different methods to evaluate it. The driver pressure state impact response (DPSIR) and multi-criteria analysis methods are used to estimate the economic value of coastal and marine ecosystem services (Ghermandi et al., 2019). Combined with the technology environment resource economy model and layered DEMATEL method, DPSIR is also used to determine the key factors of marine ranch ecological security systems and conduct sustainability assessments (Du and Li, 2022). Emergy and eco-exergy methods have been proposed to calculate the stock value of natural capital in marine reserves and supplement the economic evaluation based on market standards (Buonocore et al., 2019). An integrated life cycle assessment analysis was used to assess the resource and environmental carrying capacity of China's marine ranches (Wang and Du, 2023). The AHP entropy-based TOPSIS method was used to conduct a dynamic analysis of the marine ecological carrying capacity of Shandong Province, China (Sun et al., 2022). Wang et al. (2021) built a dynamic model of a marine ecological security comprehensive multi-function composite system, conducted data simulations and predictions, and used the Lotka Volterra model to assess the marine ecological security system.

Rees, a Canadian ecologist, first proposed the ecological footprint method to measure ecological security and sustainable development (Rees, 1992), and this was gradually improved by his students Wackernagel and others (Wackernagel and Rees, 1997; Wackernagel and Yount, 1998). This method judges and analyzes the ecological status of a region or system by comparing its ecological footprint with its ecological carrying capacity. The calculation is simple, and the conclusions are easy to understand. It effectively reflects the regeneration and replaceability of natural resources, self-purification, and biodiversity conservation (Zhao et al., 2022), and simplifies and quantifies the complex problem of the interaction between human socio-economic activities and nature. As one of the most influential quantitative methods, this method has gained worldwide attention and application owing to its new perspective and good operability (Geng et al., 2014; Ahmed et al., 2022). In marine ecosystems, this method has been applied to the production of marine products (Folke et al., 1998), the impact of climate change on the ocean (Karani and Failler, 2020), marine fisheries (Lam and Pauly, 2019; Yıldırım et al., 2022), ocean ranches (Du et al., 2022), and ocean cities (Tang et al., 2022).

With the deepening of research, scholars noticed shortcomings in the ecological footprint model, which are mainly reflected in: (1) The parameters used in the ecological footprint method, such as the equivalence factor, yield factor, and global average productivity, are based on the assumption of substitutability between artificial and natural capital. The differences in ecological advantages and time perspective of

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each region have not been fully considered, resulting in unstable measurement results, which affect the credibility of the method as a standard for measurement and comparison. (2) The ecological footprint method focuses only on the material cycle in the ecosystem and does not consider the impact of intangible factors. It fails to take into account economic, technological, cultural, social, and other factors such as waste discharges, and additionally does not consider the positive feedback and impact of the progress of these factors on ecological carrying capacity. (3) Finally, this method was originally a static analysis method, which assumed that technology, population, material consumption level were all unchanged, it can only reflect the degree of sustainability and security at a certain time, but can not effectively reflect the changes and future trends of ecosystem occupancy over time.

Based on the above analysis, our study instead adopted the emergy ecological footprint method to evaluate marine ecological security. This method was first proposed by Zhao et al. (2005). It combines the emergy analysis theory (Odum, 1988) with the ecological footprint method, discarding the controversial production and equilibrium factors in the ecological footprint method, instead first converting different types and levels of energy into solar emergy values and then using the emergy density to convert each consumption item into a corresponding bio-productive land area, namely the emergy ecological footprint, so that products with different properties can be compared based on a unified unit. The emergy ecological footprint method has been rapidly adopted worldwide owing to its scientific and theoretical basis, strong operability, extensive practicability, and other advantages (Nakajima and Ortega, 2016). Such as industrial ecological footprint (Zadgaonkar and Mandavgane, 2020), regional sustainability (Liu et al., 2022), ecological safety assessment of agricultural ecosystem (Zadehdabagh et al., 2022), biological community (Santos et al., 2021), water resources (Liu Z. et al., 2021).

In our study, when applying the emergy ecological footprint method to evaluate marine ecological security, we considered the role of economic, social, and waste discharge factors in the marine ecosystem and performed a dynamic evaluation based on long time series data. On the one hand, emergy ecological footprint analysis of marine ecosystems enriches relevant research on marine ecological security. On the other hand, it scientifically reveals the operational status, emergy structure characteristics, and ecological security status of marine ecosystems and provides appropriate suggestions for promoting the effective utilization of marine natural resources and the sustainable development of the marine economy.

The following research framework was applied to achieve the objectives of this study: Section 2 introduces the research methods, including the marine emergy ecological carrying capacity (MEEC), marine emergy ecological footprint (MEEF), and marine ecological security assessment indicators. Section 3 uses the Guangxi marine ecosystem as an example for applying this method in practice. Section 4 provides a summary of this paper and discusses the main contents and shortcomings of this study.

2 Research methods

Based on the research of the traditional ecological footprint model, this study proposes an emergy ecological footprint method to evaluate marine ecological security. This method is a combination of ecological footprint and emergy theory. It first uses the emergy conversion rate to convert different types and levels of energy in the ecosystem into comparable emergy standards, namely solaremergy, then introduces the concepts of global energy density and regional energy density, estimating the ecological space required by various natural environmental resources and wastes produced by human beings, and converted it into the area of bio productive land. By comparing the relationship between MEEC and MEEF, it can measure the regional ecological pressure and sustainable development capacity.

This method uses the global emergy baseline of 12.00 E+24 Sej y-1 (Brown and Ulgiati, 2016) to calculate the MEEC and MEEF of the analyzed regional ocean. The calculation of MEEC is based on the traditional calculation of emergy ecological carrying capacity of the natural environment, considering the positive role of human beings in improving regional resources and environmental carrying capacity (Peng et al., 2018) which has increased the socio-economic emergy ecological carrying capacity. MEEF mainly consists of two parts: the marine consumption resource footprint and marine pollution footprint (Xie et al., 2022). By measuring the ratio and difference between the MEEC and MEEF, the impact of human activity intensity on the marine ecosystem can be measured in order to determine the ecological security status of the marine ecosystem. The overall concept of the research method is shown in Figure 1.

2.1 Marine emergy ecological carrying capacity

MEEC refers to the calculation of the sea area from which natural resources can be drawn without degrading its ecological function, it reflects the ability of the natural environment to supply resources and support social development (Hu et al., 2019). Owing to the depletion of non-renewable resources in the process of economic and social development, only renewable natural resources are considered when measuring the emergy ecological carrying capacity. Therefore, the MEEC consists of the emergy ecological carrying capacity of renewable resources ($MEEC_R$) and the emergy ecological carrying capacity of

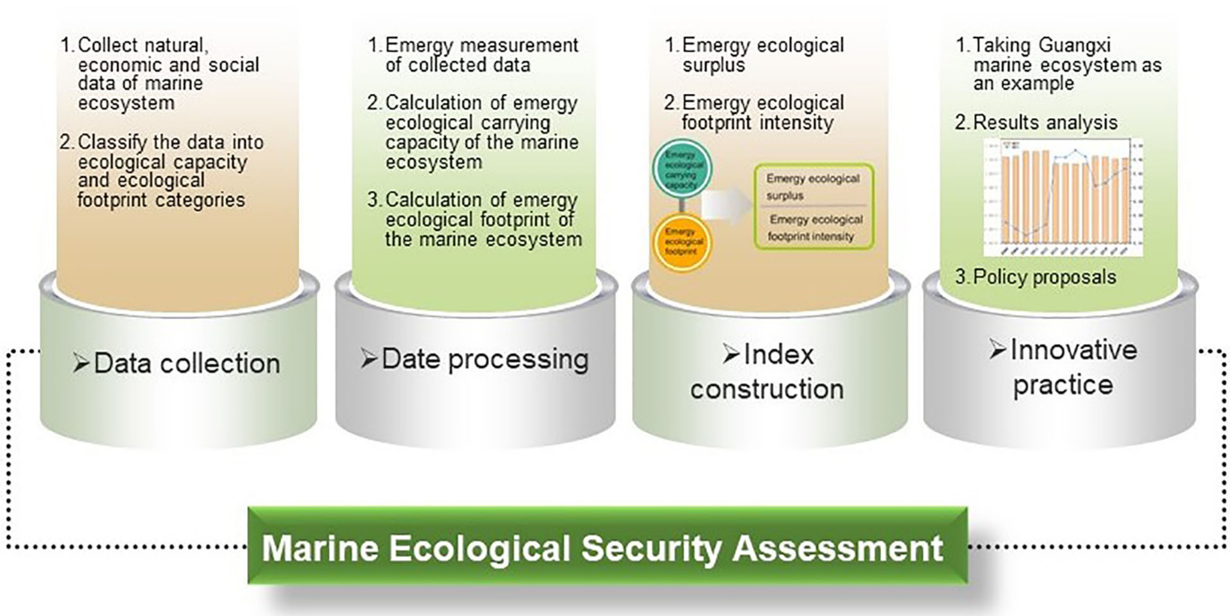

FIGURE 1
Method flow chart.

socio-economic resources ($MEEC_S$). The calculation formula is as follows:

$$MEEC = MEEC_R + MEEC_S \tag{1}$$

2.1.1 Ecological carrying capacity of renewable resources

Renewable natural resources in the marine ecosystem include solar energy, rainwater chemical energy, rainwater potential energy, wind energy, earth rotation energy, tidal energy, and wave energy. The emergy ecological carrying capacity of these renewable resources can be expressed as:

$$MEEC_R = \sum_{i=1}^{n}(R_i/p) \times (1 - 12\,\%) \tag{2}$$

where R_i represents the solar emergy of the i^{th} renewable resource provided by natural resources and p represents the global average emergy density. According to the new Earth biosphere emergy baseline (Campbell, 2016), the global emergy density is 2.35E+14 sej/ha (Pan et al, 2019), while a report of the World Commission on Environment and Development (WCED) recommends that 12% of the ecological capacity should be deducted when calculating the ecological carrying capacity to protect biodiversity.

2.1.2 Emergy ecological carrying capacity of social economic resources

In addition to renewable resources, emergy ecological carrying capacity is also affected by the social economy, science, and technology, mainly referring to the impact of labor input, economy, and technology, namely purchased renewable resources. The $MEEC_S$ reflects the role of human activities in the socio-economic ecosystem, which increase the ecological supply capacity and are considered as components of the marine ecosystem carrying capacity. The formula is:

$$MEEC_S = \sum_{i=1}^{n}(S_i/p) \times (1 - 12\,\%) \tag{3}$$

Here, S_i refers to the emergy value of the i^{th} purchased socioeconomic resource. This emergy can be used to improve the efficiency of resource utilization and plays an important role in marine ecological environment restoration and resource protection.

2.2 Marine emergy ecological footprint

The MEEF of a specific sea area refers to the balance of resources converted from various marine sources and products extracted by human beings in the region, as well as wastes generated by production activities, to which emergy value can be added or subtracted according to the corresponding conversion rate and a calculation of the total amount of emergy performed after the introduction of emergy density (Chen et al., 2018). The consumption items of the MEEF include two categories. The emergy ecological footprint of consumption resource ($MEEF_R$) includes marine fishing, mariculture, marine power, marine crude oil, sea salt, marine chemical industry, marine biomedicine, marine mining, and others, while the emergy ecological footprint of pollution ($MEEF_W$) mainly refers to the wastewater and solid waste discharged into the marine environment.

The calculation formula is as follows:

$$MEEF = MEEF_R + MEEF_W = \sum_{i=1}^{n} (C_i/p) \quad 4$$

where C_i is the solar energy value for the i^{th} type of resource consumption. p represents the global average emergy density. MEEF reflects the regional ecological and economic characteristics, indicating the load intensity of human activities to the natural resources and environment.

2.3 Ecological security assessment

2.3.1 Marine emergy ecological surplus calculation

The difference between MEEC and MEEF is the emergy ecological surplus (Zhao et al., 2005), and the formula is as follows:

$$MEES = MEEC - MEEF \quad (5)$$

The MEES can indicate marine ecological pressure and sustainable development status. When MEES ≥ 0, i this indicates a surplus or balanced state, with no excessive negative ecological pressure. When MEES< 0, it means that the pressures on marine ecological resources are greater than the ecological adaptive capacity, indicating ecological overload. The greater the negative value, the greater the ecological pressure, indicating that the ecological environment is seriously degraded and is in an unsustainable state.

2.3.2 Calculation of the marine emergy footprint intensity

To measure the marine ecological surplus, the marine emergy ecological footprint intensity index was established, and the marine ecological security status evaluated by analyzing the pressure on the ecological capacity of the ecosystem. MEES is an evaluation method based on absolute value change points, which is simple and intuitive to show the ecological sustainable development status of the study area. Compared with MEES, EFI is based on relative values, reflecting the pressure on the unit ecological capacity of the ecosystem. The calculation formula is as follows:

$$MEFI = MEEF/MEEC \quad (6)$$

When MEFI<1, it is an ecological security state. When MEFI=1, the system is in a balanced state. When MEFI>1, the pressure on the marine ecosystem is greater than the ecological capacity and ecological security cannot be achieved. It can be seen that the larger the MEFI, the worse the marine ecological security status.

3 Case study

3.1 Study area

The coastal area of Guangxi is located at the southernmost end of mainland China, facing Southeast Asia and backed by southwest China. It is the most convenient passage to the sea in southwest China, with apparent regional advantages and a prominent strategic position. The marine functional area covers approximately 7000 km^2, with 1628.6 km of mainland shoreline and 643 islands. The coastline is tortuous, with rich bays and waterways and good natural barriers. There are many kinds of marine biological and rich marine mineral resources, mainly including port resources, marine biological resources, coastal tourism resources, marine oil and gas resources, mineral resources, wind energy, and tidal energy. Thus, the development potential of the marine economy is therefore significant. The geographical location and structure of Guangxi are shown in Figure 2.

Guangxi can not only enjoy the western development policy, but also has the regional advantage of opening up the eastern coast, as well as a flexible investment environment. The development of the marine economy takes place under highly favorable basic conditions and has maintained rapid growth. In 2020, the gross marine product of Guangxi was 165.1 billion yuan, accounting for 7.5% of the total regional Gross Domestic Product and becoming an important engine for sustained and rapid economic growth in the region., and the added value of the tertiary industry increased by more than 15%, making the marine industrial economic structure more significant. With much of Guangxi's economic development focused on the sea, it is important to understand the carrying capacity of the marine environment in order to ensure sustainable development of the ecological and economic system,

3.2 Data sources

To conduct a dynamic assessment of marine ecological security in Guangxi based on the emergy ecological footprint, this study collected original data from 2008 to 2020. Raw meteorological data, such as sunshine, annual mean precipitation, and annual mean wind speed, were obtained from the China Meteorological Data Service Center (https://data.cma.cn/en). Raw socio-economic data were derived from The China statistical yearbook (2009–2020) (http://www.stats.gov.cn), The China marine statistical yearbook (2009–2020, the Guangxi statistical yearbook (2009–2021) (http://tjj.gxzf.gov.cn/tjsj/tjnj/),the Statistical Bulletin of Guangxi Marine Economy (2010–2021) (http://hyj.gxzf.gov.cn/zwgk_66846/hygb_66897/

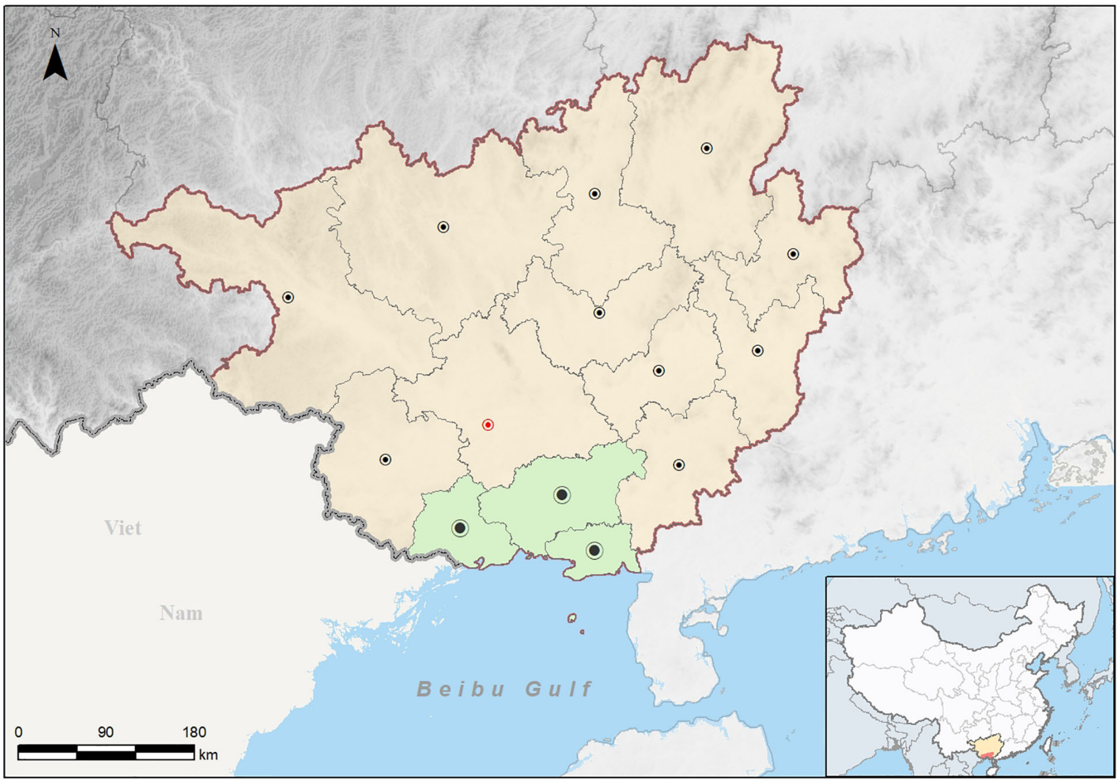

FIGURE 2
Study area.

hyjjtjgb/), and the Guangxi Water Resources Bulletin (2009–2021) (http://slt.gxzf.gov.cn/zwgk/jbgb/gxszygb/).

4 Results and discussions

Based on the emergy ecological footprint model built above, the raw data of the Guangxi marine ecological indicators were collated, and evaluations of Guangxi marine emergy ecological carrying capacity, emergy ecological footprint, and emergy ecological security were derived.

4.1 Results of MEEC

Using 2020 as an example, the calculation results of the Guangxi MEEC account are listed in Table 1.

The same method was used to calculate the MEEC of the Guangxi marine ecosystem from 2008 to 2020 (Appendix Table S1-S3); with the results shown in Figure 3. From the general trend, $MEEC_R$ showed high volatility during the study period, and the supply of natural resources was unstable. It can be seen from Table S1 that $MEEC_R$ fluctuates mainly due to the influence of precipitation, resulting in a change in emergy of renewable environmental resources. The $MEEC_S$ mainly considers two indicators: Guangxi's sea-related employment of the labor force and scientific and technological investment. During the study period, the emergy of social and economic investment steadily increased from 3.26E+22 to 3.85E+22, driving the improvement in Guangxi's total marine ecological carrying capacity (from 1.96E+08 in 2008 to 2.21E+08 in 2020).

4.2 Results of MEEF

Combined with the characteristics of Guangxi's marine ecosystem and the availability of index data and considering the ecological impact of marine consumption activities on the marine ecosystem when calculating its MEEF, the consumption resource footprint calculation uses marine fishing, mariculture, marine electricity, sea salt, and marine minerals as inputs. It is difficult to measure the exhaust gas in the discharge of pollutants from the marine ecosystem and this is thought to have little impact on the results. As a result, the pollution footprint is mainly based on the wastewater discharged into the sea by maritime economic activity. Taking 2020 as an example, Table 2 shows the calculation results for Guangxi MEEF.

The results of the MEEF (Appendix Tab. S4-S6) of the Guangxi marine ecosystem from 2008 to 2020 are shown in Figure 4. We can

TABLE 1 Emergy ecological carrying capacity of Guangxi Marine in 2020.

Emergy Item	Basic data	Unit	Transformity	Emergy (sej)	MEEC
Solar radiant energy	3.56E+19	J	1	3.56E+19	1.51E+05
Wind energy	5.43E+16	J	2.45E+03	1.33E+20	5.66E+05
Rainwater chemical energ	5.78E+16	J	3.05E+04	1.76E+21	7.50E+06
Rain, potential	1.37E+16	J	4.70E+04	6.44E+20	2.74E+06
Earth's rotational energy	1.01E+16	J	5.80E+04	5.89E+20	2.50E+06
Tidal energy	1.24E+17	J	7.39E+04	9.13E+21	3.88E+07
Wave energy	3.57E+16	J	3.00E+04	1.07E+21	4.55E+06
Sea related labor force	1.23E+06	J	3.10E+16	3.82E+22	1.63E+08
Science and technology investment	4.24E+08	CNY	8.11E+11	3.44E+20	1.46E+06

The final emergy was calculated according to each emergy transformation (Odum, 1996; Odum, 2000).
J, Joule; CNY, RMB unit; sej, emergy unit; MEEC, marine emergy ecological carrying capacity; g, gram.

see that the MEEF of Guangxi's marine ecosystem was unevenly distributed. Mariculture and marine fishing make a large contribution to Guangxi's MEEF in 2020, accounting for 68.7% and 22.9% of the total MEEF, respectively. The development of Guangxi's marine economy depends heavily on mariculture and fishing. The MEEF of mariculture changed from 3.49E+07 in 2008 to 6.80E+07 in 2020, showing a rapid upward trend. However, due to environmental problems such as sea water pollution and the reduction of marine biological species caused by marine overfishing, the government has regulated the behavior of the fishing industry,

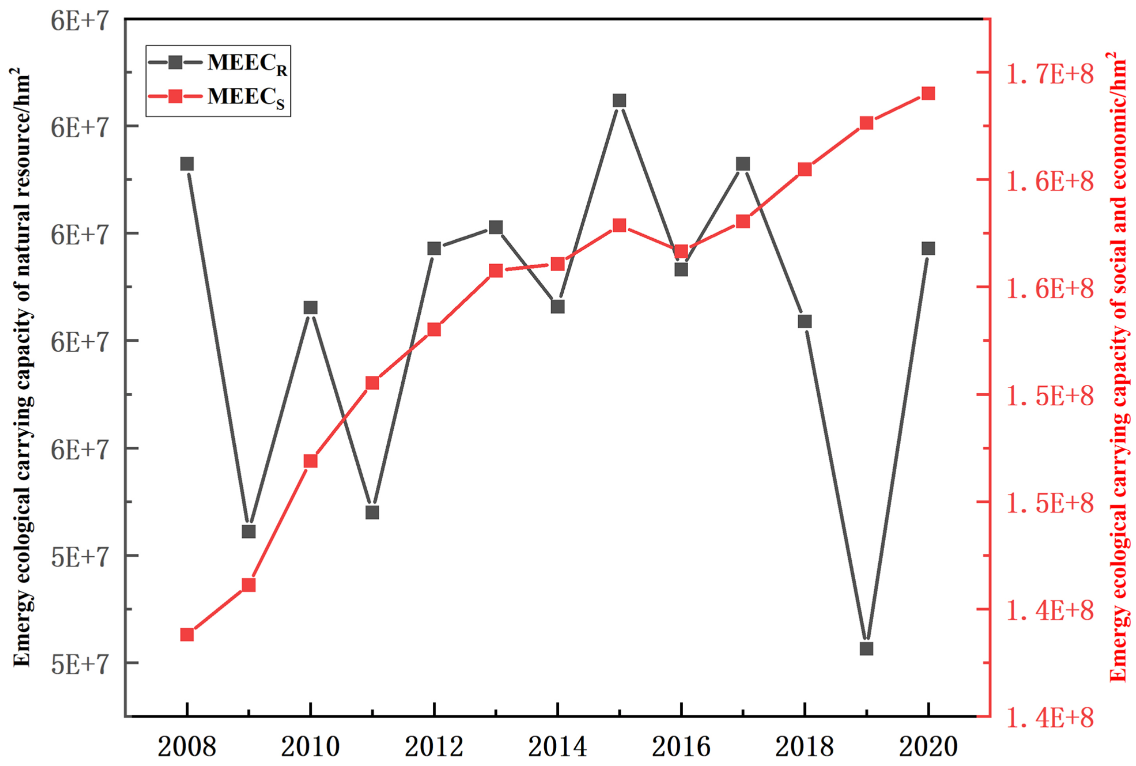

FIGURE 3
Emergy ecological carrying capacity of Guangxi Marine.

TABLE 2 Emergy ecological footprint of Guangxi Marine in 2020.

Emergy Item	Basic data	Unit	Transformity	Reference	Emergy (sej)	Ecological footprint
Marine fishing	2.72E+15	J	1.96E+06	Odum (1996)	5.32E+21	2.26E+07
Mariculture	8.15E+15	J	1.96E+06	Odum (1996)	1.60E+22	6.80E+07
Marine electricity	3.01E+14	J	1.47E+05	Brown and Ulgiati (2016)	4.43E+19	1.88E+05
Sea salt	0.00E+00	g	1.00E+09	Odum (1996)	0.00E+00	0.00E+00
Marine minerals	1.70E+12	g	1.00E+09	Odum (1996)	1.70E+21	7.23E+06
Wastewater into the sea	2.26E+14	J	6.66E+05	Kampeng et al. (2016)	1.50E+20	6.39E+05

J, Joule; CNY, RMB unit; sej, emergy unit; MEEC, marine emergy ecological carrying capacity; g, gram .

using management techniques such as the implementation of a fishing moratorium and fishing boat scrapping system. The contribution of marine fishing is slowly declining. In addition, marine mineral resource use changed greatly, with significant growth in 2013 and a significant decline in 2017. Other factors accounted for a small proportion of MEEF, with sea salt production having been stopped since 2017.

4.3 Results of ecological security assessment

Analyzing the results of the MEES and MEFI of Guangxi's marine ecosystem from 2008 to 2020 (Figure 5), it can be seen that its MEEC is greater than its MEEF, which indicates a surplus state. MEFI<1, which indicates that the ecological state

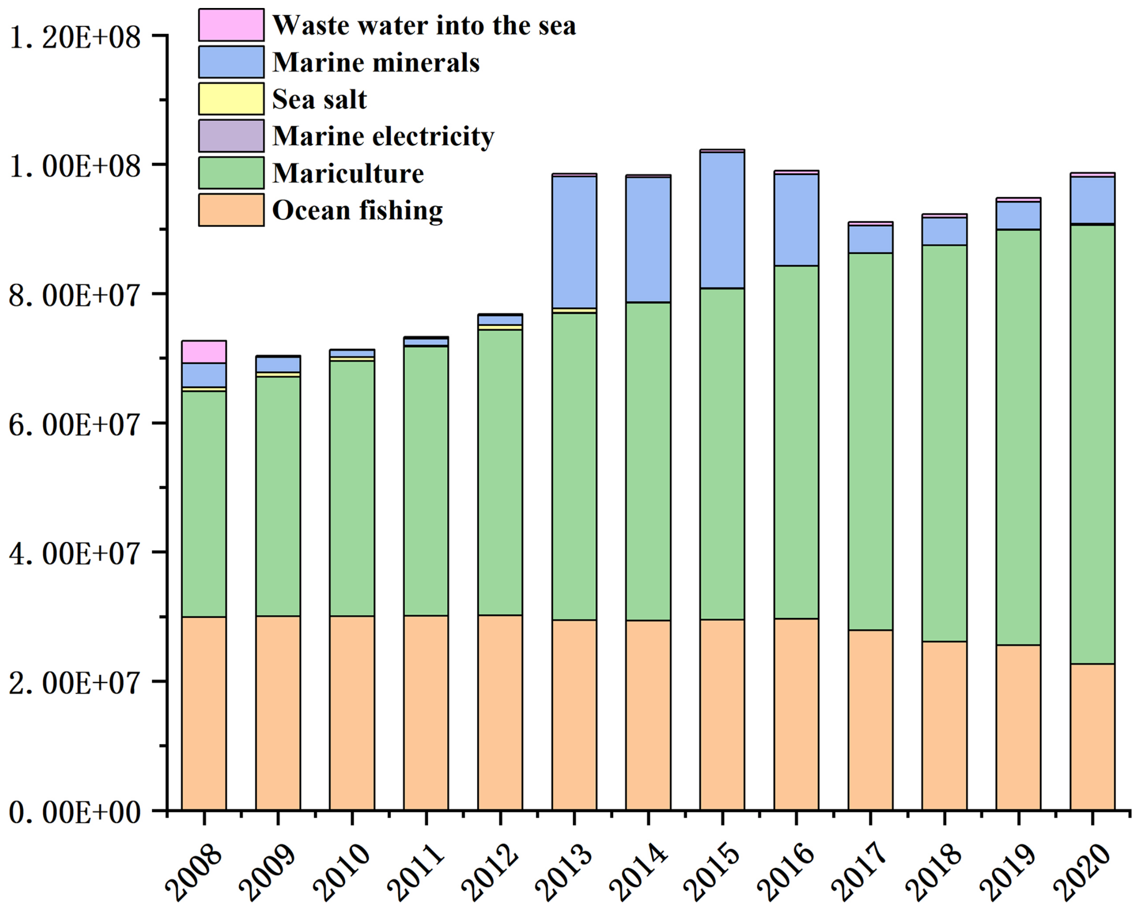

FIGURE 4
Composition of Guangxi marine ecological footprint.

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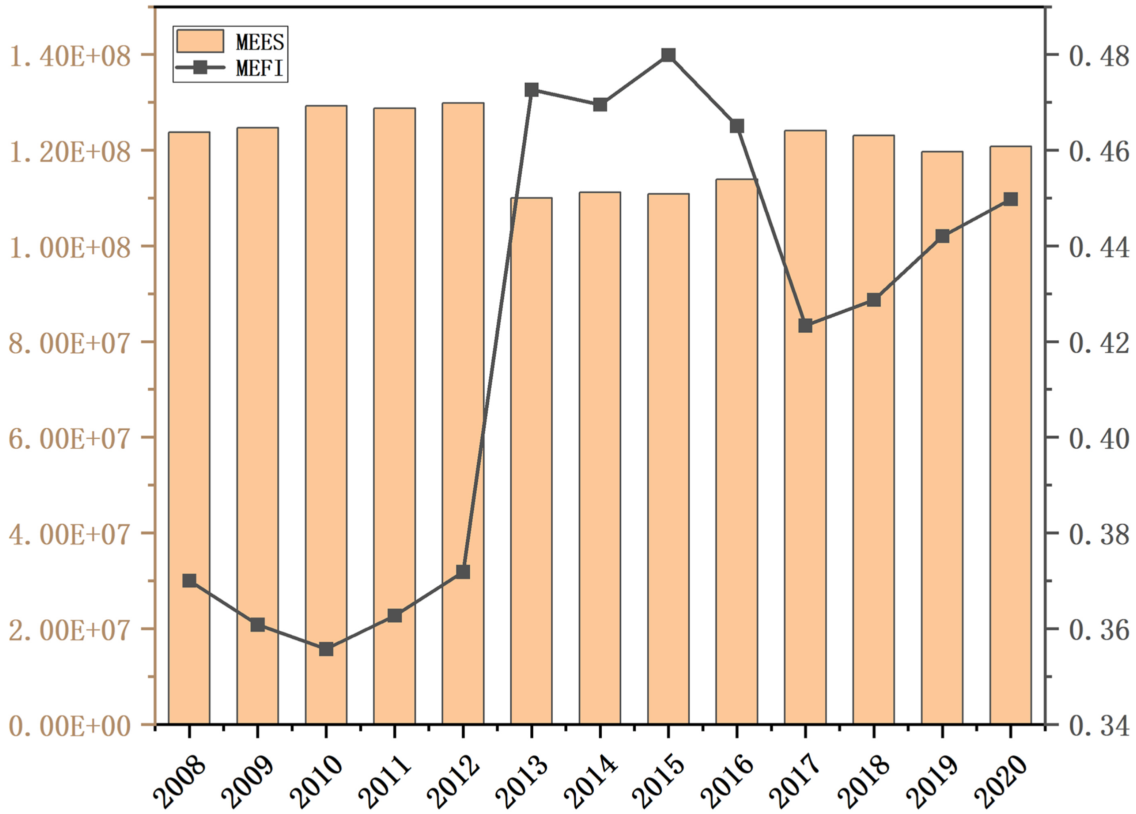

FIGURE 5
Emergy ecological security of Guangxi Marine.

is secure and that Guangxi's marine ecological economy is free of excess ecological pressure and that development can be considered sustainable. However, MEES generally declined, and MEFI began to increase in 2010. In 2012, this indicator showed a large increase. Although it declined in 2016, MEFI increased from 0.37 to 0.45 during the study period, reflecting the deterioration of the marine eco-system.

4.4 Suggestion

It can be seen from our results that Guangxi's marine ecology was in a secure state during the period 2008–2020, but due to increasing economic and environmental pressure, the marine eco-system has since deteriorated. Therefore, we propose the following suggestions for managing Guangxi's marine ecological security.

1. Make efficient use of natural resources and increase the use of renewable resources

The MEEC of the Guangxi marine ecosystem has always been greater than MEEF, which indicates an ecological surplus state because Guangxi has rich marine resources. The available renewable energy of the system has a large emergy value, and Guangxi Province has invested significant labor, scientific, and technological resources to develop the marine economy (Figure 3), giving the region a high ecological carrying capacity. From the MEEF, we can see that Guangxi lacks exploitation of marine crude oil and marine natural gas while MEEF values for marine electricity and sea salt were considerably low. Sea salt production ceased in 2017 (Figure 4) as mentioned above. The utilization rate of marine renewable resources is considerably low, and the ecosystem is in a safe state. Given this, greater use should be made of Guangxi's superior natural conditions, particularly the utilization of renewable resources. Research and development should be focused on renewable resources such as tidal energy, wind energy, and wave energy, and give more emphasis to the advantages of marine energy in island cities.

2. Increase investment in marine scientific research

It can be seen from the results of the MEEC (Figure 3) that labor, science, and technology investment have greatly increased the MEEC of Guangxi's marine ecosystem. Science and technology are important factors that affect the development efficiency of marine ecological economic systems and are the key to transforming the development mode of the marine economy as well as improving the breadth and depth of resource utilization. The rapid development of marine science and technology has not only brought about economic development but has also brought about the expansion of marine ecological capacity and the improvement of marine ecological environment quality. However, according to the second Global Marine Science Report released by UNESCO on December 14 (Isensee, 2020), the average proportion of marine science funds in the total scientific research investment in the world is only 1.7%, which is far lower than that in other major scientific fields. There is also a gap between the development level of marine science and technology in Guangxi Province and that of the rest of the world. Although investment in science and technology increased from 2016 to 2020, it has decreased considerably compared to previous years. Development momentum has slowed down due to unfavorable conditions, such as insufficient investment in marine scientific research funds and slow growth of marine scientific research personnel. Therefore, the government should increase investments in marine scientific research to ensure the stability and health of Guangxi's marine ecology.

3. Further adjust and optimize the industrial structure and develop ecological mariculture

As shown in Figure 4, fishery is the main part of Guangxi's marine industrial structure. The proportion of marine fishing in the MEEF decreased from 41.21% in 2008 to 22.95% in 2020, and the proportion of mariculture increased from 48.09% to 68.88%. The MEEF of marine mining fluctuated greatly, reaching 20.77% of the total MEEF at its peak and 7.33% in 2020. The marine industrial structure of Guangxi needs to be further optimized. First of all, with green development as the core, we should adopt "undersea forest" and "marine ranching" and other aquaculture methods to develop ecological mariculture, minimize the impact of human activities on the marine natural ecosystem, and ensure the stability and sustainable growth of aquatic resources. Secondly, the development potential of traditional industries is gradually decreasing, and new marine industries offer alternatives. Guangxi can vigorously develop new marine industries, such as clean energy, marine biological medicine, seawater utilization, and marine exploration to maximize the value of marine resources.

4.5 Discussion

This study used the emergy ecological footprint to evaluate marine ecosystems. Compared with other marine ecological security assessment methods (Todd et al., 2019; Zhao et al., 2020; Gao et al., 2022), this method has the following advantages: (1) conversion of different types and levels of energy into solar emergy values, introduction of global emergy density, and conversion of each consumption item into a corresponding bio-productive land area to enable products of different natures to be compared based on a unified unit; (2) the calculation of carrying capacity and ecological footprint takes into account economic, social, and other factors and waste emissions, fully reflecting the role of human activities in the marine ecosystem; (3) dynamic evaluation of marine ecological security based on long time series data can reflect the changing trends of ecological security.

This research has led to the following insights.

(1) Marine ecosystems are unique composite systems. The emergy ecological footprint reveals the complexity, particularity, and sustainability of the marine ecosystem by studying the flows of materials, energy, and other factors between the system and the environment. It can simply and scientifically evaluate marine ecological security. The evaluation results help us better protect the marine ecological economic system and guide the scientific development of the marine ecological economic system.

(2) In an ecological security assessment, social, economic, scientific, and technological factors have significant impacts on the improvement of carrying capacity. On one hand, these factors can directly enhance the ecological carrying capacity of the system; while on the other hand, they can indirectly enhance the ecological carrying capacity of the system by improving the ecological capacity of natural resources.

(3) To reduce the pressure on marine ecological security, we should improve the level of science and technology, optimize the marine industrial structure, and protect the environment. This requires not only making full use of regional advantages to develop marine industries according to local conditions, but also giving full play to the role of science and technology in improving the ecological carrying capacity and reducing ecological impacts. Simultaneously, in the process of development, it is necessary to simultaneously improve the efficiency of use of natural resources, control pollutant emissions, and achieve sustainable development of marine ecology.

Conclusion

A healthy marine ecological environment is a precondition for the survival of marine organisms. Once changes in the ecosystem and biological resources exceed the tolerance of the biological community, the balance of the ecosystem will be disturbed, which will damage the stability of marine ecology and threaten human development. An ecological security assessment can objectively assess the current marine ecological situation and provide suggestions for the sustainable development of the marine industry.

In this study, the emergy ecological footprint model was applied for the assessment of marine ecological security to provide an effective theoretical method for the study of sustainable development of the marine economy. The main contributions of this study are as follows: (i) The emergy method is used to measure the input and output elements of the marine ecosystem. It unifies the measurement standards to make the use of natural and human resources more comparable. (ii) An emergy ecological footprint model is established to evaluate the security of marine ecosystems, and long time series data are used for dynamic evaluation to characterize the change trend of ecological security. (iii) The emergy ecological footprint method is applied to the assessment of marine ecological security in Guangxi from 2008 to 2020, to reveal the current situation and dynamic change characteristics of marine ecological security in Guangxi and verify the effectiveness of the method. The results show that the marine system in this area is in a secure state, but with a trend towards deterioration. Based on this, corresponding management countermeasures for marine ecological security are proposed. This research provides theoretical support for the utilization of the ocean and the coordinated development of economy, society, and ecology, and is helpful to managers responsible for sustainable ecological security management of regional oceans.

Owing to the complexity of the marine ecosystem itself, many factors affect its ecological security, and these problems are complex. Moreover, it is difficult to collect all necessary data. Noting these data gaps, we have to give up after balancing, which may lead to a slight deviation between the research results and the actual situation. In addition, this study only considers the situation from 2008 to 2020 and analyzes the changes in this period but was unable to predict the future ecological security of the region. These limitations will be addressed in future work.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by CW, AL, and CL. The first draft of the manuscript was written by CW and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Review and reflections of legislation and policies on shipping decarbonization under China's "dual carbon" target

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Although shipping is a relatively energy-saving and environmentally friendly mode of transportation, the growth rate of its energy consumption and carbon emissions far exceeds that of other industries. As an important response to climate change, shipping decarbonization is not only an important part of achieving the temperature control goal of the Paris Agreement but is also an important direction for the future development of China's ecological civilization construction. China has formulated and promulgated legislation and policies on shipping decarbonization both at the national and local levels. The proposal in 2020 of the goal of carbon peaking and carbon neutrality has accelerated this process. In this context, this paper aims at reflecting on legislation and policies for decarbonization of shipping under China's "double carbon" target, and proposing suggestions for improvement. Firstly, we systematically review China's legislation and policies on shipping decarbonization to outline the normative system of China's shipping carbon reduction. Secondly, this paper evaluates China's legislation and policies on shipping decarbonization from the perspective of both achievements and challenges. Finally, this paper proposes that China's legislation and policies for decarbonization of shipping should be further improved from two aspects: enhancing mandatory force and expanding normative content.

KEYWORDS

shipping decarbonization, carbon peaking and carbon neutrality goals, legislation and policies, review, recommendations

1 Introduction

Climate change, especially global warming, is commonly considered as one of the greatest threats to human society, and is continuously affecting human health, socio-economic development, population, food security, and ecosystems at land and at sea. To address climate change, the Paris Agreement was adopted at the 21st United Nations Climate Change Conference in 2015, setting the target of keeping the global average temperature increase in the 21st century to within 1.5–2 degrees (Paris Goals; Savaresi, 2016; Lee, 2019). As a party and an active practitioner of the Paris Agreement, China has been committed to action against climate change and has taken proactive initiatives to seek new approaches to low-carbon development. In September 2020, China announced at the 75th UN General Assembly that it would strive to peak carbon dioxide (CO2) emissions by 2030 and work toward achieving carbon neutrality by 2060 goal (Liu, 2022). The introduction of the dual carbon target is both a major strategic decision for China to respond to global climate change and participate in global environmental governance, as well as a key initiative to promote the construction of domestic ecological civilization and build a community with a shared future (Liu, 2022).

The realization of the dual carbon target is related to the energy transformation and industrial upgrading of the whole country and essentially concerns all industries. The shipping industry is not only fundamental to a country's economic development but also plays an important role in international trade and economic development (Zhang, 2017) as a low-cost and widely applicable tool for bulk cargo transportation (Wan et al., 2018). Although shipping is already a more economical, environmentally friendly, and energy-efficient mode of transportation in terms of total carbon emissions, energy consumption, and carbon emissions per unit of turnover (Nast, 2013), its energy consumption and carbon emissions have increased significantly more than those of other industries (Hughes et al., 2017).

The shipping industry currently accounts for about 3% of global CO2 emissions (Sun et al., 2022), and with the yearly increase in the number of ships and the trend toward larger ships, carbon emissions from shipping are climbing at an annual rate of 1.1% to 3.4% (Bloor et al., 2015). The International Maritime Organization (IMO) Fourth Greenhouse Gas Study 2020 shows that, owing to the continued growth of global shipping trade, shipping greenhouse gas emissions have increased from 977 million tons in 2012 to 1,076 million tons in 2018 (an increase of 9.6%), and shipping carbon emissions in the global share of anthropogenic Greenhouse Gas (GHG) emissions has increased from 2.76% in 2012 to 2.89% in 2018. Without effective carbon reduction measures, carbon emissions from shipping will increase by about 90% in 2050 compared to 2018 and by about 90–130% compared to 2008 (IMO, 2020), impeding the global fight against climate change.

Carbon reduction in shipping is not only an important part of achieving the Paris goals (Hedley et al., 2016) but also an important direction for the future sustainable development of the shipping industry. There is coupling effect between port economy and urban environment (Chen et al., 2022a). Up to now, Chinese scholars' research on shipping mainly focused on the application of game theory in the analysis of port coopetition (Xu et al., 2021a), freight forwarding market and inland shipping pollution control (Xu et al., 2021b; Xu et al., 2022a), Some scholars also have studied the mechanism of Covid-19 empirical in the change of shipping industry (Xu et al., 2022b)and container shipping alliance (Chen et al., 2022b), The existing research results not only lack attention to shipping decarbonization, but also lack investigation of relevant legislation and policies of China, which is the significance of this paper. Under the institutional thrust of ecological civilization construction, China has formulated legislation and policies on carbon reduction in shipping at the national and local levels, and the introduction of dual carbon targets has accelerated this process. The purpose of this paper is to examine the latest progress in China's practices on carbon reduction in shipping and to review and reflect on them. Part 2 systematically and comprehensively compares and reviews the existing legislation and policies on carbon reduction in shipping at different levels at national and local aspects, and outlines the regulatory system of carbon reduction in shipping in China. Part 3 first summarizes the achievements of China's legislation and policies on carbon reduction in shipping from the legal system aspect, and further reflects on the shortcomings and challenges of China's legislation and policies on decarbonization of shipping in terms of system characteristics and regulatory content. Part 4 puts forward suggestions for improving the carbon reduction legislation and policies of China's shipping, including enhancing the binding force of the carbon reduction legislation and policies of shipping, expanding the content of regulations, and providing an all-round and full-process legal basis for the carbon reduction of shipping.

2 Normative construction: China's legislation and policies on shipping decarbonization

The decarbonization of shipping refers to reducing the amount of carbon dioxide produced by the shipping industry with the goal of net zero emissions, and the main path is to reduce carbon emissions and supplement these with increasing carbon sinks. Since there are many factors affecting the CO2 emissions of ships, such as ship type (Xiao et al., 2022), hull design (Lindstad and Eskeland, 2015), speed (Eide et al., 2013), operation technology (Xing et al., 2020), shipping path (Shu et al., 2022)and power fuel (Halim et al., 2018). Shipping carbon reduction thus needs cooperation of multiple sections including shipping infrastructure, shipping technology and equipment, shipping organization system, shipping governance mechanism, for instance the design of an intermodal transportation network (Bouchery and Fransoo, 2015), and other aspects (Nast, 2013; Kujanpää and Teir, 2017), with a "multicenter" characteristic (Black, 2008). In addition to technological improvements such as new technologies, fuels, and operational measures, the achievement of carbon reduction in shipping also depends on appropriate laws and policies. Through legal regulations, the certainty, predictability, and compulsory nature of carbon reduction in shipping can be increased, and the carbon reduction effect can be ensured.

2.1 National legislation and policies

In terms of national legislation, China constructs its own legal regulation system of shipping decarbonization through the constitution, laws, and regulatory documents. First, from the constitutional level, the amendment of the constitution in 2018 has written "promoting the coordinated development of material civilization, political civilization, spiritual civilization, social civilization, and ecological civilization" and building a beautiful China into the preamble of the constitution. It requires the Chinese government to follow the concept of "community of life" and "harmonious coexistence between human beings and nature" in the process of achieving carbon neutrality and carbon peaking, and implement green development, low-carbon development, and sustainable development into industrial structures, production modes, and life styles. As an organic part of social production and human life, shipping carbon emission affects the atmosphere, water, fishery and other natural resources, and is therefore an important issue under the legal regime of "dual carbon." It also provides the fundamental basis and direction for China's shipping carbon reduction legislation.

Second, from the aspect of laws, the legislative provisions on shipping decarbonization are mainly stipulated in the environmental laws, primarily regulating administrative subjects of specific watersheds. For example, Article 66 of the Yangtze River Protection Law stipulates that local governments above the county level along the Yangtze River basin shall promote the upgrading of steel, ships, and other industries to improve the level of technology and equipment, and Article 72 stipulates that they shall coordinate the construction of ship pollutant receiving and transferring. Furthermore, Article 73 provides that the governments at or above the county level in the Yangtze River basin shall coordinate the construction of ship pollutant reception and transfer facilities, ship liquefied natural gas filling stations, and develop plans for the construction and renovation of port shore power facilities and ship receiving power facilities in accordance with the provisions of financial support or policy support. The State Council and the local government should offer help to ship charging facilities in accordance with the provisions of financial subsidies, tariff concessions, and other forms of policy support. Moreover, Article 84 provides that with the conditions for the use of shore power and not in accordance with the relevant state regulations to use shore power ships to be subject to administrative punishment.

The Yellow River Protection Law Article 36 provides that the State Council departments in charge of natural resources, forestry and grassland should work with the relevant departments of the State Council and the people's government of Shandong Province, the organization of the Yellow River Delta wetland ecological protection and restoration, reduce the impact of port shipping and other activities on the estuarine ecosystem, To be more specific, Article 87 and Article 101 say that Local governments shall promote the high-quality development of manufacturing and transformation of resource-based industries, develop clean and low-carbon energy in accordance with local conditions, promote the optimization and adjustment of industrial structure, energy structure, transportation structure, and promote carbon peaking and carbon neutral work. Similarly, the Wetland Protection Law prescribes that tourism, shipping and other utilization activities within the wetland should avoid changing the natural condition of the wetland, and take measures to mitigate the adverse impact on the ecological function of the wetland, and local governments shall take water treatment, vegetation restoration and other measures to enhance the ecological function of wetlands and carbon sink function.

From the policy level, since the 18th National Congress, the ruling party and the central government have released the Opinions on Accelerating the Construction of Ecological Civilization, Overall Plan for the Reform of Ecological Civilization System and Opinions on Completely and Accurately Implementing the New Development Concept playing the role of top-level design. In this context, various departments of the State Council have formulated targeted sectoral normative documents according to their respective responsibilities for different institutional grips of carbon reduction in shipping. For example, in terms of shipping carbon emission monitoring and reporting, in November 2022 the China Maritime Safety Administration developed and released the Measures for the Management of Ship Energy Consumption Data and Carbon Intensity on the basis of the 2018 Measures for the Collection and Management of Ship Energy Consumption Data, which provides for the collection and reporting of ship energy consumption data, the management of carbon intensity of Chinese international voyages, and the supervision and management mechanism.

For port construction, the Ministry of Communications formulated and released the Green Port Evaluation Grade Standard in 2013, which includes low carbon and energy saving as one of the evaluation indexes of green port grade, and has formulated specific evaluation score calculation methods. In order to optimize the shipping organization system, the General Office of the State Council issued the Work Plan for Optimizing the Adjustment of Transport Structure (2021-2025), which proposed to improve the green development policy of transportation in order to promote energy conservation, emission reduction and carbon reduction, specifically including developing Promote the development of multimodal transport and the adjustment of the transport structure of carbon emission reduction policies, encourage the introduction of new energy and clean energy vehicles and vessels to facilitate the passage of policies. In special sensitive protection areas, encourage innovation and promotion of green and low-carbon transport organization mode, to guard the natural ecological security boundary.

2.2 Local legislation and policies

Regarding local legislation, 14 provincial governments in China, including Shanghai, Jiangsu, Anhui, and Hunan, have issued carbon peak implementation plans, and several provinces have incorporated the development of green and low-carbon transformation of shipping into their plans. For example, the Guizhou Carbon Peak Implementation Plan proposes to promote energy conservation and clean energy utilization in ports, accelerate the orderly construction of shore power facilities in existing terminals according to needs, and guide existing ships to speed up the equipping of receiving power facilities and increase the proportion of using shore power facilities. Hunan, Jiangsu, Heilongjiang, Jiangxi, Hainan, and other provinces have proposed promoting the application of green ships and green port construction, promoting new energy and clean power energy ships, accelerating the elimination of low efficiency, high energy consumption of old ships and ship receiving power facilities, and port shore power facilities reform as the key tasks of the implementation plan.

In addition, several provinces and cities have promulgated more targeted and detailed action plans or implementation plans regarding shipping decarbonization. For example, in the Pearl River basin, the Ministry of Transport and the four provinces of Guangdong, Guangxi, Guizhou, and Yunnan jointly released the Action Plan for Promoting the Green Development of Pearl River Waterway Transport (2018–2020) in 2018, which proposed that by 2020, compared with 2015, the energy consumption per unit transport turnover of operating ships in the Pearl River water system would be reduced by 6%, and the carbon dioxide emissions per unit transport turnover would be reduced by 7%. In 2021, Guangdong Province also released a series of implementation plans on shipping decarbonization consisting of the Overall Division Plan for Guangdong Province to Improve Inland Shipping Capacity and Promote the Green Development of Inland Shipping, the Implementation Plan for Guangdong Province's Inland Shipping Capacity Improvement, and the Implementation Plan for Guangdong Province's Inland Shipping Green Development Demonstration Project, proposing to accelerate the high-quality green development of inland navigation, optimize the port layout and waterway network, and accelerate the popularization of Liquefied Natural Gas (LNG) powered ships. Moreover, as early as 2016, Shenzhen issued the Five Year Action Plan for the Construction of a Green and Low Carbon Port in Shenzhen (2015–2020), which proposed that by the end of 2020, the comprehensive energy consumption of container throughput per unit of port production and operation would be 5% lower than that in 2015, and the carbon emissions of container throughput per unit of port production and operation would be 4% lower than that in 2015. In the Yangtze River basin, Shanghai has successively issued the Three Year Action Plan for Shanghai Green Port (2015–2017), the 13th Five Year Plan for Energy Conservation and Climate Change in Shanghai, and the 14th Five Year Plan for the Construction of the Shanghai International Shipping Center to promote energy conservation and carbon reduction in port construction and ship governance, and proposed the goal of achieving 100% coverage of shore power facilities in specialized berths of ports by 2025. In addition, the People's Government of Zhoushan City, Jiangsu Province, issued Several Opinions on Supporting the High Quality Development of a Modern Shipping Service Industry in 2022 to "support the development of green digital shipping." For important projects that have been identified as directly contributing to "carbon peak, carbon neutral" and "green shipping development in the Yangtze River Economic Belt," appropriate rewards will be granted according to the construction investment of individual projects. See Table 1 for examples of China's local legislation and policies on shipping decarbonization.

3 Normative evaluation: Achievements and challenges of China's legislation and policies on shipping decarbonization

As an important countermeasure against climate change, China has continued to promote the green and low-carbon transformation

TABLE 1 Shipping Decarbonization in China's Local Legislation and Policies.

Normative documents	Green Channel	Green Port	Green Ship	Green Transportation Organization Mode
Action Plan for Promoting Green Development of Pearl River Water Transport (2018–2020) is Jointly formulated by the Ministry of Transport and provincial governments	Build ecological channels	1.Port shore power facilities 2. Decrease the comprehensive energy consumption per unit throughput and the carbon dioxide emissions per unit throughput of port production by 2% in 2020, (compared with 2015).	Compared with 2015, the energy consumption per unit transport turnover of operating ships decreased by 6%, and the carbon dioxide emissions per unit transport turnover decreased by 7%.	1.Multimodal transport system 2. Smart water transport
1.Guangdong Provincial Waterway Development Plan (2020-2035) 2.Overall Division Plan of Guangdong Province for Improving the Capacity of Inland Waterway Shipping and Promoting the Green Development of Inland Waterway Shipping	1.Characteristic channel of ecotourism 2.Waterway ecological restoration project.	1. Port shore power facilities. 2. LNG filling station.	1.Implement ship type standardization project 2. LNG power transformation of inland ships.	1.Improve the river-sea intermodal transport system 2.Multimodal transport.
1. Jiangsu Province's "Fourteenth Five-Year Plan" for Green Transport Development 2. Implementation Opinions on Promoting High-quality Development to Achieve Carbon Peak and Carbon Neutralization	1. Regional channel ecological restoration project 2. Quality Inspection Standard for Ecological Revetment Works of Inland Waterway	1. Jiangsu Province Green Port Evaluation Index System. 2. Normalized use of shore power facilities by ships berthing at the port.	1.Ship fuel emission limit 2. Obsolete ships with high energy consumption and high emissions. 3. LNG power transformation.	1.Multimodal transport. 2.River, sea and river combined transport.
1."The Fourteenth Five-Year Plan" for Comprehensive Transportation Development in Shanghai 2.The 14th Five-Year Plan for the Construction of Shanghai International Shipping Center 3.Three-year Action Plan for Shanghai Green Port (2015-2017)	1. Ecological restoration of water area. 2. Ecological construction of transportation infrastructure.	1.The coverage rate of specialized berth shore power facilities will reach 100% in 2025. 2.Energy conservation and emission reduction technical transformation of container terminal handling equipment.	1.Standard of inland river ship types, and oil. 2. Obsolete ships with high energy consumption and high emissions. 3.LNG filling facilities. 4.Energy efficiency design index (EEDI) for new ships and Energy Efficiency Management Plan (SEEMP) for ships in use.	1.Multimodal transport 2.High-quality integrated collection and distribution network

of the shipping industry on the track of the rule of law, and has formulated and promulgated legislation and policies on carbon reduction in shipping at the national and local levels one after another, providing a normative basis to promote carbon reduction in shipping. In this process, China has made certain achievements but has also had shortcomings and faces a series of challenges.

3.1 Achievements of China's legislation and policies on shipping decarbonization

As we can see above, China has initially established a multi-level shipping carbon reduction regulation system oriented by the double carbon target and unified by the constitution, which covers many aspects and mechanisms. According to the different natures of regulatory instruments, China's legal system of shipping decarbonization can be divided into two types, namely, "command and control" and "incentive and regulation." Both have their respective strengths and cooperate with each other to provide a strong and diversified legal guarantee for carbon reduction in shipping.

First, the "command and control" rules have a high degree of compulsion, and the administrative subject sets a certain "shall" behavior pattern for each shipping subject through compulsory order. "Command and control" rules include the following:

(1) Plans, such as the Guizhou Province Carbon PeakImplementation Plan. It proposes that by 2025 and 2030, to achieve a target in which the proportion of new and updated new energy, clean energy-powered ships will reach 40%, the ship unit conversion turnover of carbon emissions intensity than in 2020 will decrease by about 9.5%. In 2022, the 14th Five-Year Plan for the Development of Tianjin Ports also proposes to achieve the target of the utilization rate of low-sulfur fuel oil for ships in port and the proportion of ships with electricity receiving facilities using shore power in port to reach 100% by 2025;
(2) Standards, such as the Green Port Evaluation Grade Standard and Technical Requirements for Ship Energy Consumption Data Collection and Reporting. Both are transportation industry standards; the former specifies the green port grade evaluation index system, score calculation method, and manner of grade evaluation, among others, while the latter specifies the scope of ship energy consumption data collection, ship energy consumption information and related data collection method, data quality assurance plan, and manner of data reporting, among others;
(3) Licensing, such as the Implementation Opinions on Accelerating the Green and Intelligent Development of Inland Waterway Ships, which proposes studying and implementing the access system of the Energy Efficiency Design Index (EEDI) for new domestic inland waterway ships;
(4) Monitoring, such as the Measures for the Management of Ship Energy Consumption Data and Carbon Intensity, which stipulate the collection and reporting of ship energy consumption data and verification rating;
(5) Administrative punishment, such as the Yangtze River Protection Law. Article 84 of Chapter 8, "Legal Liability," stipulates that if a ship with conditions for using shore power fails to use shore power in accordance with relevant state regulations, the competent department shall order to stop, give a warning, and impose a fine of 10,000 yuan or more than 100,000 yuan; if the circumstances are serious, a fine of If the circumstances are serious, a fine of more than 100,000 yuan and less than 500,000 yuan shall be imposed. The Guidance on Promoting the Green Shipping Development of the Yangtze River Economic Belt proposes to study the establishment of a shipping blacklist system and increase the punishment for non-compliant enterprises.

Second, the "incentive and regulation" rules have a highly voluntary nature, and the administrative subject indirectly guides shipping behavior that is beneficial to carbon reduction by providing economic benefits or navigational convenience. This type of control includes the following:

(1) Financial subsidies, such as the 2022 Shanghai Transportation Energy Conservation and Emission Reduction Special Support Funds Management Measures, which specify that for ship projects using liquefied natural gas instead of fuel oil, a one-time subsidy will be given according to 2500 RMB per ton of standard oil for the replaced fuel, the amount of subsidy for a single ship will not exceed 400,000 RMB, and the amount of subsidy will not exceed 30% of the total investment amount. For electric ship projects, 30% of the cost of the ship's power system shall be subsidized, of which 40% of the operating passenger ships shall be subsidized, and the maximum amount of subsidy for a single ship shall not exceed 5 million yuan. The Implementation Rules of the Interim Measures for the Management of Subsidy Funds for Green Low-carbon Port Construction in Shenzhen, which came into effect in 2018, states that for the construction of port shore power facilities and the transformation of ship shore power receiving facilities shall be subsidized according to 30% of the project construction and transformation costs, and the power supply demand fees for port shore power facilities shall be fully subsidized according to the actual generation;
(2) Tax relief, such as Article 4 of the Vehicle and Vessel Tax Law, which stipulates that vehicles and vessels that conserve energy and use new energy may be reduced or The Notice on Preferential Policies for Energy-saving and New Energy Vehicles and Vessels issued by the Ministry of Finance and other four departments in 2018 clearly exempts vessels whose main propulsion power unit is pure natural gas engine" from vehicle and vessel tax. In addition, the China (Zhejiang) Pilot Free Trade Zone Extended Area Program promulgated by the State Council in 2020 stipulates that LNG is allowed to enjoy a bonded policy as fuel for international vessels. With reference to the Interim Measures for the Operation and Management of Bonded Oil for International Vessels in China (Zhejiang) Pilot Free Trade Zone, LNG as fuel for international voyages can enjoy tax incentives of 9% VAT on import links and 1% import tariffs and consumption taxes;
(3) Economic incentives, such as the Opinions on Supporting the High-Quality Development of Modern Shipping Service Industry issued by the People's Government of Zhoushan City, Jiangsu Province in 2022. It is clearly stipulated that

green shipping projects that are recognized as directly related to carbon peak and carbon neutral shall be appropriately rewarded according to the construction investment of individual projects, and the standard of reward may be appropriately increased. The proportion of reward for a single project shall not exceed 30% of the construction investment, and the total amount shall not exceed 3 million yuan;

(4) Facilitation of navigation, such as in Guangdong Province and Jiangsu Province, which have both introduced specific implementation measures for LNG-powered vessels to have priority in passing through their gates. The Guidance on Priority Passage of LNG-powered Vessels by the Guangdong Provincial Department of Transportation stipulates that operating units shall give priority to accept, arrange, and dispatch LNG vessels' passage. The Management Measures for Priority Passage of Ships on Inland Waterways in Jiangsu Province states that LNG-powered ships are given priority passage and exempted from priority passage fees on the Beijing-Hangzhou Canal and Huaihe Waterway in Jiangsu Province, and LNG-powered ships pass the locks after dangerous cargo ships, container ships, and key emergency material ships. Other provinces are also studying the policy of giving priority to LNG-powered vessels; for example, the Shanghai Municipal People's Government proposed in the Three-year Action Plan for the Construction of the Shanghai International Shipping Center (2018–2020) to give priority to new energy and clean energy vessels in navigating through the locks, and the Anhui Provincial People's Government proposed to promote the implementation of transport structure adjustment and study the introduction of LNG-powered ships priority through the locks, priority berthing, and other support policies.

As China's legislation and policies on shipping decarbonization have been implemented diversely in local regions with different progress and for a relatively short period, there are no comprehensive national statistics on their implementation effects. However, the existing data show that several pieces of legislation and policies have achieved good results regarding certain aspects of shipping decarbonization. For example, in terms of shore power construction, dozens of Chinese ports have adopted command or incentive control systems to promulgate distinctive legislation and policies on port decarbonization (see Table 2 below). Among them, Tianjin Port, under the incentive of relevant preferential policies, has increased the use of shore power from 19 times in 2019 to 278 times in 2021 by taking measures such as wind and photovoltaic power generation, building a clean energy fleet, building a comprehensive energy management and control service platform, and promoting the use of shore power. The use rate of shore power and low-sulfur oil for its own ships has reached 100%. In 2021, compared with 2012, the cargo throughput of Tianjin Port increased by 12%, container throughput increased by 64%, and carbon emission intensity decreased by 16%. In addition, the Asia Clean Air Center, an international environmental protection organization, released the report "2020 Blue Port Pioneer: Evaluation of Air and Climate Synergy of Typical Ports in China" in April 2022. The report tracked and evaluated decarbonization actions of 11 typical Chinese coastal ports such as Ningbo Zhoushan Port, Shanghai Port, and Qingdao Port, and four typical inland ports, including Yueyang Port, Suzhou Port, Wuhu Port, and Jiujiang Port, for two consecutive years. The report shows that 14 of the 15 typical Chinese ports surveyed have reached the goal of 50% shore power coverage of specialized berths by the end of 2020, and the shore power coverage of four inland ports has reached 100%, double the abovementioned target. The use of shore power for port ships is evidently better than that for freight ships. Except for the missing data of Yingkou, Jiujiang, and Wuhu Ports, the use of shore power for port ships in the remaining 12 ports has essentially achieved 100%, exceeding the 90% target set forth in the Implementation Plan for Special Action on Ship and Port Pollution Prevention (2015–2020). See Table 3 for shore power construction and use of shore power for port ships of typical ports in China.

3.2 Challenges of China's legislation and policies on shipping decarbonization

While China's shipping carbon reduction legislation and policies have made the above achievements, the following shortcomings still exist, which affect the implementation of rules.

TABLE 2 Incentive Policies on Shore Power Construction and Use of Typical Ports in China.

Port	Relevant Legislation and Policies	Content regarding Encouraging Shore Power Construction and Shore Power Use
Shenzhen	Detailed Rules for the Implementation of Shenzhen Transport Special Funds for Port and Shipping in the Field of Green Transport Construction	Financial subsidies
Shanghai	Shanghai Port Green Convention	Priority of navigation
Tianjin	Notice of Tianjin Port and Waterway Administration on Measures to Further Promote the Use of Shore Power for Ships Arriving in Tianjin	Priority of navigation
Xiamen	Interim Measures of Xiamen Municipality on the Administration of the Use of Shore Power for Ships Berthing at Ports	Financial subsidies Economic rewards
Rizhao	Rizhao Port Group Ship Shore Power Management Measures	Priority of navigation
Suzhou	Jiangsu Province Notice on Further Promoting the Use of Shore Power for Ship Berthing	Priority of navigation Service fee exemptions
Jiujiang	Implementation Plan for Port and Ship Shore Power Facility Reconstruction and Promotion (2020)	Priority of navigation
	Guiding Opinions on Port Shore Power Charging	Electricity charge reductions

TABLE 3 Construction and Use of Shore Power in Typical Ports of China.

Port		Shore Power Coverage of Specialized Berths	Utilization Rate of Shore Power for Port Ships
Coastal port	Qingdao	100%	100%
	Yingkou	91%	——
	Ningbo Zhoushan	84%	100%
	Shenzhen	80%	100%
	Shanghai	79%	100%
	Rizhao	54.4%	100%
	Xiamen	50%	100%
	Tianjin	50%	100%
	Lianyungang	36.5%	100%
Inland port	Jiujiang	100%	——
	Yueyang	100%	100%
	Wuhu	100%	——
	Suzhou	100%	100%

(The utilization rate of shore power is primarily sourced from government information disclosure, and the calculation method is the ratio of the number of times that cargo ships use shore power to the number of berths that park in shore power. "——"means relevant data is missing.)

3.2.1 The strong "soft law" characteristic of the current normative system on shipping decarbonization

First, at the level of national legislation, since Article 2 of China's Air Pollution Prevention and Control Law clearly stipulates the implementation of synergistic control of particulate matter, sulfur dioxide, and other air pollutants and greenhouse gases, China's environmental law does not treat CO2 as an air pollutant; hence, it is not feasible to rely on the Air Pollution Prevention and Control Law to implement carbon reduction in shipping in China. At the same time, China has not yet issued the "Climate Change Response Law," which would specifically regulate greenhouse gases. Therefore, at the legal level, there are few regulatory bases for carbon reduction in shipping, which are mainly scattered across environmental laws related to watershed and wetland protection. This also indirectly leads to the limited scope of application of relevant provisions and regulatory subjects and incomplete coverage on shipping decarbonization; for example, the relevant provisions in the Yangtze River Protection Law are only applicable to ships and local governments passing in the Yangtze River basin.

At the same time, it is difficult to locate relevant provisions on carbon reduction in shipping in administrative regulations and local regulations. For example, from the aspect of administrative regulations, the Regulations on Prevention and Control of Marine Environment Pollution from Ships make general provisions on how to prevent and control marine pollution from ships and their related operation activities, including the discharge and reception of pollutants from ships, the prevention and control of pollution from ships' operation activities, and the emergency disposal of ship pollution accidents, but there are no provisions on how to deal with carbon dioxide emissions from ships and carbon leakage caused by oil leakages. In general, the regulation of carbon reduction in shipping in China is mainly concentrated in the low-level departmental normative documents and other policies, which has strong characteristics of "soft law."

As for local legislation, the regulation of carbon reduction in shipping mainly includes the implementation plan, development plan, and guidance issued by provinces and municipalities, and the binding force of the law is also weak. Carbon emissions from shipping are mobile, borderless, and cross-regional. The local legislation on carbon reduction of shipping is not unified because the legislative concept and content of each place are closely related to its economic development level and geographical location, which also limits the final realization of the carbon reduction effect of shipping.

Second, except for Article 84 of the Yangtze River Protection Law, which provides for warning and fines for "ships not using shore power according to regulations," most of the norms regulating carbon reduction in shipping are advocacy provisions and lack of supporting legal responsibilities. For example, in Chapter 3 of the Wetland Protection Law, "Wetland Protection and Utilization," Article 25 provides that shipping activities within the wetland should avoid changing the natural condition of the wetland and take measures to mitigate the adverse impact on the ecological function of the wetland. However, Chapter 6, "Legal Liability," does not see the corresponding administrative legal responsibilities such as fines and orders to suspend production and business. Once there is a situation of acidification of wetland waters and damage to ecological functions due to carbon leakage from ships, it is impossible to impose administrative sanctions on the relevant shipping entities, and the responsible person will only be liable for civil liability at most. Another example is that the Measures for the Management of Energy Consumption Data and Carbon Intensity of Ships, which stipulates in Article 5 of Chapter 2, "Data Reporting and Collection," that Chinese domestic marine vessels and inland river vessels shall record the energy consumption data of ships on a daily basis or on each voyage, and the energy consumption data recorded by ships shall be kept for at least two years, but the measures do not set up a chapter of "Legal Liability.". According to Article 21 of Chapter 4, "Supervision and Administration,", if the maritime administration finds that a ship fails to report the ship's energy consumption data as required, it shall, in accordance with the Regulations of the PRC on the Prevention and Control of Pollution of the Marine Environment by Ships and Their Related Operating Activities and the requirements of these measures, be dealt with. Such a liability provision is too general and lacks operability and legal deterrence.

3.2.2 The normative content of established rules needs to be improved

Shipping decarbonization is a systematic project that involves shipping infrastructure, shipping technology and equipment, shipping organization systems, shipping governance mechanisms, and more aspects.

First, carbon emission trading mechanisms are out of place. At present, the institutional measures for carbon reduction in China's shipping industry are mainly the regulatory measures led by administrative organs and lack the participation of market-based mechanisms. Market-based mechanisms are designed to internalize the external costs of GHG emissions based on the polluter-pays principle (Wang et al., 2021)and provide economic incentives related to GHG emission reduction (Harilaos, 2012; Daniel, 2018). It has been manifest that the market transaction policy can enhance the economic and emission reduction potential more than the command control policy can (Wang et al., 2016).The adoption of carbon reduction measures based on market mechanisms is the current choice of instruments for regulating GHG emissions in many countries and the International Maritime Organization (Kirval and ÇaliŞkan, 2022). For example, the European Commission voted in July 2021 to adopt the "fit for 55" action plan package. The plan proposes to achieve at least a 55% reduction in GHG emissions by 2030 compared to 1990 emission levels and to achieve carbon neutrality by 2050 (Jeong et al., 2022). As part of the proposed legislation, the European Commission proposes to include shipping in the EU Emissions Trading System (EU ETS), which operates using the "allowances and trading" principle to cap the total amount of greenhouse gas emissions that can be emitted by factories, power plants, ships, and other entities. Over time, the cap is lowered, thereby gradually reducing the total amount of carbon emissions (Harilaos, 2021). In November 2022, the European Parliament, European Commission, and European Council reached a basic agreement on the inclusion of shipping in the EU ETS, with a preliminary agreement covering the timing, applicable ship tonnage, coverage of emissions from navigation, coverage of emissions, use of funds, and other specifics.

China has carried out carbon emissions trading pilot projects in seven provinces and cities, including Beijing, Tianjin, and Shanghai, since 2011 (Zhang et al., 2020), and in 2020, the Ministry of Ecology and Environment officially announced the Carbon Emissions Trading Management Measures (for Trial Implementation), which opened the construction of the national carbon emissions trading market. In 2021, the Carbon Emissions Registration Management Rules (for Trial Implementation), Carbon Emissions Trading Management Rules (for Trial Implementation), and Carbon Emissions Settlement Management Rules (for Trial Implementation) were issued one after another, providing strong rules to support the construction of China's carbon emission trading market.

However, according to the Notice on the Key Work Related to the Management of Enterprise Greenhouse Gas Emissions Reporting in 2022 issued by the Ministry of Ecology and Environment of China in March 2022, the industries covered by carbon emissions trading in China currently include power generation, petrochemicals, chemicals, building materials, iron and steel, non-ferrous, paper making, and civil aviation, and the shipping industry has not yet been included. Nonetheless, Shanghai has taken the lead in trying to include shipping in the carbon emission trading mechanism since 2015 and has made useful exploration of carbon emission accounting, carbon quota allocation, and trading rules for shipping enterprises. Unfortunately, China's carbon emissions trading has not yet covered most domestic shipping enterprises and international operating ships. In the future, China needs to introduce a carbon emission trading mechanism to reduce carbon emissions from shipping and construct detailed legal rules on the scope of participation of shipping enterprises, carbon emission accounting systems, and quota allocation scheme, among others, by combining the characteristics of carbon emissions from shipping.

Second, incentives for shipping decarbonization are fragmented and have not been fully promoted nationwide. Well-designed incentives can guarantee the independent choice of market players on the one hand, and help achieve the expected environmental goals of society on the other. Shipping carbon reduction incentives mainly include energy saving and emission reduction tax incentives, subsidies, rewards, navigation facilitation, and other contents. At the national legislation level, both Article 73 of the Yangtze River Protection Law and Article 101 of the Yellow River Protection Law are only advocacy provisions to encourage the development of incentives, which are more general and lack detailed implementation rules.

For local legislation, only some provinces and municipalities in China have introduced incentives owing to the different degrees of importance attached to carbon reduction in shipping. For example, Shenzhen issued the Interim Measures for the Management of Green Low-carbon Port Construction Subsidy Funds in Shenzhen in 2017 and 2018, and the Rules for the Implementation of the Interim Measures for the Management of Green Low-carbon Port Construction Subsidy Funds in Shenzhen to refine the management of shore power subsidy, clean energy-powered ship subsidy, ship exhaust gas purification facility subsidy, and ship online monitoring equipment subsidy. Shanghai issued the Shanghai Port Shore Power Construction Program in 2019, which formulated supporting policies for shore power construction subsidies, operation subsidies, preferential shore power service fees for ships calling at ports, and preferential shore power tariffs for port construction.

Meanwhile, Zhejiang Province issued in 2022 the Zhejiang Port Shore Power Incentive Scheme, which refines the scope and requirements of port shore power construction subsidies and specifies specific subsidy standards according to the type, frequency, capacity, and transformation completion time of shore power. From this, it can be seen that the implementation of China's shipping carbon reduction incentives is still stuck in pilot exploration at the local level and lacks the guidance of national unified implementation rules. This is not conducive to the formation of stable legislation or policy expectations for carbon reduction in shipping by relevant enterprises and may reduce the enthusiasm of shipping enterprises for the construction of port shore power facilities and the use of ship shore power.

Finally, there is a lack of a financial support mechanism for carbon reduction in shipping industries. As a typical capital-intensive industry, the development of the shipping industry depends on the financial support provided by the financial system. One of the biggest obstacles to carbon reduction in shipping is the huge capital costs required for cleaner, energy-efficient technologies (Rebelo, 2020). The dual-carbon context requires strong financial support for alternative fuel use, new energy technology research and development, and port shore power retrofitting. As the green and low-carbon transformation of the shipping industry continues to advance, the demand for capital in the shipping industry is increasing daily. Providing strong financial support for carbon reduction in shipping can effectively guide enterprises to upgrade their technology and equipment, thus realizing industrial upgrading and green low-carbon transformation.

At present, China's shipping carbon reduction financial support mechanism is relatively scarce, which is not conducive to the research and development of energy-saving and emission-reduction technology and innovation. Both national and local legislation are in principle lacking operability. For example, according to the Guidance on Building Green Financial System jointly issued by seven ministries and commissions, including the People's Bank of China, the Ministry of Finance, and the Development and Reform Commission, green finance clearly includes "financial services provided for investment and financing, project operation, and risk management of green transportation projects," but the specific operation, financial support mechanism for shipping industry regarding management, approval process, and other contents have not been formulated and formed uniformity rules.

Article 22 of the Huzhou City Green Finance Promotion Regulations stipulates that financial institutions can provide medium- and long-term financial support for the construction of green roads, railroads, waterways, ports, and other green low-carbon transportation infrastructure. However, this article is a principle provision, and the specific rules of the way, type, standard, and application scope of financial support for shipping carbon reduction in practice are not yet clear. At the international level, 28 large banks in the world, including Citibank, Societe Generale, and Credit Suisse, have signed the Poseidon Principles, which aim to incorporate climate change factors into shipping financing decisions and have great normative value in promoting carbon neutrality in shipping (Rebelo, 2020; Kavussanos and Tsouknidis, 2021). The principles now cover more than 50% of total global shipping loans. The Poseidon Principles are a global industry framework, and under the trend of the globalization of green finance, China's legislation and policies on carbon reduction in shipping should respond to it.

4 Normative perfection: Recommendations for the improvement of China's legislation and policies on shipping decarbonization

Under the background of actively promoting carbon peaking and carbon neutrality, China has initially established a regulatory system for carbon reduction in shipping, but the relevant legislation and policies are still inadequate and face real challenges. Based on China's national conditions, this paper proposes the following suggestions for the improvement of shipping carbon reduction legislation and policies.

4.1 Strengthening mandatory force of legislation and policies on shipping decarbonization

On the one hand, the mandatory force of legislation and policies on shipping decarbonization should be enhanced. First, the legal rank of shipping carbon reduction legislation should be improved, and it is suggested that the State Council or the Ministry of Ecology and Environment and the Ministry of Transport should take the lead in formulating special administrative regulations or departmental regulations on shipping carbon reduction, coordinating the scattered policy norms and local legislation, strengthening the connection between institutional norms such as the construction of shore power in ports, the transformation of ships receiving electricity, the promotion of low-carbon powered ships and the verification of carbon emission data in shipping, and improving the carbon reduction norms of shipping.

More importantly, the legal responsibilities corresponding to the relevant systems should be clarified. A law without responsibility is a "tiger without teeth." Since the illegal behavior of shipping carbon reduction mainly violates the environmental management order and infringes on the public interest of the ecological environment, the legal responsibility of shipping carbon reduction is mainly public law responsibility, mainly administrative responsibility, and criminal responsibility should be investigated according to Chapter 6, Section 6, of the Criminal Law ("Crime of damaging environmental resources protection"). According to Article 9 of the Administrative Punishment Law, the legal responsibilities for carbon reduction in shipping include warning, notification and criticism, fine, confiscation of illegal income, confiscation of illegal property, suspension of license, reduction of qualification level, revocation of license, restriction of production and operation activities, order to stop production and business, order to close, restriction of practice, and administrative detention. In addition, since shipping carbon reduction violations may also cause ecological damage such as acidification of water bodies and reduction of biodiversity (Cooley and Mathis, 2013; Shi and Gullett, 2018), ecological restoration can be considered a legal responsibility for shipping carbon reduction.

At the same time, since shipping decarbonization not only refers to reducing carbon emissions of shipping but also includes "increasing carbon sink," therefore, "subscribing carbon sink" can be considered as one of the ways to fulfill the legal responsibility of carbon reduction in shipping. At present, in judicial practice, the courts in Xiamen, Zhangzhou, Ningde, and other places in China have explored attempts to make alternative restoration through the defendant's purchase of marine carbon sinks to compensate for the ecological damage caused by illegal fishing or sea sand mining. Xiamen also set up the first marine carbon sink trading platform and the first ecological judicial public-interest carbon account in the country. This method of responsibility fulfillment is not only helpful to solve the problems of insufficient restoration capacity of responsible persons and limited actual restoration conditions, but it also contributes to the early realization of the double carbon goal.

4.2 Expanding normative content of legislation and policies on shipping decarbonization

On the other hand, the normative content of regulations should be expanded so as to provide an all-round and whole process legal basis for shipping decarbonization.

4.2.1 Providing normative support for shipping carbon emissions trading

First, China should provide regulatory support for carbon emission trading in shipping. At present, the legal mechanism of carbon reduction in China's shipping industry is dominated by control measures led by administrative organs and lacks the participation of market-oriented mechanisms. Carbon emissions trading in the shipping industry is an important means of market-based carbon reduction measures, which is a "cap-and-trade" system and a quantity-control approach. There are advantages in terms of certainty about mitigation outcomes and cost-effectiveness (Xing et al., 2020), while improving the total industrial output value (Zhang et al., 2020). Research also shows that emissions trading could reduce China's carbon intensity by 20.06% under the unconstrained situation by keeping the total GDP of the country unchanged (Zhang et al., 2017).

In the Chinese context, since the promulgation of the Measures for the Administration of Carbon Emission Trading (for Trial Implementation) in 2021, carbon emission trading has flourished nationwide. In this case, legislators should further improve the existing rules of China's carbon emission trading. In the primary market of carbon emissions trading, China should gradually expand the scope of carbon emissions trading, including the types of greenhouse gases and the industry sectors included in the carbon emissions trading system, and include the shipping industry in the national carbon emissions trading system. In the secondary market of carbon emissions trading, legislators should introduce incentives to promote the diversification of shipping enterprises' participation, and the competent authorities should formulate and improve the rules for trading baseline carbon emissions and certified voluntary emission reductions of shipping enterprises as soon as possible, determining the appropriate level of cap, carbon pricing (Aldy and Stavins, 2012; Hermeling et al., 2015; Rahim et al., 2016)and regulating the monopoly of emission allowances.

Moreover, legislators should improve the carbon emissions trading regulatory mechanism by combining the characteristics of shipping emission reduction. Among them, the collection of ship fuel consumption data and carbon emission data is particularly important for the development of regulations, and it is also a prerequisite for the smooth development of shipping carbon emission trading (Ibna et al., 2017; George et al., 2019). legislators should further improve China's shipping monitoring, reporting, and verification mechanism (MRV) based on the existing Measures for the Management of Energy Consumption Data and Carbon Intensity of Ships, clarify the content and format of the ship energy efficiency management plan and the annual energy consumption report of ships, refine the standards for the assessment of carbon intensity of ships, and also pay attention to the alignment of the relevant standards with the Paris Agreement and the dual carbon targets when designing specific rules.

4.2.2 Concretizing the "incentive and regulation" rules regarding shipping decarbonization

Second, based on local experience, the Ministry of Transport should take the lead in issuing national regulations on carbon reduction incentives for shipping, setting subsidies and rewards for all aspects of carbon reduction in shipping. Up to now, "incentive and regulation" rules, which have been promulgated on shipping decarbonization, are mainly focused on the promotion of low-carbon ports and low-sulfur fuel oil. In the future, types of subsidies/rewards should be expanded, including but not limited to subsidies/rewards for the construction of port shore power facilities, transformation of ship shore power receiving facilities, shore electricity price, shore power use, clean energy powered ships, facilities for purifying ship exhaust gas, online monitoring equipment of ship emissions, and so on. At the same time, the regulations should also specify and detail the standards, calculation methods, application procedures, approval and distribution, supervision, and management of subsidies/rewards by category, aiming at increasing the certainty, operability, and predictability of "incentive and regulation" rules regarding shipping decarbonization, guiding and promoting carbon reduction in shipping with positive incentives. In addition, under the existing framework of the Vehicle and Vessel Tax Law, legislators should conduct research on fuel consumption standards, product technical standards, and special inspection standards for energy-saving ships and new energy ships in line with energy-saving cars and new energy cars, formulate a "catalogue of energy saving and new energy ships exempted from vehicle and vessel taxes," exploring the extension of new energy tax reduction and exemption provisions to the use of low-sulfur oil, shore power, and clean energy ships other than LNG, so as to reduce the technical research and development and infrastructure operation costs of shipping enterprises in an all-round and whole process manner.

4.2.3 Constructing green financial rules that help shipping decarbonization

Finally, China should construct green financial rules to help shipping decarbonization. The China Banking Regulatory Commission (CBRC) and the China Insurance Regulatory Commission (CIRC) should formulate normative documents to (1) clearly stipulate the ways, types, standards, and scope of application of financial support for shipping carbon reduction; (2) establish the financial institutions' shipping carbon reduction investment assessment system and environmental information disclosure system, stipulate the project conditions for financial institutions to carry out assessment, the content of assessment and the subject, content, form, and period of information disclosure; (3) guide financial institutions to innovate green financial products specifically for carbon reduction behaviors, such as shipping infrastructure renovation and technology and equipment upgrading—for example, insurance for new energy ships can be introduced, certain premium preferences can be provided in combination with the carbon reduction of ships, and exclusive rates can be set for new energy ships; and (4) encourage banks, insurance companies, and other financial institutions to use carbon emission assessment as their decision-making basis for loans or underwriting. With reference to the Poseidon Principles, a standard can be established for quantitative assessment and disclosure of whether financial business conforms to the dual carbon goals from four aspects: assessment, accountability, law enforcement, and transparency.

5 Conclusions

As an important response to climate change, China is continuing to promote the green and low-carbon transformation of the shipping industry under the framework of the rule of law to help achieve the goals of carbon peak and carbon neutrality. Previous research on shipping carbon reduction lacks investigation of Chinese context. This paper first gives a comprehensive literature review on measures for shipping decarbonization in terms of China's legal frameworks, with comments and suggestions for improvement. Specifically speaking, focusing on shipping decarbonization, we reviews relevant legislation and policies both at the national and local levels in China. To date, China has preliminarily established a multi-level shipping carbon reduction regulatory system guided by dual carbon goals and governed by its constitution. The normative content of the existing regulatory system covers shipping infrastructure, shipping technology and equipment, shipping organization system, shipping governance mechanism, and other sectors, including port shore power construction, transformation of ship power receiving facilities, promotion of green low-carbon ships (especially LNG-powered ships), shipping carbon emissions data verification, carbon emissions trading, and other specific institutional norms. Under the joint adoptions of a "command and control" system and "incentive and regulation" system, China's legislation and policies on shipping decarbonization has achieved initial positive results. However, China's' legislation and policies on shipping decarbonization are still insufficient in two aspects, affecting the effectiveness of regulations. On the one hand, the normative system of shipping decarbonization has a strong "soft law" feature, and its mandatory force is insufficient. On the other hand, the normative content of legislation and policies on shipping decarbonization is limited and requires improvement. For example, China urgently needs to introduce a market mechanism of carbon emission trading into shipping decarbonization, its incentive measures for shipping decarbonization are fragmented and have not been uniformly promoted nationwide, and there is also a lack of a financial support mechanism for shipping decarbonization. Correspondingly, when China improves its legislation and policies on shipping decarbonization in the future, on the one hand, it is necessary to strengthen the mandatory force of that normative system by improving the legal hierarchy of relative legislation and clarifying the specific legal responsibilities of different legal systems. On the other hand, China should expand the normative content of its legislation and policies on shipping decarbonization to provide comprehensive and full process legal support for shipping decarbonization by providing a legal basis for shipping carbon emissions trading, concretizing the "incentive and regulation" rules regarding shipping decarbonization, and constructing green financial rules that help shipping decarbonization.

Author contributions

WY and XC completed the literature collection and wrote the main part of the article, contributing equally to this paper, and are therefore listed as the co-first author. YL provided the framework for the article and supervised the work, and is therefore listed as the second and corresponding author. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Evolutionary game between government and shipping enterprises based on shipping cycle and carbon quota

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With the opening of the national carbon trading market and the coming of the post-epidemic era, the government actively promotes the carbon quota policy to fundamentally achieve carbon emission reduction. This paper corresponds the shipping cycle to the shipping market demand situation during the epidemic, incorporates the shipping cycle characteristics and government quota characteristics into a multi-stage evolutionary game model. Later, the study analyzes the equilibrium points of the game parties at each stage and finally investigates the influence of factors such as technological improvement on the strategy choice of shipping enterprises through sensitivity analysis. The study found that the government's carbon quota policy is influenced by shipping market demand. During the peak shipping season, the government's quota policy is binding on shipping enterprises. In the low season of shipping, the binding effect of government's quota policy on shipping enterprises will be reduced, or even appear to be invalid. Therefore, the government should forecast the demand situation of the shipping market, gradually relax the regulation during the peak season of shipping, and strengthen the regulation before the low season of shipping. Shipping enterprises should increase the research and development of carbon emission reduction technology to reduce carbon emissions from the root to realize the sustainable development of ports and marine-related industries in the post-epidemic era.

KEYWORDS

carbon quota, shipping cycle, government, shipping enterprises, dynamic game

1 Introduction

Ports are important nodes in the cargo transportation process (Yin et al., 2021), which plays an important role in economic growth. However, the carbon emissions from ports are high. This issue has attracted widespread attention given the development needs of countries and the increasing awareness of environmental protection. In recent years, with the steady growth of port activities in China, carbon emissions from Chinese ports have increased significantly, and China must actively address the issue of carbon emission reduction (Wang et al., 2020). However, the global spread of COVID-19 has had a significant impact on the productive lives of people (Xu et al., 2021), where the negative impact on port throughput mainly includes the closure of shipping routes, transport market disruptions and increased health risks to international cargo. Given that the impact of the epidemic varies from region to region, the carbon emissions vary from region to region. According to the International Energy Agency's World Energy Report 2020, the global energy demand declined by 3.8% and global carbon emissions declined by 5% in the first quarter of 2020 compared with 2019 (Yang et al., 2022).

Nevertheless, according to the trend and internal motivation of carbon emissions after the outbreak, a series of policies to stimulate economic recovery will affect the improvement of energy efficiency with the arrival of the post-epidemic era. Carbon emissions have the possibility of retaliatory rebound, laying a hidden danger for the port to achieve carbon emission reduction targets in the future (Li and Li, 2021). In addition, during the epidemic, ship carbon emissions increase during normal cruising conditions when ships are berthing and anchoring operations. Some ports have shore power equipment (Shi and Weng, 2021), which can replace auxiliary diesel engines with shore-supplied electricity to achieve carbon reduction from ships. However, shore power is not a fundamental solution. On the one hand, the technical standards for the construction of shore power facilities are insufficient, and power expansion is more difficult to achieve. Shore power technology is not easy to promote. On the other hand, shore power is not a zero-emissions technology; it is essentially a transfer of energy production from the ship to a grid power plant away from the port area. Carbon emissions are closely related to how the power is produced, with a 20% increase in carbon emissions for shore power generated using thermal power plants compared with ships using auxiliary power generation (Peng et al., 2019). Therefore, the marine and port-related industries are in urgent need of environmentally friendly, cost-effective concepts and practical solutions to achieve near-zero emission technologies (Misra et al., 2017).

The government has an irreplaceable role in the process of carbon reduction in port-related industries (Liu et al., 2021). Governments intervened early in the process of reducing carbon emissions. In 1992, countries signed the United Nations Framework Treaty on Climate Change. The treaty is the first international climate cooperation framework in the world that aims to reduce the economic cost of carbon emissions reductions through market-based economic instruments. In 1997, the relevant countries signed the Kyoto Protocol, which designed three flexible emission reduction mechanisms through emissions trading, joint compliance, and the clean development mechanism (He, 2016). It also lays the foundation for the development of a carbon trading system. In 2015, 195 countries signed the Paris Agreement, which avoided the problem of choosing and formulating emission reduction plans compared with the "top–down" allocation of emission reduction tasks in the Kyoto Protocol. The "bottom-up" submission of national autonomous contribution targets for greenhouse gas emission reductions is more conducive to the implementation of the treaty (Zhang, 2021). The framework of the global carbon emissions trading system has been basically completed (Rui, 2021).

The carbon emissions of the shipping industry have been a hot topic of concern for various countries. However, the issue of carbon emission reduction in the shipping industry has been excluded from the legal text of international climate negotiations. Although the International Maritime Organization has conducted lengthy negotiations with various parties on the issue of shipping emission reduction, it has been pending on what market-based emission reduction measures to adopt. Provisions were made to include the shipping industry in the carbon emissions trading system in the "Trial Measures for the Management of Carbon Emissions in Shanghai" released in 2017 (Commission SMDAR, 2017). The "Measures for the Management of Carbon Emissions Trading (Trial)" was considered and adopted by the Ministerial Meeting of the Ministry of Ecology and Environment on 25 December 2020 (China MOEAEOTPSRO, 2020) and came into effect from 1 February 2021. The document addresses the carbon reduction problems faced by the maritime and port-related industries at the source by binding shipping enterprises to their carbon emissions and encouraging them to make technological improvements.

The carbon trading system in China is still in its infancy, and the realization of double carbon goals cannot be achieved without the guidance and implementation of government policies. This paper constructs a multi-stage evolutionary model to improve the theoretical framework of carbon trading research. From a practical point of view, this paper constructs a multi-stage evolutionary model based on the existing carbon quota policy to find out the strategy choice and explores the impact of technological improvements and other factors on the design of the carbon trading mechanism. This paper also makes suggestions for the strategy choice of the game parties. It can mitigate the possible retaliatory rebound of carbon emissions in the post-epidemic era and ensure the successful achievement of the Chinese double carbon goal.

2 Literature review

In recent years, the issue of carbon emission reduction has been widely concerned by scholars, who have conducted many studies on carbon emission reduction from various perspectives and using different theories. This paper focuses on carbon trading, evolutionary games, and the application of carbon reduction in the shipping industry. The number of studies on each topic is shown in Figure 1.

Carbon trading is one of the more widely used initiatives in carbon reduction measures. In the evolution of carbon trading literature, it is impossible to avoid the discussion on the issue of carbon price (Shen et al., 2020). Carbon trading price distortion, that is, the deviation of the actual trading price from the marginal abatement cost of carbon may have a serious impact on the effect of the carbon trading market (Wu, 2021). According to the China Carbon Trading Price Index, the EU carbon trading price and the AQI have a direct impact on the carbon trading price in China. At the same time, the CSI Energy Index, the Industrial Index, and the HS300 have a positive and indirect impact on the carbon trading price. In addition, the volatility of China's carbon trading price is mainly internally driven, while the volatility of the other economic variables studied is mainly driven by the EU carbon trading price index, and the industrial index (Yin et al., 2019). The effects of coal prices, oil prices, and stock indices on carbon prices in China have also been studied using vector autoregressive models. The results show that carbon

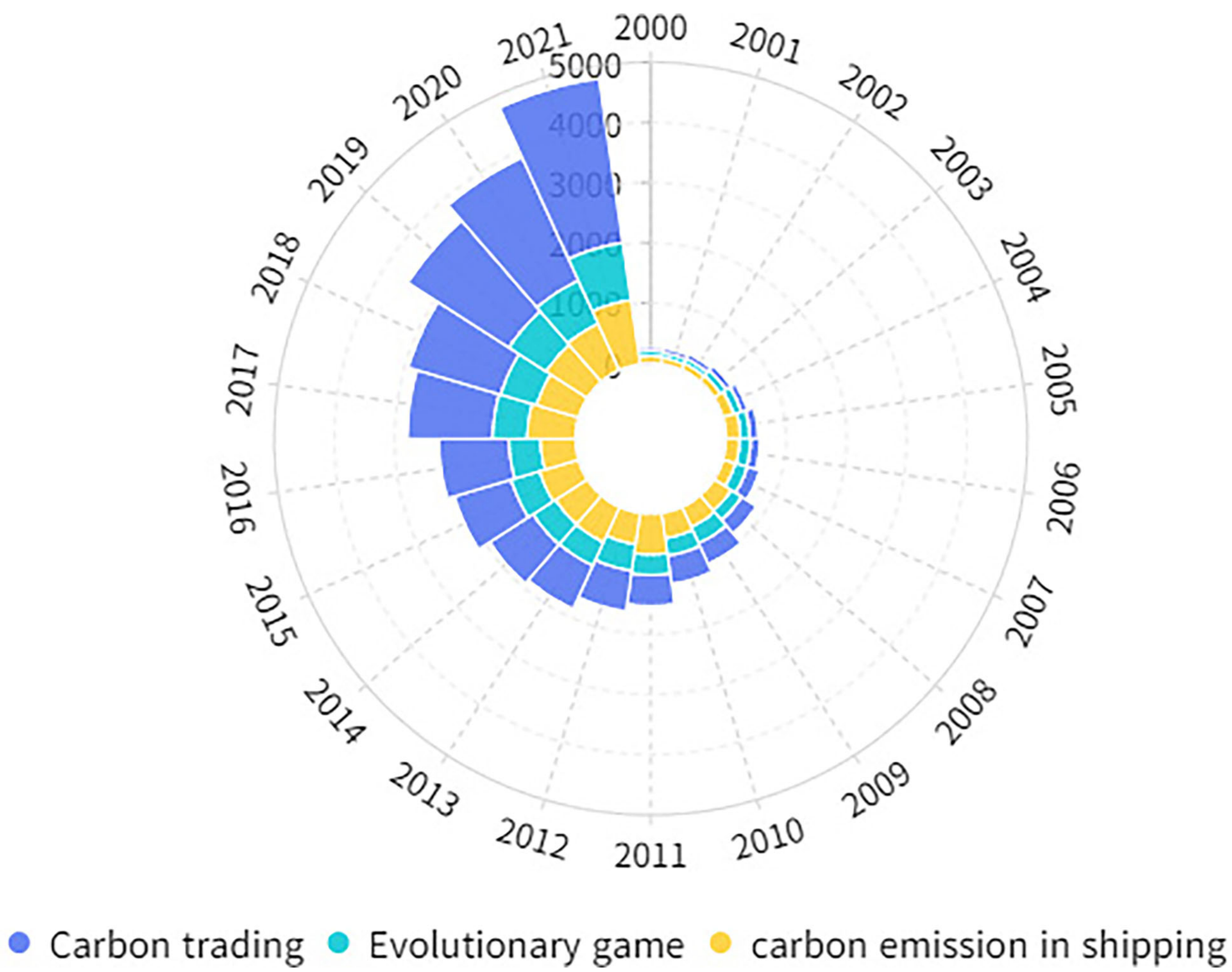

FIGURE 1
Statistics on the number of literatures from 2000-2021.

price is mainly influenced by its own historical price. Coal price and stock index have a negative impact on carbon price, while oil price has a negative impact on carbon price in the first three weeks and then has a positive impact on carbon price. In addition to the influence of carbon price, enterprise technology innovation is also conducive to improving market efficiency and carbon emission trading mechanism (Jiang et al., 2018). In the relationship between corporate innovation and carbon emission trading mechanism, high carbon trading price and high price volatility can promote corporate innovation. Therefore, carbon emission trading policy can effectively promote corporate carbon emission reduction innovation (Lv and Bai, 2021). Carbon trading mechanisms are a useful complement to carbon cap policies. Manufacturers strategically choose to trade carbon credits or invest in carbon reduction technologies when the government provides reasonable oversight (Yuan et al., 2022). A static optimal model is used to compare the clean innovation effects of carbon tax and cap-and-trade system. Both approaches can stimulate technological innovation and reduce emissions, but the effect of cap-and-trade system is more significant. However, regulators should choose appropriate emission limits and carbon trading prices to address global climate change to ensure the efficiency of the cap-and-trade system (Chen et al., 2020). From the perspective of Carbon Emissions from Land Use (CELU), the carbon emission reduction effect of carbon trading policy has some regional heterogeneity. The carbon trading policy has a significant reduction effect on the average CELU of pilot areas of at least four million tons per year (Xia et al., 2021).

The evolutionary game has been widely used in recent years. The stability of the evolutionary game model differs under two scenarios of static carbon trading price and dynamic carbon trading price, and there is a gap in the impact of government policies on the carbon trading market. When the government implements a static carbon trading price, the evolutionary game cannot achieve stability. Under the dynamic carbon trading price, the evolutionary game has an evolutionary stabilization strategy, which is an effective measure to promote carbon emission reduction (Zhang et al., 2019). Scholars have conducted extensive research on different game subjects. Some scholars have used government–enterprise and enterprise–enterprise–government as game subjects respectively. They constructed evolutionary game models based on multi-intelligence drive mechanism, evolutionary game theory and scenario simulation to prove that carbon trading behavior is influenced by the joint role of enterprises and government (Yu et al., 2022). Zhao and Zhang used the government-generator as the evolving game subject. They have simulated the evolution of the game behavior strategy using the System Dynamics (SD) model to investigate how the government controllable key factors affect the system stability. They found no evolutionary stable strategy in the government-generator game system, and the hybrid strategy of the game system has Evolutionary Stabilization Strategy (ESS) when the government implements dynamic subsidies or penalties. Both lower unit subsidies and higher unit penalties promote positive behavior of generators (Zhao and Zhang, 2018). Yuan and Zheng constructed a game model for the evolution of low-carbon technology innovation with government-firm-consumer as the game subjects. They found that the evolution process is influenced by the initial willingness of the game subjects, and the government regulation strength, innovation subsidy strength, and carbon tax rate have different effects on firms and consumers (Yuan and Zheng, 2022). Studies have also been conducted at different levels under the same subject. Zhao and Liu established a government and coal-fired power plants evolutionary game framework and constructed an evolutionary game model using the conflicting interests of game parties in the adoption of Carbon Capture and Storage (CCS). The process of evolutionary game is influenced by the initial willingness of the game parties. Strengthening government regulation and increasing the motivation of power plants to use CCS is beneficial for the system to converge to the optimal ESS (Zhao and Liu, 2019). Other scholars have established an evolutionary game model of government–manufacturer interaction based on static carbon taxes and carbon subsidies. In encouraging low-carbon manufacturing, the government imposes carbon taxes more effectively than government subsidies. Manufacturers' behavioral strategies are mainly influenced by government policies, so the government needs to respond with dynamic strategic adjustments according to the real situation (Chen and Hu, 2018).

Carbon reduction in the shipping industry is an issue that must be faced by China's development. Factors such as economic growth and population growth will affect carbon emissions, and China, as a developing country, needs to carry out carbon emission reduction (Chen, 2014). Academics have studied how to reduce carbon emissions in the shipping industry from several perspectives. Large differences may arise in the distribution trends of pollutant emissions for ships of different ship types and sailing conditions (Xiao et al., 2022). Chen et al. used the allometric approach to explore the potential relationship between ship size and the corresponding greenhouse gas emissions. The result showed that the implementation of the energy efficiency design index and energy efficiency operating index is generally effective (Chen et al., 2019). The reduced speed vessel scheduling method considers the combination of port vessel scheduling optimization and speed reduction, which is more effective when compared with the traditional vessel reduction method (Xia et al., 2021). Some scholars have included carbon emission factors into a multimodal irregular ship scheduling and speed optimization model and proposed a genetic simulated annealing algorithm based on variable neighborhood search. They used the model and algorithm to verify that the joint optimization of ship scheduling and speed can achieve carbon emission reduction (Fan et al., 2019). Electrifying the tire gantry crane to curb emissions can also achieve both carbon reduction and lower energy costs (Ding et al., 2021). In addition to considering the sailing speed, Gao et al. proposed a longitudinal tilt optimization method for inland sea vessels based on operational data and integrated learning. The experimental results show that the energy consumption and carbon emission of ro-ro passenger ships are reduced by 1.4641% through longitudinal tilt optimization, which is beneficial to the green and low-carbon navigation of ships (Gao et al., 2022). At the technical level, the use of methods such as automatic identification system, ship emission estimation model, and geographic information system mapping to create the ship emission scenario simulation model. The model can evaluate and improve the current ship emissions and various "what-if" scenarios in the port area to achieve carbon emission reduction (Kao et al., 2022). A cross-section of ship owners and operators was investigated by Nishatabbas. The study suggested that if the carbon emissions of ships wish to be in line with the rest of the industry in the future and follow a decarbonization path, they cannot be limited to current regulation-driven technologies, but need to improve energy efficiency and carbon reduction technologies (Rehmatulla et al., 2017). The application of alternative carbon-neutral fuels is the consensus among carbon reduction technologies. Carbon neutral fuels enable the use of effective emission control technologies that can simultaneously reduce the climate, health, and environmental burdens of shipping (Aakko-Saksa et al., 2023). Yan et al. proposed a method to calculate the annual carbon emissions of different alternative fuel ships under different freight growth prospects and power scenarios. The results show that LNG blends, LNG and methanol fuels are the most suitable choices at present (Yan et al., 2023). In addition to carbon reduction through speed adjustments and ship scheduling, the capture of carbon in the environment is also a direction of scholarly thinking. A recent International Union for Conservation of Nature Report focused on the concept of payments for the conservation of blue carbon (i.e., carbon captured by coastal ecosystems such as mangroves, seagrasses, and intertidal marshes) (Ullman et al., 2013). Blue carbon strategies have the full potential to be exploited in China. They can create ecological co-revenues of coastal protection and seaweed farming, set habitat for fish and other biota, mitigate eutrophication, hypoxia and acidification, and create good environmental revenues by capturing carbon (Wu et al., 2020). In addition to the low-carbon shipping technologies mentioned above, the application of CCS to ships is also an effective way to reduce carbon emissions from shipping (Zhou and Wang, 2014). In the post-epidemic era, reducing carbon emissions from shipping is a common expectation.

Shortcomings remain in the game study of carbon trading policy through the above literature combing analysis. Previous studies only consider the cyclical characteristics of shipping or carbon quota characteristics in the model, and few consider the model from the long-term perspective, so the game models of existing studies are mostly single-stage games. Compared with the existing literature, the innovations of this paper are mainly the following two points. On the one hand, we introduce shipping cycle and carbon quota into the game model. On the other hand, we construct a multi-stage evolutionary game model from the perspective of periodicity and long-term and analyze the strategy choice of each party in the game, which is closer to reality. The purpose of this paper is to improve the theoretical framework related to carbon trading and provide policy recommendations for relevant departments.

3 Material and methods

The core of this paper is a multi-stage evolutionary model, in which the first two stages correspond to the peak shipping season and the last stage corresponds to the low shipping season, and the model derivation is carried out in this way. Subsequently, a sensitivity analysis is conducted to observe the evolution of the strategies of both sides of the game by varying the technological improvement coefficients and the carbon revenue coefficients. Finally, a discussion is held to give relevant policy recommendations and conclusions are drawn.

3.1 Relevant assumptions and symbol definitions

The government has an irreplaceable role in achieving carbon emission reduction in shipping. The government can formulate carbon emission reduction policies for shipping enterprises, encourage shipping enterprises to research and develop energy-saving technologies, and solve the carbon emission reduction problems of ports and other related industries from the root (Fan and Lu, 2022). Reasonable government subsidies and carbon taxes can increase the motivation of relevant entities to carry out carbon reduction (Liu et al., 2020). Excessive government regulation and excessive carbon prices can be counterproductive, even fatal, to a carbon trading system (Fang et al., 2018). Therefore, government actions are classified as "high regulation" and "low regulation." In the carbon trading market (i.e., EU ETS), the trading behavior of emitters is divided into two categories: "compliant trading" and "non-compliant trading," depending on their positions (Wang et al., 2019). Carbon emissions trading policies can effectively promote enterprises' carbon emission reduction innovation (Lv and Bai, 2021). Accordingly, the following assumptions are used in this research.

3.1.1 Model assumptions

H1: *The participants of the game are local governments (all the governments mentioned later represent local governments) and shipping enterprises. The game order of the two parties is government-shipping enterprises. All parties of the game are completely rational, and the information is completely open between the parties of the game. The government and shipping enterprises are aiming at maximizing their own revenues.*

H2: *The participants are faced with two strategy choices. The strategy set of government is (high regulation, low regulation). The high regulation strategy means that the local government invests human, material, and financial resources to strictly regulate the shipping enterprises. The low regulation strategy means that the local government relaxes the regulation of the shipping enterprises and intervenes less in the violations of the shipping enterprises. In high regulation, as long as the government inspects, the emission violation of shipping enterprises will be discovered, and there are no case of concealment without detection. The amount of violation of emissions will be accurately detected.*

H3: *The strategy set of shipping enterprises is (standardized operation, non-standardized operation). The standardized operation strategy means that the shipping enterprises comply with government regulations and actively invest in technological improvements. When carbon emissions of shipping enterprises exceed the limitation, carbon credit trading is conducted. The non-standardized operation strategy means that the shipping enterprises do not comply with the regulations of local government, do not invest in technology improvement, and refuse to buy carbon credits when the carbon emission exceeds the allowance.*

H4: *The government and shipping enterprises are assumed to be risk neutral. The government gives carbon credits to shipping enterprises periodically, and the government specifies the carbon emissions of shipping enterprises once a year. One year corresponds to one shipping cycle. The remaining carbon credits of shipping enterprises can be used in subsequent years, and the carbon credits of the next year will be reduced in equal amount for the false or concealed reporting part. The shipping cycle can be divided into low, recovery, peak, and recession. The theoretical basis is shown in* Table 1. *The peak period and recovery period are the peak shipping season, which corresponds to the shipping market demand in the post-epidemic era. The low and recession periods are the low shipping season, which corresponds to the shipping market demand during the epidemic.*

3.1.2 Revenue parameter setting

The objective of each party of the game is to maximize the revenue, and the revenue parameters can influence the decision of the game parties by affecting their revenue. In the existing literature, the benefits of the government mainly involve the human, material and financial costs of government regulation, the incentives and penalties of the government to enterprises, the benefits of the government through regulation. The benefits of shipping enterprises mainly involve the costs of low carbon technology innovation investment, the initial allocation of carbon quotas, the costs of standardized operation of shipping enterprises, the costs of non-standardized operation and the carbon revenue coefficient (Zhao and Zhang, 2018; Zhang et al., 2019; Yu et al., 2022). The revenue of each party of the game is an important part of the model, and we will make assumptions about it.

When the government chooses a high regulatory strategy, the cost of investing human, material and financial resources is C_1. Government incentives (or technical subsidies) for enterprises to regulate their operations are A. Penalties for shipping enterprises' non-standardized operation are F. When choosing a low-regulation strategy, the input costs are C_2 ($C_1 > C_2$). The social benefits gained by the government are G_1,G_2,G_3,G_4 . This component includes the revenue gained from controlling carbon emissions and the revenue gained from improving the government's image, and the size of social revenue in different states is $G_1>G_3>G_2>G_4$.

When shipping enterprises cooperate with the government, it makes technological improvements and operates normally in that phase, that is, the carbon revenue coefficient is e_1. The technological improvement coefficient is t. When shipping enterprises do not cooperate, their carbon revenue coefficients in the next phase will be reduced to e_2 under two consecutive phases of high government

TABLE 1 The rationale for the shipping cycle.

Reference	Content
Chiste and Van Vuuren (2014).	The cyclical behavior of the shipping market was studied, using Fourier analysis to extract cycle frequency information from Hodrick-Prescott filtered data (Chiste and Van Vuuren, 2014).
Angelopoulos et al. (2016).	The authors use monthly composite indices and annual freight indices to examine the long- and short-term spectral dynamics of the dry cargo shipping market. The study shows that focusing on periodicity rather than amplitude information provides insights into dynamic cyclical patterns (Angelopoulos et al., 2016).
Goulielmos and Stropoulou (2006).	The ship buying and selling market exhibits a highly "irregular" (or "volatile") and strongly deterministic cyclical behavior (Goulielmos and Stropoulou, 2006).
Stopford (2008).	Stopford systematically analyzed the characteristics of each cycle of the world shipping industry from 1741 to 2007 and pointed out that there are three different components in the shipping cycle, a long-cycle component of 60 years, a short-cycle component of 5–10 years and a seasonal component of less than 1 year (Stopford, 2008).
Ma (2009).	The shipping cycle is closely related to the economic cycle, and the shipping market change cycle is divided into three types, such as long cycle, short cycle, and seasonal cycle, etc. The short cycle of shipping market generally goes through four stages: market trough, market recovery, market peak, and market recession (Ma, 2009).
Wu et al. (2018).	According to the shipping cycle theory, the shipping market cycle is divided into four stages: trough, recovery, peak, and recession (Wu et al., 2018).
Merika and Theodoropoulou (2015).	Authors study 117 internationally listed shipping enterprises (about 60% of the total) and explore the potential determinants of capital structure choices during expansionary, peak, trough, and lateral moves (Merika and Theodoropoulou, 2015).
Yin et al. (2019).	The dry bulk shipping market has cyclical fluctuations. The shipping cycle can be divided into four phases: trough, recovery, peak, and recession (Yin et al., 2019).

regulation. The cyclicality factor will reduce the constraints of government quota policies for shipping enterprises and also reduce the overall revenue (carbon emission-related revenue is the main revenue, much larger than other parts of the revenue), so the cyclicality coefficient in the third stage is k_1. The cyclicality coefficient affecting the overall return is k_2. When shipping enterprises choose to match the strategy, shipping enterprises invest in technology research and development costs as C_3. The image revenue gained is R. When shipping enterprises choose the non-standard operation strategy, they invest 0 in technology research and development costs, and the carbon emission-related revenue of shipping enterprises is U.

3.1.3 Decision variable setting

We assume that the government has a high regulatory probability of P_1 and a low regulatory probability of $1 - P_1$ in the first stage. In the second stage the high regulatory probability is P_{21} and the low regulatory probability is $1 - P_{21}$. In the second stage the high regulatory probability is P_{31}, and the low regulatory probability is $1 - P_{31}$.

We assume that the probability of shipping enterprises choosing standardized operation in the first stage is P_2, the probability of non-standardized operation is $1 - P_2$. The probability of standardized operation in the second stage is P_{22}, and the probability of non-standardized operation is $1 - P_{22}$. The probability of standardized operation in the third stage is P_{32}, and the probability of non-standardized operation is $1 - P_{32}$. Where $P_1,P_2,P_{21},P_{22},P_{31},P_{32}\in[0, 1]$.

3.2 Multi-stage evolutionary model

The shipping enterprises and the government play a three-stage evolutionary game: in stage one, the government and the shipping enterprises make strategic choices and reach a partial equilibrium. After observing the information in stage one, the government and shipping enterprises choose their respective actions in stage two, and so on in the subsequent stages. Tables 2-4 show the revenue matrices of the game parties in each stage.

(1) First stage

The first stage is the initial stage of the game, at this time, the carbon emission allowance of shipping enterprises is uniformly allocated by the government, and its carbon gain coefficient is all 1. Given that the shipping enterprises choose to regulate the operation, they will make technical improvements. Regardless of the government's strategy choice, there are technical improvement revenues. In the subsequent stage, the carbon gain coefficient of shipping enterprises will increase or decrease with the choice of the

TABLE 2 Revenue matrix of the first stage.

	Government revenues	Shipping enterprise revenues
(high, standardized)	$G_1–C_1–A$	$tU + A - C_3 + R$
(low, standardized)	$G_3–C_2$	$tU - C_3+R$
(high, non-standardized)	$G_2–C_1+F$	$U - F$
(low, non-standardized)	$G_4–C_2$	U

TABLE 3 Revenue matrix of the second stage.

	Government revenues	Shipping enterprise revenues
(high, standardized)	G_1-C_1-A	$e_1tU+A-C_3+R$ $e_2tU+A-C_3+R$ $tU+A-C_3+R$
(low, standardized)	G_3-C_2	tU+R_1-C_3
(high, non-standardized)	G_2-C_1+F	$e_1U-Fe_2U-FU-F$
(low, non-standardized)	G_4-C_2	U

government and shipping enterprises for the strategy, which is the key place where the government quota policy plays a role.

The high regulatory revenue to the government is

$$E_h = P_2(G_1 - G_2) - P_2(A + F) + G_2 - C_1 + F \quad (1)$$

The low regulatory revenue to the government is

$$E_l = P_2(G_3 - G_4) + G_4 - C_2 \quad (2)$$

The standardized operation revenue of shipping enterprises is

$$E_s = AP_1 + tU - C_3 + R \quad (3)$$

The non-standardized operation revenue of shipping enterprises is

$$E_n = U - FP_1 \quad (4)$$

The expected revenue to the government is

$$E_g = P_1P_2(G_1 - G_2 - G_3 + G_4 - A - F) + P_2(G_3 - G_4) + G_4 - C_2 + P_1(G_2 - G_4 - C_1 + C_2 + F) \quad (5)$$

The expected revenue of the shipping enterprise is

$$E_e = P_1P_2(A + F) + P_2(R - C_3) + U - FP_1 + P_2(tU - U) \quad (6)$$

The replication dynamics equation for the government is

$$F(P_1) = P_1(1 - P_1)[P_2(G_1 - G_2 - G_3 + G_4 - A - F) + G_2 - C_1 + F - G_4 + C_2] \quad (7)$$

TABLE 4 Revenue matrix of the third stage.

	Government revenues	Shipping enterprise revenues
(high, standardized)	G_1-C_1-A_1	$e_1^2tk_2U+A-C_3+R$ $e_1e_2tk_1k_2U+A-C_3+R$ tk_2U+A-C_3+R $e_1e_2tk_2U+A-C_3+R$ $e_2^2tk_1k_2U+A-C_3+R$ $e_1tk_2U+A-C_3+R$ $e_2tk_1k_2U+A-C_3+R$
(low, standardized)	G_3-C_2	$e_1tk_2U+R-C_3$ tk_2U+R-C_3 $e_2tk_2U+R-C_3$
(high, non-standardized)	G_2-C_1+F_1	$e_1^2k_2U-F$ $e_1e_2k_1k_2U-F$ k_2U-F $e_1e_2k_2U-F$ $e_2^2k_1k_2U-F$ e_1k_2U-F $e_2k_1k_2U-F$
(low, non-standardized)	G_4-C_2	e_1k_2U k_2U e_2k_2U

The replication dynamics equation for shipping enterprises is

$$F(P_2) = P_2(1 - P_2)[AP_1 + tU - C_3 + R - U + FP_1] \quad (8)$$

According to the differential equation theorem, P_1 is subject to the following conditions $F(P_1)=0$, $\frac{\partial F(P_1)}{\partial P_1} < 0$.

According to $F(P_1) = 0$, we know that $P_1 = 0$ or $P_1 = 1$ or $P_2 = \frac{G_4 - G_2 + C_1 - C_2 - F}{G_1 - G_2 - G_3 + G_4 - A - F}$.

When $\frac{\partial F(P_1)}{\partial P_1} = (1 - 2P_1)[P_2(G_1 - G_2 - G_3 + G_4 - A - F) + G_2 - C_1 + F - G_4 + C_2] < 0$, we know that

$P_1 = 0,\ 0 \le P_2 < \frac{G_4 - G_2 + C_1 - C_2 - F}{G_1 - G_2 - G_3 + G_4 - A - F}$

$$P_1 = 1,\ \frac{G_4 - G_2 + C_1 - C_2 - F}{G_1 - G_2 - G_3 + G_4 - A - F} < P_2 \le 1$$

According to the differential equation theorem, P_2 is subject to the following conditions $F(P_2)=0$, $\frac{\partial F(P_2)}{\partial P_2} < 0$ According to $F(P_2)=0$, we know that $P_2 = 0$ or $P_2 = 1$ or $P_1 = \frac{U - tU + C_3 - R}{A + F}$.

According to $\frac{\partial F(P_2)}{\partial P_2} = (1 - 2P_2)[AP_1 + tU - C_3 + R - U + FP_1] < 0$, we know that

$P_2 = 0$,.

$$P_2 = 1,\ \frac{U - tU + C_3 - R}{A + F} < P_1 \le 1$$

According to the local stability criterion of the Jacobi matrix *J*, for a general two-sided evolutionary response, the equilibrium point is ESS when all the eigenvalues of the Jacobi matrix *J* are negative. The equilibrium point is the instability point when all the eigenvalues of the Jacobi matrix *J* are positive. The equilibrium point is the saddle point when one or two eigenvalues are positive. In this model, because the equilibrium solution of the two-party evolutionary game is a strict Nash equilibrium, only the above four points are considered a Jacobi matrix *J*. The main eigenvalues of the different equilibrium points are shown in Table 5.

(2) Second stage

In the second stage, the carbon emission-related revenue in this stage is related to the first stage of the shipping enterprise and the government as well as the current stage strategy choice. There are 16 possibilities for the revenue of the shipping enterprise under each strategy choice (the case of the revenue not written out represents that the revenue expression is the same as the revenue expression already in the revenue matrix and is not repeatedly written. It is not repeated in the subsequent part).

The replication dynamics equation for the government is

$$F(P_{21}) = P_{21}(1 - P_{21})[P_{22}(G_1 - G_2 - G_3 + G_4 - A - F) + G_2 - C_1 + F - G_4 + C_2] \quad (9)$$

The replication dynamics equation for shipping enterprises is

$$\begin{aligned} F(P_{22}) = P_{22}(1 - P_{22})[&P_{21}[P_1P_2e_1tU + P_1(1 - P_2)e_2tU \\ &+(1 - P_1)tU - P_1P_2e_1U - P_1(1 - P_2)e_2U - (1 - P_1)U] \\ &+P_{21}(A - tU + F) + tU + R - C_3 - (1 - P_{21})U] \end{aligned} \quad (10)$$

We can draw the following conclusions.

$$P_{21} = 0,\ 0 \le P_{22} < \frac{G_4 - G_2 + C_1 - C_2 - F}{G_1 - G_2 - G_3 + G_4 - A - F}$$

$$P_{21} = 1,\ \frac{G_4 - G_2 + C_1 - C_2 - F}{G_1 - G_2 - G_3 + G_4 - A - F} < P_{22} \le 1$$

$$P_{22} = 0,\ 0 \le P_{21} < \frac{U - tU + C_3 - R}{\begin{aligned}&P_1P_2e_1tU + P_1(1 - P_2)e_2tU + (1 - P_1)\\ &tU - P_1P_2e_1U - P_1(1 - P_2)e_2U\\ &-(1 - P_1)U + A + F + U - tU\end{aligned}}$$

$$P_{22} = 1,\ \frac{U - tU + C_3 - R}{\begin{aligned}&P_1P_2e_1tU + P_1(1 - P_2)e_2tU + (1 - P_1)\\ &tU - P_1P_2e_1U - P_1(1 - P_2)e_2U\\ &-(1 - P_1)U + A + F + U - tU\end{aligned}} < P_{21} \le 1$$

The main eigenvalues of the different equilibrium points of the second stage Jacobi matrix are shown in Table 6.

(3) Third stage

In the third stage, the carbon emission-related revenue in this stage is related to the strategy choices of shipping enterprises and the government in the previous two stages as well as the current stage. Therefore, there are 64 possible revenue scenarios for shipping enterprises under each strategy choice.

The replication dynamics equation for the government is

$$F(P_{31}) = P_{31}(1 - P_{31})[P_{32}(G_1 - G_2 - G_3 + G_4 - A - F) + G_2 - C_1 + F - G_4 + C_2] \quad (11)$$

TABLE 5 Eigenvalues of Jacobian matrix J (first stage).

Equilibrium points	Eigenvalue 1	Eigenvalue 2
(0, 0)	$R-U+tU-C_3$	$F-C_1+C_2+G_2-G_4$
(0, 1)	$-R+U-tU+C_3$	$-A-C_1+C_2+G_1-G_3$
(1, 0)	$A+F+R-U+tU-C_3$	$-F+C_1-C_2-G_2+G_4$
(1, 1)	$-A-F-R+U-tU+C_3$	$A+C_1-C_2-G_1+G_3$

TABLE 6 Eigenvalues of Jacobian matrix J (second stage).

Equilibrium points	Eigenvalue 1	Eigenvalue 2
(0, 0)	$F - C_1 + C_2 + G_2 - G_4$	$R + tU - C_3 - U$
(1, 1)	$A + C_1 - C_2 - G_1 + G_3$	$-A - F - R + C_3 + U(1 - P_1) - tU(1 - P_1)$ $+Ue_2P_1(1 - P_2) - tUe_2P_1(1 - P_2) + Ue_1P_1P_2 - tUe_1P_1P_2$
(0, 1)	$-A - C_1 + C_2 + G_1 - G_3$	$-R + U - tU + C_3$
(1, 0)	$-F + C_1 - C_2 - G_2 + G_4$	$A + F + R - C_3 - U(1 - P_1) + tU(1 - P_1)$ $-Ue_2P_1(1 - P_2) + tUe_2P_1(1 - P_2) - Ue_1P_1P_2 + tUe_1P_1P_2$

The replication dynamics equation for shipping enterprises is

$$\begin{aligned} F(P_{32}) = {} & P_{32}(1 - P_{32})[[P_{31}[P_1P_2P_{21}P_{22}(e_1^2tk_2U) + P_1P_2P_{21}(1 - P_{22}) \\ & (e_1e_2tk_1k_2U) + (1 - P_{21})(tk_2U) \\ & + P_1(1 - P_2)P_{21}P_{22}(e_1e_2tk_2U) + P_1(1 - P_2) \\ & P_{21}(1 - P_{22})(e_2^2tk_1k_2U) + (1 - P_1)P_{21}P_{22}(e_1tk_2U) \\ & + (1 - P_1)P_{21}(1 - P_{22})(e_2tk_1k_2U) + A] + (1 - P_{31})[P_1P_2P_{21} \\ & (e_1tk_2U) + P_1(1 - P_2)P_{21}(e_2tk_2U) \\ & + (1 - P_1P_{21})(tk_2U)] + R - C_3] - [P_{31}[P_1P_2P_{21}P_{22}(e_1^2k_2U) \\ & + P_1P_2P_{21}(1 - P_{22})(e_1e_2k_1k_2U) \\ & + (1 - P_{21})(k_2U) + P_1(1 - P_2)P_{21}P_{22}(e_1e_2k_2U) + P_1 \\ & (1 - P_2)P_{21}(1 - P_{22})(e_2^2k_1k_2U) \\ & + (1 - P_1)P_{21}P_{22}(e_1k_2U) + (1 - P_1)P_{21}(1 - P_{22})(e_2k_1k_2U) - F] \\ & + (1 - P_{31})[P_1P_2P_{21}(e_1k_2U) + P_1(1 - P_2)P_{21}(e_2k_2U) + \\ & (1 - P_1P_{21})(k_2U)]]] \end{aligned} \tag{12}$$

We can draw the following conclusions.

$$P_{31} = 0, \quad 0 \le P_{32} < \frac{G_4 - G_2 + C_1 - C_2 - F}{G_1 - G_2 - G_3 + G_4 - A - F}$$

$$P_{31} = 1, \quad \frac{G_4 - G_2 + C_1 - C_2 - F}{G_1 - G_2 - G_3 + G_4 - A - F} < P_{32} \le 1$$

$$P_{32} = 0, \ 0 \le P_{31} < \frac{\begin{array}{c} P_1P_2P_{21}(e_1k_2U) + P_1(1 - P_2)P_{21}(e_2k_2U) + (1 - P_1P_{21})(k_2U) - P_1P_2P_{21}(e_1tk_2U) \\ -P_1(1 - P_2)P_{21}(e_2tk_2U) - (1 - P_1P_{21})(tk_2U) - R + C_3 \end{array}}{\begin{array}{l} P_1P_2P_{21}P_{22}(e_1^2tk_2U) + P_1P_2P_{21}(1 - P_{22})(e_1e_2tk_1k_2U) + (1 - P_{21})(tk_2U) + P_1(1 - P_2)P_{21}P_{22}(e_1e_2tk_2U) \\ +P_1(1 - P_2)P_{21}(1 - P_{22})(e_2^2tk_1k_2U) + \\ (1 - P_1)P_{21}P_{22}(e_1tk_2U) + (1 - P_1)P_{21}(1 - P_{22})(e_2tk_1k_2U) + A \\ -P_1P_2P_{21}(e_1tk_2U) - P_1(1 - P_2)P_{21}(e_2tk_2U) - (1 - P_1P_{21})(tk_2U) - P_1P_2P_{21}P_{22}(e_1^2k_2U) - P_1P_2P_{21}(1 - P_{22})(e_1e_2k_1k_2U) \\ -(1 - P_{21})(k_2U) - P_1(1 - P_2)P_{21}P_{22}(e_1e_2k_2U) \\ - P_1(1 - P_2)P_{21}(1 - P_{22})(e_2^2k_1k_2U) - (1 - P_1)P_{21}P_{22}(e_1k_2U) \\ -(1 - P_1)P_{21}(1 - P_{22})(e_2k_1k_2U) + F + P_1P_2P_{21}(e_1k_2U) + P_1(1 - P_2)P_{21}(e_2k_2U) + (1 - P_1P_{21})(k_2U) \end{array}}$$

$$P_{32} = 1, \ \frac{\begin{array}{c} P_1P_2P_{21}(e_1k_2U) + P_1(1 - P_2)P_{21}(e_2k_2U) + (1 - P_1P_{21})(k_2U) - P_1P_2P_{21}(e_1tk_2U) \\ -P_1(1 - P_2)P_{21}(e_2tk_2U) - (1 - P_1P_{21})(tk_2U) - R + C_3 \end{array}}{\begin{array}{l} P_1P_2P_{21}P_{22}(e_1^2tk_2U) + P_1P_2P_{21}(1 - P_{22})(e_1e_2tk_1k_2U) + (1 - P_{21})(tk_2U) + P_1(1 - P_2)P_{21}P_{22}(e_1e_2tk_2U) \\ +P_1(1 - P_2)P_{21}(1 - P_{22})(e_2^2tk_1k_2U) + (1 - P_1)P_{21}P_{22}(e_1tk_2U) + (1 - P_1)P_{21}(1 - P_{22})(e_2tk_1k_2U) + A \\ -P_1P_2P_{21}(e_1tk_2U) - P_1(1 - P_2)P_{21}(e_2tk_2U) - (1 - P_1P_{21})(tk_2U) - P_1P_2P_{21}P_{22}(e_1^2k_2U) - P_1P_2P_{21}(1 - P_{22})(e_1e_2k_1k_2U) \\ -(1 - P_{21})(k_2U) - P_1(1 - P_2)P_{21}P_{22}(e_1e_2k_2U) - P_1(1 - P_2)P_{21}(1 - P_{22})(e_2^2k_1k_2U) - (1 - P_1)P_{21}P_{22}(e_1k_2U) \\ -(1 - P_1)P_{21}(1 - P_{22})(e_2k_1k_2U) + F + P_1P_2P_{21}(e_1k_2U) + P_1(1 - P_2)P_{21}(e_2k_2U) + (1 - P_1P_{21})(k_2U) \end{array}} < P_{31} \le 1$$

TABLE 7 Eigenvalues of Jacobian matrix J (third stage).

Equilibrium points	Eigenvalue 1	Eigenvalue 2
(0, 0)	$F - C_1 + C_2 + G_2 - G_4$	$R - C_3 - Ue_2k_2P_1(1 - P_2)P_{21} + tUe_2k_2P_1(1 - P_2)P_{21} - Ue_1k_2P_1P_2P_{21}$ $+tUe_1k_2P_1P_2P_{21} - Uk_2(1 - P_1P_{21}) + tUk_2(1 - P_1P_{21})$
(1, 1)	$A + C_1 - C_2 - G_1 + G_3$	$-A - F - R + C_3 + Uk_2(1 - P_{21}) - tUk_2(1 - P_{21})$ $+Ue_2k_1k_2(1 - P_1)P_{21}(1 - P_{22}) - tUe_2k_1k_2(1 - P_1)P_{21}(1 - P_{22})$ $+Ue_2^2k_1k_2P_1(1 - P_2)P_{21}(1 - P_{22}) - tUe_2^2k_1k_2P_1(1 - P_2)P_{21}(1 - P_{22})$ $+Ue_1e_2k_1k_2P_1P_2P_{21}(1 - P_{22}) - tUe_1e_2k_1k_2P_1P_2P_{21}(1 - P_{22})$ $+Ue_1k_2(1 - P_1)P_{21}P_{22} - tUe_1k_2(1 - P_1)P_{21}P_{22} + Ue_1e_2k_2P_1(1 - P_2)P_{21}P_{22}$ $-tUe_1e_2k_2P_1(1 - P_2)P_{21}P_{22} + Ue_1^2k_2P_1P_2P_{21}P_{22} - tUe_1^2k_2P_1P_2P_{21}P_{22}$
(0, 1)	$-A - C_1 + C_2 + G_1 - G_3$	$-R + C_3 + Ue_2k_2P_1(1 - P_2)P_{21} - tUe_2k_2P_1(1 - P_2)P_{21}$ $+Ue_1k_2P_1P_2P_{21} - tUe_1k_2P_1P_2P_{21} + Uk_2(1 - P_1P_{21}) - tUk_2(1 - P_1P_{21})$
(1, 0)	$-F + C_1 - C_2 - G_2 + G_4$	$A + F + R - C_3 - Uk_2(1 - P_{21}) + tUk_2(1 - P_{21})$ $-Ue_2k_1k_2(1 - P_1)P_{21}(1 - P_{22}) + tUe_2k_1k_2(1 - P_1)P_{21}(1 - P_{22})$ $-Ue_2^2k_1k_2P_1(1 - P_2)P_{21}(1 - P_{22}) + tUe_2^2k_1k_2P_1(1 - P_2)P_{21}(1 - P_{22})$ $-Ue_1e_2k_1k_2P_1P_2P_{21}(1 - P_{22}) + tUe_1e_2k_1k_2P_1P_2P_{21}(1 - P_{22})$ $-Ue_1k_2(1 - P_1)P_{21}P_{22} + tUe_1k_2(1 - P_1)P_{21}P_{22} - Ue_1e_2k_2P_1(1 - P_2)P_{21}P_{22}$ $+tUe_1e_2k_2P_1(1 - P_2)P_{21}P_{22} - Ue_1^2k_2P_1P_2P_{21}P_{22} + tUe_1^2k_2P_1P_2P_{21}P_{22}$

The main eigenvalues of the different equilibrium points of the Jacobi matrix in the third stage are shown in Table 7.

Table 7 shows that determining the stability of each point is difficult due to the numerous parameters. Thus, finding the optimal solution by mathematical methods is more difficult, and numerical simulation analysis is required.

4 Numerical simulation

In the numerical simulation section, we construct an SD simulation model by combining both sides of the evolutionary game. The relationship between the variables is shown in Figure 2. Specifically, the evolutionary game model describes the long-term evolutionary behavior of the government and shipping enterprises. Based on this, we use different parameter values to evaluate the strategy combinations of the two parties.

The game model is further explored by numerical simulations using Matlab. Firstly, the effect of initial values on the choice of both sides of the game is considered. Secondly, sensitivity analysis is performed to consider the effect of parameter changes on the behavior of both sides of the game. We set up two scenarios (1, 1) and (0, 1).

(1) Scenario 1

Scenario 1 is conducted in the context of the government's choice of a high-regulation strategy. When the government chooses high regulation, the efficiency of shipping enterprises can be maximized only through standardized operation. Firstly, we determine the relationship between some parameters through realistic situations, for example, in this model, $C_1 > C_2$, $G_1>G_3>G_2>G_4$. Secondly, the relationship between the relevant parameters is constrained according to the scenario setting. For example, the scenario is simulated with high government regulation and standardized operation of shipping enterprises as the initial state, so the parameters should satisfy $-A-F-R+U-tU+C_3<0$ and $A+C_1-C_2-G_1+G_3<0$. The specific parameter values are as follows.

$G_1=17, G_2=9, G_3=14, G_4=8, C_1=6, C_2=5, C_3=5, A=1, F=3, R=2, U=25, t=1.2, e_1=1.2, e_2=0.8, k_1=1.15, k_2=0.7$.

1) Evolutionary paths with different initial probabilities

The initial probabilities of both sides are randomly distributed in [0, 1], and the path evolution of the two-party response system with different initial probabilities. From Figure 3, in this parameter background, the initial probability has no effect on the final strategy choice of both sides of the game, but the higher the initial probability of both sides, the faster the game system reaches the steady state. Therefore, the government needs to regulate itself and strengthen the

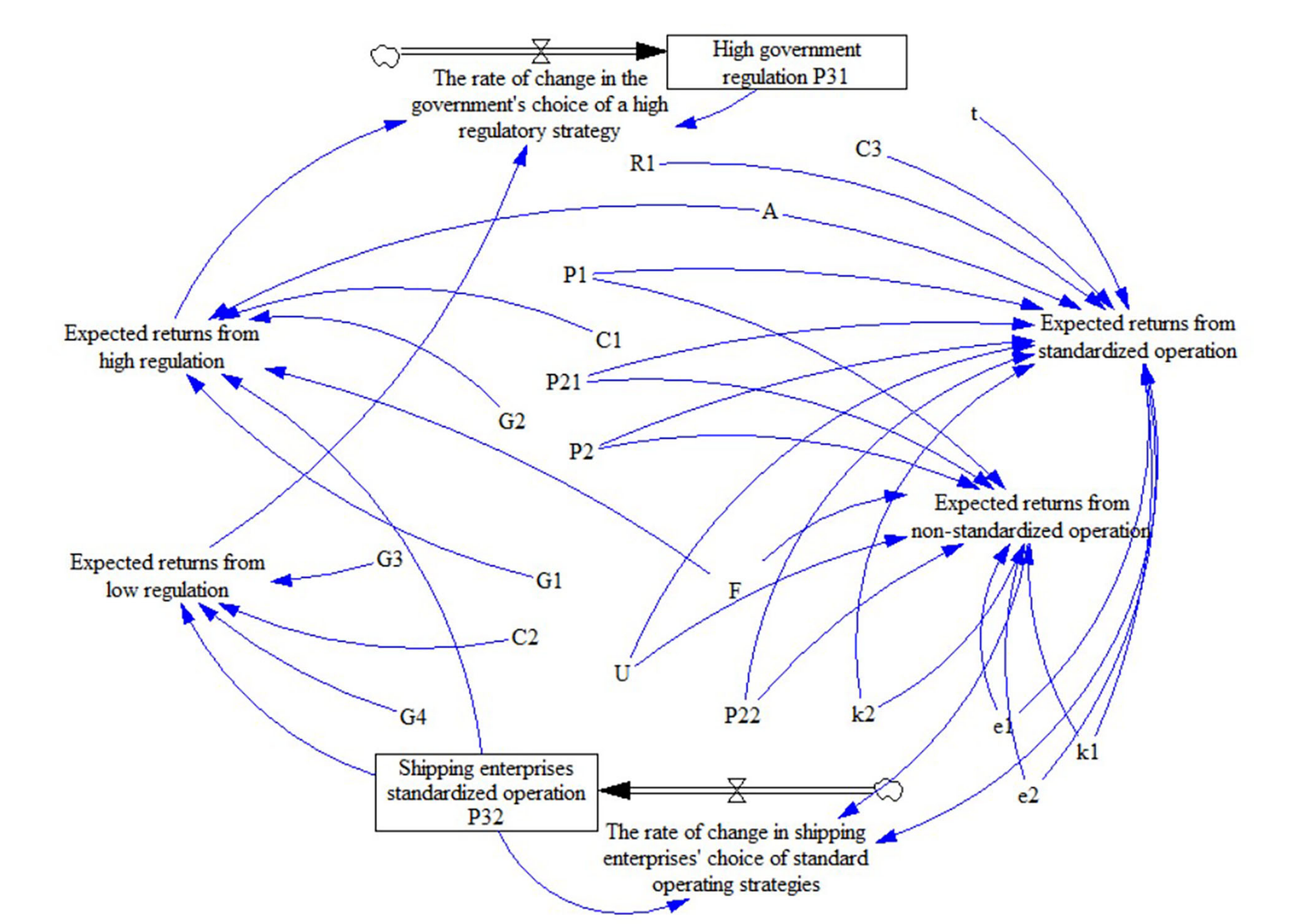

FIGURE 2
SD simulation models of governments and shipping enterprises.

environmental awareness of shipping enterprises. Afterward, the policy effect of carbon quotas can be brought into play as soon as possible and the carbon emission reduction target of the shipping industry can be achieved.

Figure 3 shows the evolutionary results of the first stage with different initial probabilities. In this paper, the evolutionary game model is under three stages. Figure 4 show the evolution of each stage in the context of this parameter.

2) Evolutionary path of each stage

In the first stage, when the initial probability of government and shipping enterprises is 0.5, the curves of government and shipping enterprises converge to the equilibrium point (1, 1). Given that the first stage is the initial stage, no previous strategy choice affects the revenue of this stage, and the revenue of this stage is only related to the current stage.

In the second stage, the initial probability of the government and shipping enterprises is 0.5. The curves of the government and shipping enterprises also converge to the equilibrium point (1, 1) under the influence of the strategy choice in the first stage. Although Figures 4A, B look less different, the return function in the second stage is related to the strategy choice in the first stage. We substitute the final stable value P_1, P_2 in the first stage into the return function in the second stage and continue performing the simulation.

In the third stage, the initial probability of government and shipping enterprises is 0.5, and we add the influence of cyclical factors. In this stage, the shipping cycle changes from the peak shipping season to the low shipping season. With the government maintaining a high regulation, shipping enterprises tend to operate unregulated in this phase due to the accumulation of carbon credits in the first two stages, which also reflects the impact of parameter k_1, k_2. When the demand of the shipping industry decreases and the government still tends to practice high regulation, shipping enterprises tend to operate unstandardized. The impact of the value will not be discussed subsequently in the sensitivity analysis module.

(2) Scenario 2

Scenario 2 is conducted in the context of the government's choice of a low-regulation strategy. First, $C_1>C_2$, $G_1>G_3>G_2>G_4$ is determined based on the actual situation. Secondly, the scenario is simulated with the initial state of low government regulation and standardized operation of shipping enterprises, so the parameters should satisfy $-R+U-tU+C_3<0$ and $-A-C_1+C_2+G_1-G_3<0$. The specific parameter values are as follows.

$G_1=17, G_2=9, G_3=16, G_4=8, C_1=6, C_2=5, C_3=5, A=1, F=3, R=2, U=25, t=1.2,$

$$e_1 = 1.2, e_2 = 0.8, k_1 = 1.15, k_2 = 0.7.$$

1) Evolutionary paths with different initial probabilities

In the scenario where the initial state is (0, 1), the final evolutionary strategy of the game player remains the same for different initial probabilities. Figure 5, compared with Figure 3, shows that the strategy choice of the game player is independent of the initial probability and related to the initial state.

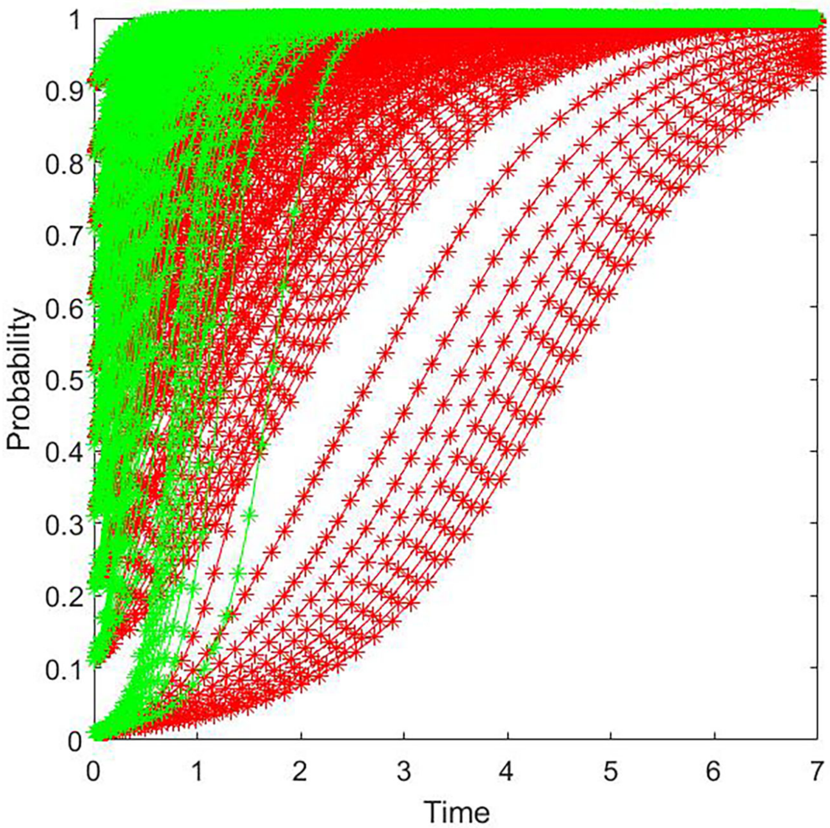

FIGURE 3
Evolutionary path diagram of the two-party game system with different initial probabilities (Scenario 1). (Note: The red curve represents the government and the green curve represents shipping companies).

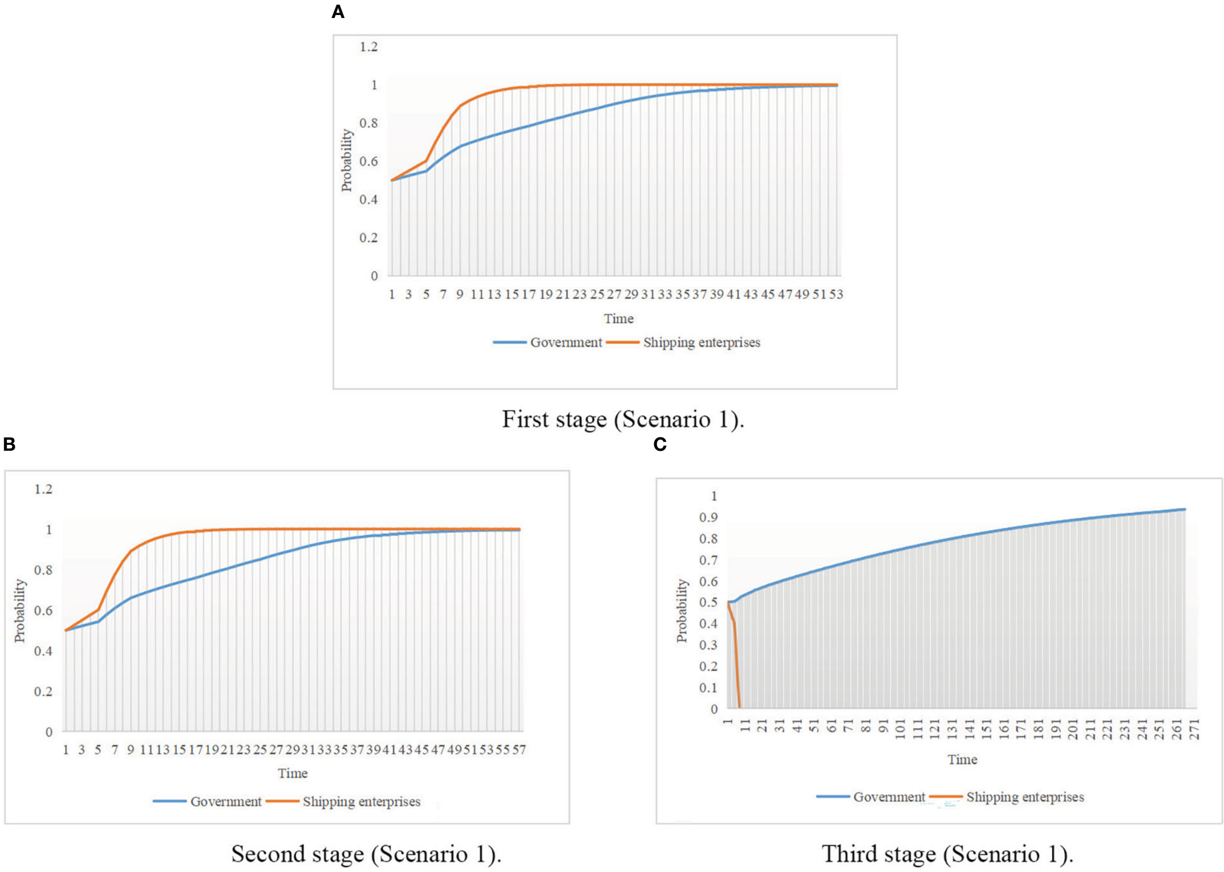

FIGURE 4
Evolutionary path of both sides (Scenario 1).

2) Evolutionary path of each stage

Compared with Figures 4A, B, in Figures 6A, B, the final evolution of the graph is (0, 1) due to the change of the initial state. According to the model assumptions, both the first and second stage are in the peak shipping season and the government's decision is not influenced by *t*. Therefore, the government has been in a low regulatory state, and the purpose of the carbon quota policy is to guide shipping enterprises to regulate their operation, which is reflected in the graph as the curve of shipping enterprises tends to 1. Also, because the graph and the graph itself are evolved under the initial scenario of (0, 1), in summary, the evolution graphs of the first and second stage are very similar.

According to Figures 4C, 6C, it can be seen that although their numerical backgrounds are different, they all eventually tend to (1, 0) under the influence of shipping off-season, which indicates that the shipping cycle factor has a high sensitivity and the attention to shipping cyclicality should be strengthened.

Ideally, we hope that the government can adjust its own policies to achieve cooperative regulation and win–win benefits. At the same time, shipping enterprises can actively respond to the government's call to improve carbon reduction technology and improve the inland shipping environment. Therefore, in the subsequent analysis of the results, we will pay more attention to the impact of changes in different factors on the evolutionary game equilibrium.

4.1 Sensitivity analysis

In scenarios (1, 1) and (0, 1), the initial state of shipping enterprises does not change. Factors such as technological improvement coefficients do not affect the government's strategic choice, and we choose a numerical background with an initial state of (1, 1) for sensitivity analysis.

4.1.1 Changing the technological improvement coefficient *t*

In this section, all parameters in the game model are fixed values (initial probability of 0.5 for government and shipping enterprises) except for the technological improvement coefficient *t*, which is 0.8, 1.2, and 1.6. The values of each fixed parameter are shown in scenario 1, and the results are shown in Figure 7.

Given that the technological improvement coefficient is only related to the final revenue of shipping enterprises, Figure 7 represent the system evolution diagram of the shipping enterprise. In the first two stages, when the technological improvement coefficient changes from 0.8 to 1.2, the final strategy choice of shipping enterprises changes from non-standardized operation to standardized operation with higher sensitivity. When it changes from 1.2 to 1.6, the final strategy choice of shipping enterprises remains

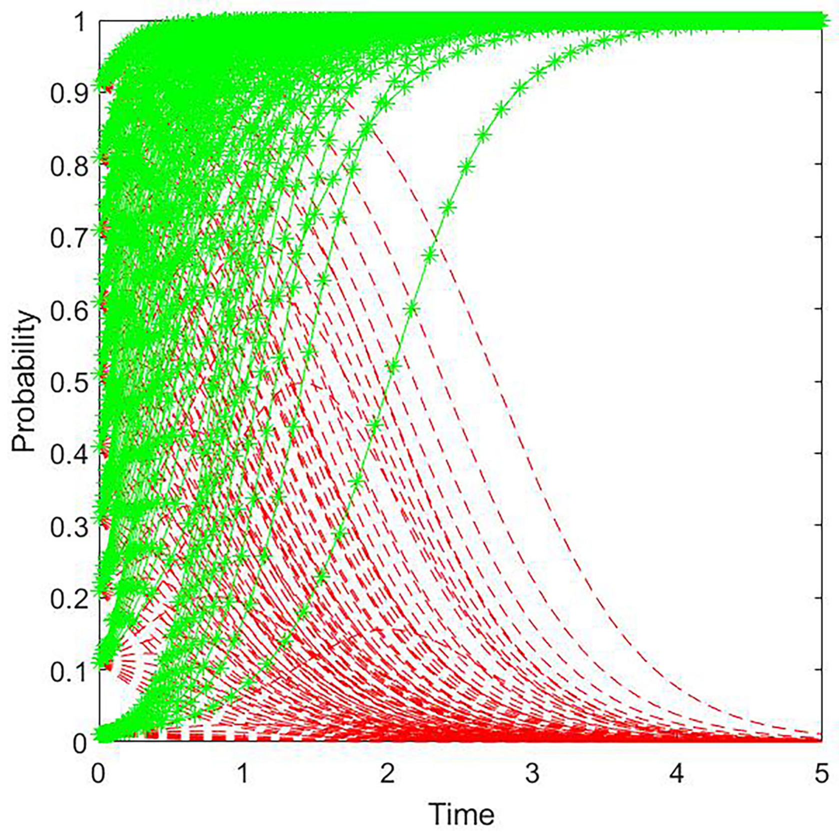

FIGURE 5
Evolutionary path diagram of the two-party game system with different initial probabilities (Scenario 2). (Note: The red curve represents the government and the green curve represents shipping companies).

unchanged, but the larger the parameter value of t, the faster it tends to the stabilization point. In the third stage, the parameter values t take 0.8, 1.2, and 1.6, due to the influence of shipping periodicity, it eventually all tends to the non-standardized operation strategy with reduced sensitivity and t = 1.2 is the fastest tending to the unstable strategy.

The evolution results indicate that when the technological improvement coefficient is large enough, in the first two stages, shipping enterprises tend to regulate their operation. However, due to the influence of cyclicality coefficient, in the third stage, shipping enterprises will still tend to operate irregularly, reflecting the importance of the government's dynamic regulation. By contrast, with a smaller technological improvement coefficient, shipping enterprises will tend to operate irregularly, which is not conducive to achieving the carbon emission reduction target of China.

4.1.2 Changing the carbon revenue coefficient e_1

In this section, all parameters in the game model are fixed values except for the carbon benefit coefficient e_1 ($e_1-1=1-e_2$), which is 1, 1.2, and 1.4. The values of each fixed parameter are shown in scenario 1 (the initial probability of the government and shipping enterprises is 0.5), and the results are shown in Figure 8.

Given that the carbon revenue coefficient is only related to the final revenue of the shipping enterprise, the figure represents the system evolution diagram of the shipping enterprise. In the first two stages, when the technological improvement coefficient changes from 1 to 1.2 to 1.4, the final strategy choice of the shipping enterprise is a standardized operation with low sensitivity. When the parameter value of e_1 is larger, its convergence to the stabilization point is faster. In the third stage, the parameter values e_1 take 1, 1.2, and 1.4, due to the cyclicality of shipping, they all eventually tend to be associated with the non-standard operation strategy and the sensitivity decreases. When the parameter value of e is larger, its tendency to non-standard operation is faster.

The evolution results indicate that when the carbon revenue coefficient is large enough, shipping enterprises tend to regulate their operation in the first two stages. Nevertheless, because of the influence of cyclical factors, shipping enterprises will tend to operate irregularly in the third stage. Therefore, achieving the standardized operation of shipping enterprises can be easier by changing the carbon revenue coefficient, reflecting the effectiveness of the government carbon quota policy during the peak season of shipping.

4.2 Discussion

According to the numerical background, the evolution path of the three stages is (1, 1)–(1, 1)–(1, 0). The government's carbon quota policy can better guide the standardized operation of shipping enterprises. If the carbon quota policy remains unchanged, the government's quota may belong to the invalid state when the market demand changes. The larger the carbon gain coefficient is,

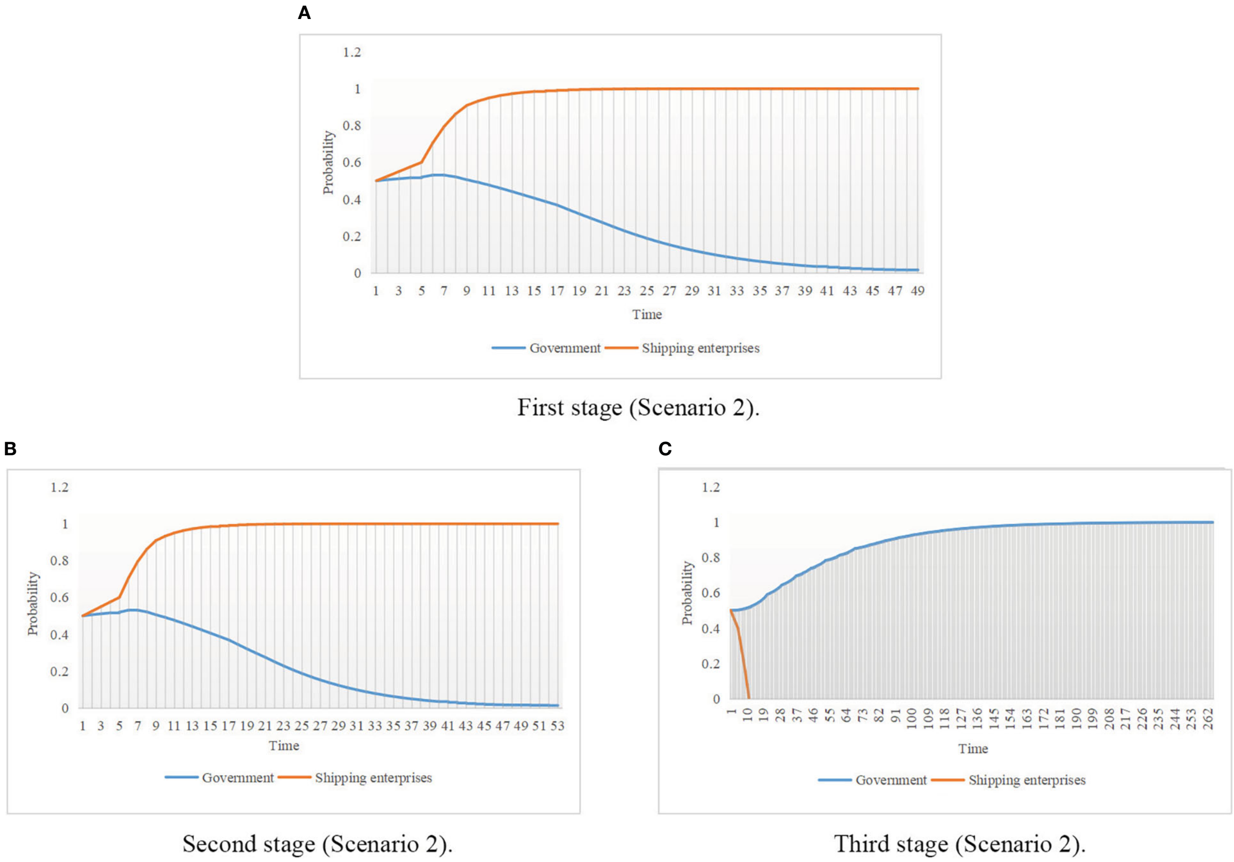

FIGURE 6
Evolutionary path of both sides (Scenario 2).

the faster the shipping enterprises' strategy becomes a non-standardized operation.

For the government, according to $\frac{G_4-G_2+C_1-C_2-F}{G_1-G_2-G_3+G_4-A-F}$, the punishment of government to shipping enterprises and the difference between social revenue under high government regulation and social revenue under low regulation have a positive effect on the probability of government choosing high regulation. The reward of the government to shipping enterprises has a negative effect on the probability of the former choosing high regulation. At the same time, the government's strategic choice is also related to the strategic choice of shipping enterprises.

Therefore, the government should improve the laws and policies related to the carbon trading system, solicit more opinions from all sectors of society, cultivate the awareness of emission reduction among all sectors, and improve the image of the government. The government should forecast the market demand for shipping, gradually relax the regulation during the peak season of shipping, and strengthen the regulation before the arrival of the low season of shipping to realize the scientific and dynamic management of the government. The government should adopt a punishment-based strategy, supplemented by rewards, which can reduce its own regulatory cost and promote the standardized operation of shipping enterprises. At this stage, most propulsion systems of ships are fueled by heavy fuel oil or diesel, and there are fewer zero-carbon fuel-based propulsion systems such as ammonia and hydrogen. A long time is needed to improve and innovate the technology of propulsion systems, and the cost of zero-carbon fuel is also high. These limitations are difficult to accept for shipping enterprises. A Danish catalyst enterprise has predicted that the cost of environmentally friendly ammonia will keep falling. However, the cost of environmentally friendly ammonia is still high compared to fuel (Huang et al., 2021). In addition, due to the increasing technical requirements for carbon emission reduction, the cost of acquiring new ships for shipping enterprises is also increasing, which is not only a huge shock to the shipbuilding industry but also exerts economic pressure on shipping enterprises. Taking into account various factors, the government should consider subsidizing the technological research and development of shipping enterprises to promote their enthusiasm for these efforts to lay the foundation for achieving the carbon emission reduction target of China.

For shipping enterprises, the government's reward and punishment to shipping enterprises, the image revenue of shipping enterprises, and the technological improvement coefficient have a positive effect on the probability of shipping enterprises choosing standardized operation. The technology R&D cost has a negative effect on this probability. The current strategy choice of shipping enterprises is also related to the strategy choice probability of the government and shipping enterprises in the previous stage.

Consequently, shipping enterprises should increase their research and development on carbon reduction technologies from a long-term perspective. Before the low carbon target was proposed, important shipping enterprises reduced their carbon emissions by lowering their

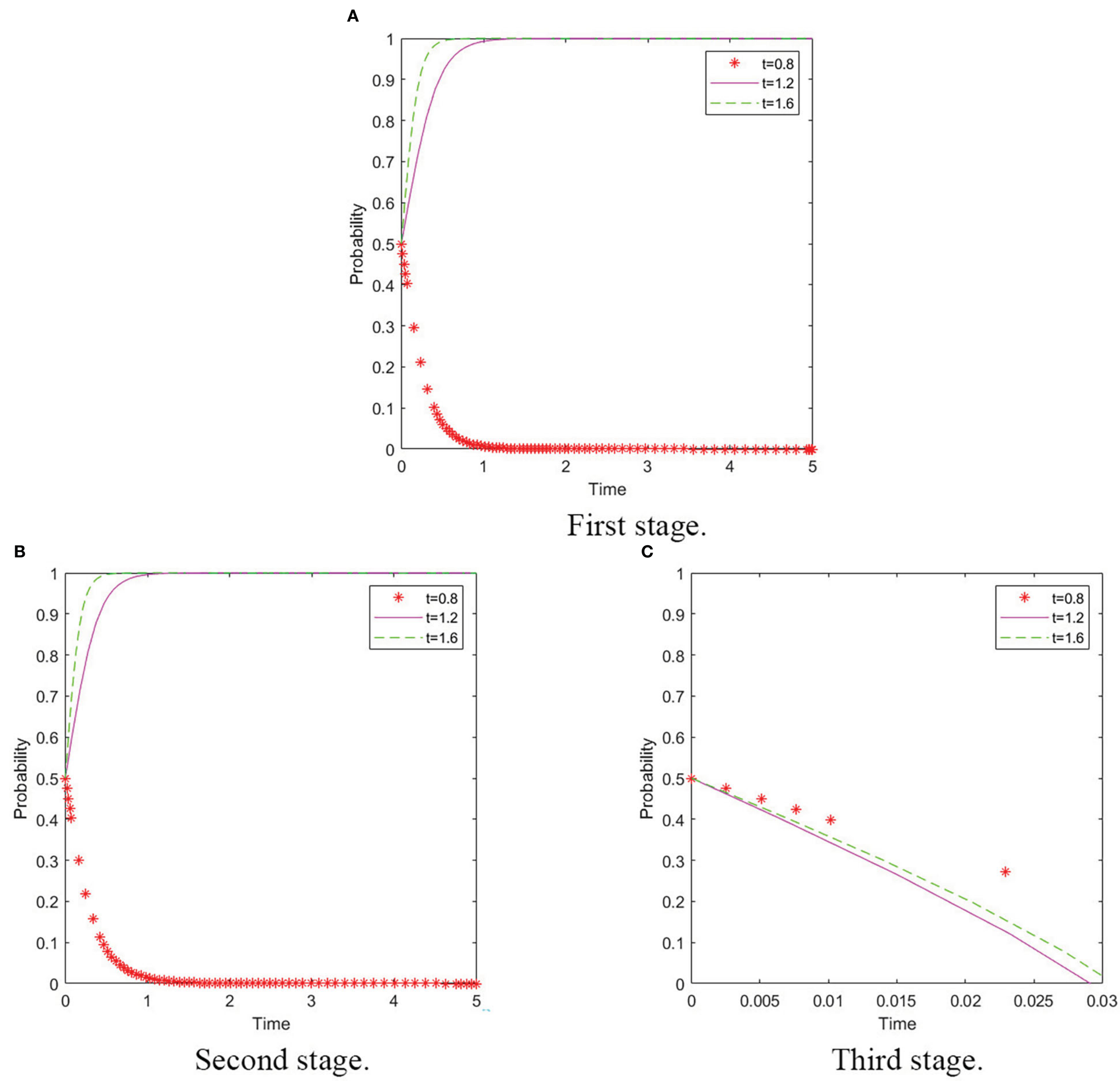

FIGURE 7
Changing the evolutionary path of the technological improvement coefficient.

shipping speed. However, with the continuous promotion of the carbon peak and carbon neutral targets, the previous carbon reduction methods can no longer meet the needs of the target. Shipping enterprises must look for more effective carbon reduction measures. At this stage, various measures are in place to reduce carbon emissions from ships, mainly involving energy efficiency technologies, clean fuels for ships, power plants, and CCS. The application of single or multiple energy efficiency technologies mentioned above can effectively improve the energy efficiency of ships and reduce carbon emissions. However, to cope with the medium and long-term emission reduction targets, the application of clean fuels is the fundamental solution. The main marine clean fuels with certain application experience and development potential currently include LNG, methanol, biodiesel, hydrogen, and ammonia. The development of clean fuels and the development of power units are complementary, so shipping enterprises are required to develop the best power units applicable to these clean fuels. For example, the hybrid system can choose different propulsion modes according to the different propulsion requirements of the working conditions. The hybrid system can enhance the adaptability and flexibility of the ship and reduce the carbon emission of the ship, which is currently applied to ships such as passenger ships and inland river cargo ships. The energy saving and emission reduction is about 15% compared with traditional fuel-powered ships (Society CC, 2021). In addition, shipping enterprises need to pay close attention to carbon capture, utilization, and storage technology, which will have a profound impact on the low-carbon development of the shipping industry when its application in ships is mature. Shipping enterprises should actively undertake relevant social responsibilities, regulate their own behavior, improve their enterprise image, and cultivate the low carbon awareness of staff within the shipping enterprises. They also should formulate perfect rules and regulations, regulate the operation

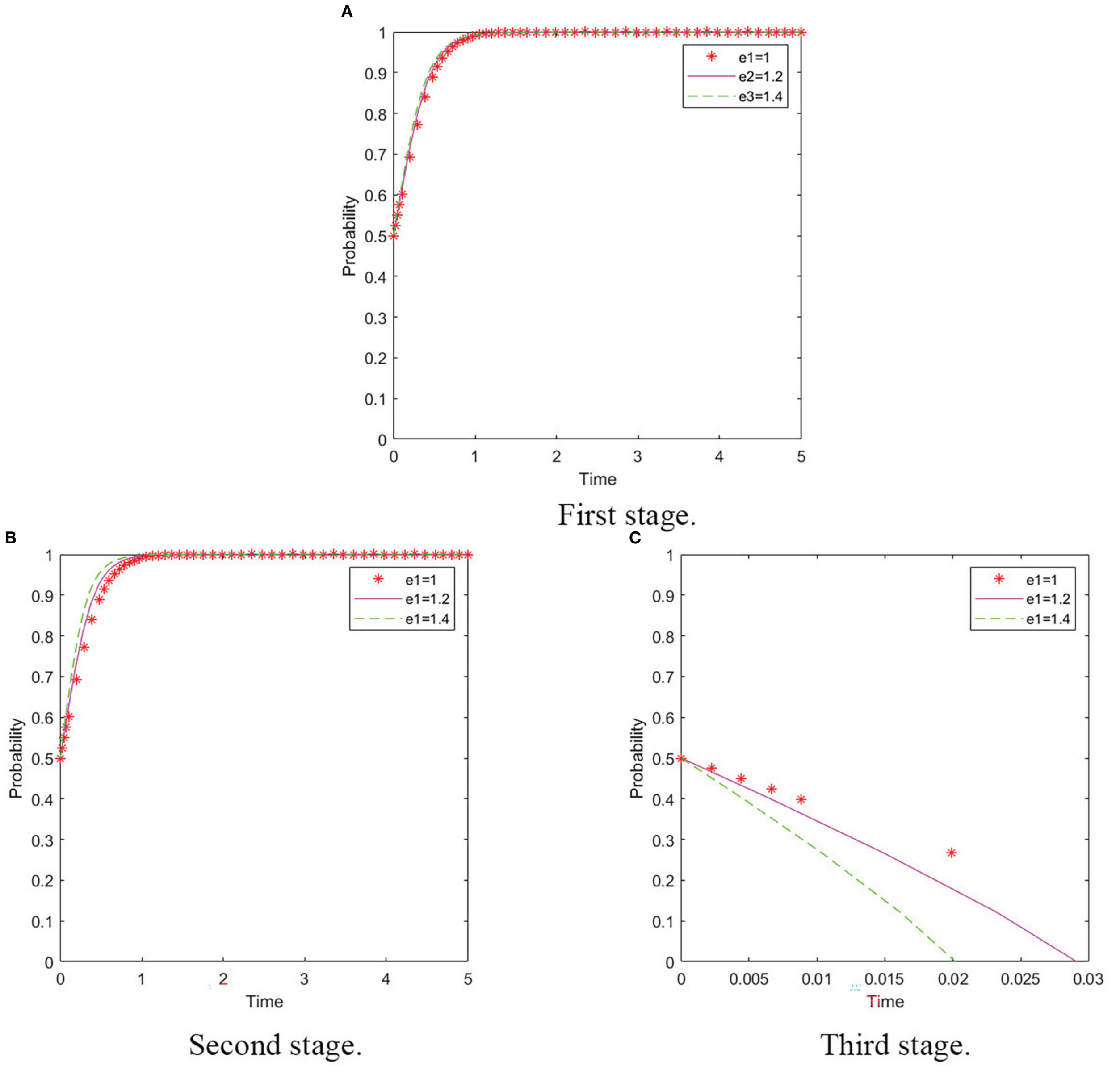

FIGURE 8
Changing the evolutionary path of the carbon revenue coefficient.

of staff, and have complete standards to measure the effectiveness of carbon emission reduction. Shipping enterprises should contribute to carbon emission reduction in the shipping industry and marine environmental protection.

5 Conclusions

In this paper, we construct a multi-stage evolutionary game model based on the carbon quota policy and the cyclical characteristics of shipping and consider the strategic choices of government and shipping enterprises from a long-term perspective. Subsequently, we conduct a sensitivity analysis to provide guidance for government policy formulation and shipping enterprises' behavior, which is of great significance. Our findings are as follows.

(1) In the peak season of shipping, the sensitivity of technological improvement coefficient is higher, while the sensitivity of carbon revenue coefficient is lower. The technological improvement coefficient and carbon revenue coefficient have a positive influence on the strategy choice of shipping enterprises, and the larger the value of technical gain coefficient and carbon gain coefficient, the faster they tend to stabilize.

(2) The government's carbon quota policy is influenced by the market demand for shipping. In the peak season of shipping, the government's quota policy is binding to shipping enterprises. With the continuation of the peak season of shipping, shipping enterprises have the tendency to regulate their operation actively to maximize revenue. In the low season of shipping, the binding effect of the government's

quota policy on shipping enterprises will be reduced, and even a state of failure will appear.

However, this paper still has many shortcomings. For example, the revenues or expenses of shipping enterprises in carbon trading are not put into the model calculation. Similarly, the precondition that the total carbon emissions should be a fixed value in each stage is not considered, which is different from the actual situation. In the future, we will integrate more revenue scenarios into the model and consider the premise that the total carbon emissions are a fixed value to bring the model closer to reality. Then, we can provide better suggestions for governments and shipping enterprises.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

GX and WC all contributed to the data collection process and the analysis of the findings. The work was planned, created, designed and all revision and data analysis were done by GX and WC. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Quantitative evaluation of China's shipping decarbonization policies: The PMC-Index approach

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In the past few decades, ship-source GHG emissions have increased significantly. As a large country with massive shipping activities, China has issued a number of governmental policies with the aim of promoting shipping decarbonization and achieving green shipping. This study adopts the Policy Modeling Consistency Index (PMC-Index) approach to quantitatively evaluate 15 representative policies that are dealing with shipping decarbonization affairs to different extents in China. The results show that there exists an overall good policy consistency with the average PMC index scoring 6.26, but all studied policies have certain aspects to be further improved. By reviewing these representative policies, it reveals that more emphasis has been placed by the Chinese government on the development and application of clean energy, coordination between shipping and port industries, and governance mechanism for shipping decarbonisation issues. In addition, two policy implications are draw for policy-makers in China.

KEYWORDS
decarbonization, green shipping, policy evaluation, policy modeling consistency, emission control

1 Introduction

As the backbone of the global economy, maritime transport enables the smooth operation of global logistics supply chains but also generates various negative externalities such as greenhouse gas (GHG) emissions (Grzelakowski et al., 2022). In the past few decades, ship-source GHG emissions have increased significantly. According to the second and fourth GHG studies of International Maritime Organization (IMO), total shipping GHG emissions had climbed from 1,046 million tonnes in 2007 to 1,076 million tonnes in 2018 (IMO, 2009; IMO, 2020). It is estimated that maritime transport accounts for 3% of the world's anthropogenic GHG emissions roughly (Lindstad et al., 2021). To mitigate global climate change, shipping decarbonization has been emphasized by various stakeholders including carriers, cargo owners, and regulators (Wan et al., 2018). Particularly, IMO, as the United Nations specialized agency that is responsible for global shipping safety and security and prevention of pollution by ships, has issued a series of policies to reduce GHG emissions from ships (Herdzik, 2021). Due to the polycentric nature of environmental governance, which indicates that there exist a number of multiple centers of decision making and each of them operates with some degree of autonomy, thus regional and local policies are also important for shipping decarbonization (Gritsenko, 2017).

As a large country with massive shipping activities, China has issued a number of governmental policies with the aim of promoting shipping decarbonization and achieving green shipping. For example, China promulgated "*The 14th Five-year Development Plan for Green Transportation*" in 2021, in which numerous measures such as development of clean energy powered ships and usage of shore power were highlighted to reduce GHG emissions from ships and port operations. However, till now there are no studies focusing on the evaluation of China's shipping decarbonization-related policies. From the perspective of policy improvement, it is actually necessary to holistically evaluate those shipping decarbonization policies and figure out their policy strengths and weaknesses. By doing so, we can better understand China's policies on shipping decarbonization. To this end, the current paper devotes to conducting the quantitative evaluation of China's relevant shipping decarbonization policies by applying the "Policy Modeling Consistency Index (PMC-Index)" approach, which concentrates on the policy consistency assessment with consideration of important policy variables as many as possible from various perspectives. The major contributions of this study are two-fold. First, PMC-Index model is introduced and applied to evaluate policies quantitatively in the domain of shipping decarbonization. Second, several characteristics of China's shipping decarbonization policies are identified.

The remainder of the present paper is organized as follows. Section 2 presents existing literature on shipping decarbonization policies worldwide and policy evaluation. In Section 3, the PMC-Index model is introduced in detail, and the studied China's representative shipping decarbonization policies are listed. The quantitative evaluation of the studied policies is conducted by constructing the PMC-Index model in Section 4. Section 5 further discusses China's shipping decarbonization policies beyond the results of the PMC-Index approach. Section 6 concludes the paper.

2 Literature review

2.1 Shipping decarbonization policies

Due to the challenge of global warming and the critical role that maritime transport plays in GHG emissions (Alamoush et al., 2020), shipping decarbonization policies have attracted increasing attention from academia and industry in recent years. Notably, IMO plays a vital role in reducing GHG emissions from ships (Grzelakowski et al., 2022). To show IMO's ambition and strategies to address GHG emissions from international shipping, the resolution "*Initial IMO strategy on reduction of GHG emissions from ships*" was adopted by the 72th session of the Marine Environment Protection Committee of IMO in 2018, which presented candidate short-, mid- and long-term future measures to reduce GHG emissions and set out the reduction goals (i.e., reducing carbon intensity of international shipping by at least 40% by 2030, towards 70% by 2050; and reducing the total annual GHG emissions by at least 50% by 2050, compared to 2008) (IMO, 2018). However, Van Leeuwen and Monios (2022) argue that the IMO's goals are still not ambitious and propose a much bolder policy target of full decarbonization (i.e., zero carbon emissions) and a complete ban on fossil fuel use in shipping domain by 2050. The business-as-usual institutional logic is competing with the logic of sustainability, which to a great extent constrains the introduction of stricter environmental legislation at the IMO level (Monios and Ng, 2021). According to Herdzik (2021), there are only five main specific mandatory measures adopted by the IMO with the aim of addressing shipping GHG emissions, namely, regulations on Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), Carbon Intensity Indicator (CII), Data Collecting System (DCS) and Ship Energy Efficiency Management Plan (SEEMP). Although these regulations targeting shipping emissions generally are benefit for the reduction of GHG emissions from ships, they still may have some limitations in certain cases. For example, the EEDI regulation would even lead to a slight increase in CO_2 emissions by large crude oil carriers when operating on higher revolutions-per-minute engines (Wan et al., 2018). Psaraftis (2021) points out that CII reductions would greatly depend on which assessment metric is used, supply-based metric (i.e., Annual Efficiency Ratio) or demand-based metric (i.e., Energy Efficiency Operational Indicator).

In addition to the IMO's shipping decarbonization policies, there are various regional and national regulatory policy frameworks that aim at reducing shipping GHG emissions (Alamoush et al., 2022). For instance, the EU has introduced the Monitoring, Reporting and Verification (MRV) regulation to measure the GHG emissions from ships in EU ports (Gritsenko, 2017). Recently, the European Commission has launched its "Fit for 55" package of proposals with the aim of reducing the EU's total GHG emissions by 55% by 2030, paving the way for climate neutrality in the Union by 2050. As a result, the shipping industry is facing more stringent EU regulations including the European Trading System Directive, FuelEU Maritime Regulation, Alternative Fuels Infrastructure Regulation and Energy Taxation Directive (DNV GL, 2021). California Air Resources Board (CARB) has set up regulations to reduce emissions from ocean-going vessels since the 2000s (Port of Los Angeles, 2021). In China, a number of non-binding policies in a guiding nature have been issued to promote shipping emissions reduction from various aspects, but specific binding policies with controlling functions are still lacking from the technical perspective (Li W. et al., 2021). Regarding the methods that are used to analyze shipping decarbonization policies, it is worth mentioning that the overwhelming majority of the existing relevant literature adopt qualitative approaches, only few studies conducts quantitative analysis (e.g., Dirzka and Acciaro, 2021; Lindstad et al., 2022).

2.2 Policy evaluation

Policy evaluation is mainly about the assessment of the effects of a policy under certain assumptions (Brock et al., 2007). A scientific and reasonable policy evaluation analysis can effectively help policymakers further adjust and improve their policies (Zhang et al., 2022). Choosing an appropriate method is critical for the policy evaluation. In the policy evaluation literature, scholars have proposed many qualitative and quantitative methods to evaluate policy effects (Peterman, 2011). Compared with the qualitative methods for policy evaluation (e.g., case study, expert interview, conceptual framework), quantitative methods such as difference-in-difference (DID) model and regression discontinuity (RD) approach dealing with typical statistical data or atypical data have attracted more attention because of the revival of quantitative positivism (Albaek, 1989; Tang, 2007). For example, Liu et al. (2022) adopt the DID model to measure the policy effects of air pollution control policies in the Jing-Jin-Ji region, and find that those policies can reduce air pollution overall but not emission of every pollutant. Zhang et al. (2020) demonstrate that there exists a causal relationship between the sulfur dioxide emission reduction and the implementation of emission control area policy in Shanghai Port by using the RD method. It is noticeable that these commonly used policy evaluation methods actually have their deficiencies to some extent (Li and Guo, 2022). Take the DID method as an example, several assumptions such as the existence of parallel trends and stable unite treatment value assumption are supposed to hold when using the DID to detect a mean causal policy effect (Lee and Lemieux, 2010).

Unlike those policy evaluation methods focusing on the detection of policy effects, the PMC-Index model, as a quantitative method, not only provides evaluation for a single policy but also enables the consistency comparison among different policies by considering various policy elements based on the policy contents (Estrada, 2011; Kuang et al., 2020; Tian et al., 2022). Due to the significant comprehensiveness and operability, the PMC-Index model has been widely introduced into the domain of policy evaluation. For instance, Yang et al. (2021) use the PMC-Index method to evaluate the Chinese new-energy vehicle industry policies in the context of technical innovation, and find out that those policies are generally reasonable and well designed. Liu and Zhao (2022) evaluate 126 textile industry policies issued from 2014 to 2020 in China, and point out that the policy nature is relatively single and the incentive guarantee needs further improvement. In addition to the quantitative evaluation, the PMC-Index approach can also visualize the policy strengths and weaknesses by constructing the PMC surfaces according to the results of the PMC index matrix (Lu et al., 2022; Wang et al., 2022).

3 Method and data collection

3.1 PMC-Index model

As a newly developed method for policy evaluation, the PMC-Index model is proposed by Estrada (2011) based on the "Omnia Mobilis" assumption to provide quantitative evaluation of relevant policies and their strengths and weaknesses. Unlike the "Ceteris Paribus" assumption that is often applied to policy evaluation in early studies, the "Omnia Mobilis" assumption holds that everything is dynamic and interconnected, and no important relevant variables should be ignored or belittled when building a policy evaluation model (Estrada and Yap, 2013). Therefore, the PMC-Index model focuses on policy consistency assessment by considering important relevant variables as many as possible from various perspectives (Estrada, 2011; Kuang et al., 2020; Li and Guo, 2022).

There are four basic steps to apply the PMC-Index model. Specifically, (I) Classification of variables. An indicator system for policy evaluation is built, which includes main-variables and corresponding sub-variables. Indicators are generally set with the aim of reflecting key policy elements, such as policy makers, policy types and policy topics. (II) Identification of parameters and establishment of a multi-input-output table. Due to the qualitative nature of evaluation indicators, the parameters of specific sub-variables are set in binary (i.e., 0 and 1) according to the full policy text reading and in-depth analysis. If a sub-variable fits into the policy modeling, its parameter is set to 1, otherwise the parameter is set to 0 (Estrada, 2011). A multi-input-output table is constructed to present the value of parameters of all sub-variables. (III) Calculation of the PMC index. The value of the PMC index equals to the sum of all main-variables. Thus, the PMC index is measured as:

$$\mathrm{PMC} = \sum_{i=1}^{m}(X_i[\sum_{j=1}^{n}\frac{X_{ij}}{T_i(X_{ij})}]) \qquad (1)$$

where X_i is the value of the main-variable i. $X_{i,j}$ denotes the value of the sub-variable j that belongs to the main-variable i . $T_i(X_{i,j})$indicates the total number of sub-variables of the main-variable i . (IV) Construction of the PMC surface. The surface is used to graphically show the results of the PMC index matrix, which can help better understand policy consistency from a visual multi-dimensional perspective.

3.2 Data collection

To effectively sort out the authoritative China's shipping decarbonization policies, we adopt a three-step approach to form our research database. Firstly, we set down eligibility criteria according to our research focus: (i) only national shipping-related or transportation-related policies issued by the State Council and the Ministry of Transport are considered. Here it is worth clarifying that the reason why we focus on the relevant policies of the State Council and the Ministry of Transport is because these two policy-makers represent the central government and its specialized transport management department, respectively. Thus, they are authoritative national administrative organizations in the transport sector; (ii) all or parts of the contents of the selected policies should be closely related to the topic of shipping decarbonization; (iii) the policies should be issued within the past decade from January 2012 to June 2022. Secondly, we search the relevant policies on the websites of the State Council and the Ministry of Transport by using the above-mentioned eligibility criteria. Thirdly, a collective discussion is organized among the authors after the full reading of the selected policies to refine our

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policy collection. We finally collect the 15 representative policies (see Table 1) that are dealing with shipping decarbonization affairs to different extents as our research database. Note that among these 15 policies, there are two policies P_7 and P_9 (i.e., "*Guiding Opinions on Promoting the Development of Green Shipping in the Yangtze River Economic Belt*" and "*Action Plan for Promoting Green Development of Pearl River Water Transport (2018-2020)*") focusing on the regional rather than national river waters. Notwithstanding, there two policies can be still considered as national policy representatives because the Yangtze River and Pearl River are the two most important navigable inland waters in China with massive shipping activities and large affected areas.

4 PMC-Index model construction for shipping decarbonization policies

In this section, the PMC-Index model is constructed for China's representative shipping decarbonization policies based on the four basic steps, namely, classification of policy variables, identification of parameters and establishment of a multi-input-output table, calculation of the PMC index, and construction of the PMC surface.

4.1 Classification of policy variables

Building a system of policy variables for quantitative evaluation is critical to the construction of the PMC-Index model (Estrada, 2011). Based on the existing literature on policy evaluation, such as Yang et al. (2021) and Wang et al. (2022), and the contents of China's shipping decarbonization policies, 9 main-variables and 38 sub-variables are proposed for the constructed PMC-Index model. Each main-variable is formed by several corresponding sub-variables. Moreover, different main-variables aim to mirror various key policy elements of shipping decarbonization policies through its sub-variables. Concretely, the main-variable "Policy nature (X_1)" focuses on the general functions (e.g., prediction, supervision, suggestion) of the studied policies; "Policy timeliness (X_2)" concentrates on the length of policy implementation period (e.g., long term over ten years, medium term between 5-10 years, short term less than 5 years); "Policy issuing agency (X_3)" is about

TABLE 1 China's representative policies related to shipping decarbonization since 2012.

Item	Policy name	Policy issuing agency	Year
P_1	The 12th Five-year Plan for Energy Conservation and Emission Reduction of Highway and Waterway Transportation	Ministry of Transport	2012
P_2	Guiding Opinions on Accelerating the Development of Green Circular and Low-carbon Transportation	Ministry of Transport	2013
P_3	Guiding Opinions on Promoting Port Transformation and Upgrading	Ministry of Transport	2014
P_4	Several Opinions on Promoting the Healthy Development of the Maritime Shipping Industry	State Council	2014
P_5	The 13th Five-year Plan for Water Transport Development	Ministry of Transport	2016
P_6	The 13th Five-year Development Plan for Energy Conservation and Environmental Protection in Transportation	Ministry of Transport	2016
P_7	Guiding Opinions on Promoting the Development of Green Shipping in the Yangtze River Economic Belt	Ministry of Transport	2017
P_8	Opinions on Comprehensively and Deeply Promoting the Development of Green Transportation	Ministry of Transport	2017
P_9	Action Plan for Promoting Green Development of Pearl River Water Transport (2018-2020)	Ministry of Transport, Provincial Governments of Guangdong, Guangxi, Guizhou and Yunnan	2018
P_{10}	Guiding Opinions on Building World-class Ports Ministry of Transport, and other eight national ministries and commission	Ministry of Transport, and other eight national ministries and commissions[1]	2019
P_{11}	Guiding Opinions on Vigorously Promoting the High Quality Development of the Maritime Shipping Industry	Ministry of Transport, and other six national ministries and commissions[2]	2020
P_{12}	National Carbon Peak Action Plan by 2030	State Council	2021
P_{13}	The 14th Five-year Development Plan for Green Transportation	Ministry of Transport	2021
P_{14}	The 14th Five-year Development Plan for Waterway Transportation	Ministry of Transport	2022
P_{15}	Implementation Opinions on "Opinions of the CPC Central Committee and the State Council on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job of Carbon Peak and Carbon Neutralization"	Ministry of Transport, National Railway Administration, Civil Aviation Administration of China, State Post Bureau	2022

[1]They are National Development and Reform Commission, Ministry of Finance, Ministry of Natural Resources, Ministry of Ecological Environment, Ministry of Emergency Management, General Administration of Customs, General Administration of Market Supervision and Administration, and China National Railway Corporation.
[2]They are National Development and Reform Commission, Ministry of Industry and Information Technology, Ministry of Finance, Ministry of Commerce, General Administration of Customs, State Administration of Taxation.

the identities of policy-makers, which to a great extent determines the policy authority; "Policy type (X_4)" is closely related to the policy classification (e.g., development planning, policy guidance, implementation program); "Policy topic (X_5)" denotes the specific policy subjects, which include "shipping", "port" and "multimodal transportation" in the current paper; "Policy preliminary assessment (X_6)" places attention on whether there exist clear objectives, comprehensive contents and adequate bases; "Policy area (X_7)" refers to the broader sectors (e.g., economic field, technological domain) beyond transportation that relevant policy measures belong to from a macro-perspective; "Policy focus (X_8)" manifests the pertinent policy measures that are taken within the scopes of policy topics with the aim of achieving policy objectives; "Policy guarantee (X_9)" emphasizes on the supporting measures (e.g., financial backing, policy propaganda, personnel training) that are taken to ensure the achievement of policy goals. It is worth mentioning that the personnel training within the scope of policy guarantee actually means the foster of talents specialized in green shipping development in the current study. Table 2 presents the main-variables and the corresponding sub-variables that are set for the evaluation of China's shipping decarbonization policies.

4.2 Parameters identification for policy variables

As mentioned in Section 3.1, two parameters (i.e., 0 and 1) are adopted in the construction of the PMC-Index model for sub-variables. Specifically, we analyze the texts of our studied policies and have a collective discussion to determine whether the meanings of sub-variables are clearly conveyed by the contents of policies. For a particular policy, if the text of the policy keeps in line with the meaning that a sub-variable represents, then the parameter of this sub-variable is set to 1. On the contrary, if the policy is analyzed and identified to be irrelevant with a sub-variable, then the value of this sub-variable is 0. Table 3 as a multi-input-output table fully shows the parameters of sub-variables for each studied policy, from which we can easily figure out the different and same policy points covered by those studied China's shipping decarbonization policies. Notably, the identification of these parameters provides the important basis for calculation of PMC indexes of relevant policies.

4.3 PMC index calculation results

According to the identified parameters of sub-variables that are presented in the multi-input-output table (see Table 3), the PMC index of each policy is calculated based on the formula (1) proposed in Section 3.1. Table 4 shows the results of PMC index calculation for China's shipping decarbonization policies. To effectively evaluate the policy consistency, the evaluation criteria based on the PMC index scores are often adopted (Estrada, 2011). Table 5 presents the commonly used evaluation criteria in PMC-Index studies (e.g., Kuang et al., 2020; Yang et al., 2021).

In general, there exists an overall good policy consistency of China's shipping decarbonization policies because the average PMC index scores 6.26. Specifically, 12 policies are evaluated as having good consistency with PMC index scores between 6 and 7.99, while 3 policies are evaluated as only having acceptable consistency with PMC index scores between 4 and 5.99. Notably, no policy is identified with low consistency or perfect consistency. The policy P_8, namely "*Opinions on Comprehensively and Deeply Promoting the Development of Green Transportation*" issued by the Ministry of Transport, gains the highest PMC index with a score of 6.71, which to a great extent shows that this policy has taken comprehensive policy elements into the consideration. Comparatively, the policy P_{15}, namely "*Implementation Opinions on 'Opinions of the CPC Central Committee and the State Council on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job of Carbon Peak and Carbon Neutralization'*" promulgated by Ministry of Transport, National Railway Administration, Civil Aviation Administration, and State Post Bureau, scores the lowest. Although P_{15} is still classified into the acceptable level regarding the policy consistency, it can further improve its consistency from the perspective of policy completeness.

4.4 PMC surface construction

The PMC surface can graphically display the components of the PMC index *via* a stereo image, which is very useful to manifest the strengths and weaknesses of each policy (Lu et al., 2022). Due to the fact that nine main-variables are selected in the current study, a 3×3 PMC matrix can be established for each policy consequently. The value of the PMC matrix that is used to construct PMC surface can be measured as:

$$\text{PMC surface} = \begin{bmatrix} X_1 & X_2 & X_3 \\ X_4 & X_5 & X_6 \\ X_7 & X_8 & X_9 \end{bmatrix} \quad (2)$$

Figure 1 presents the PMC surfaces for China's representative shipping decarbonization policies, respectively. The depression degrees of the PMC surface can intuitively show the policy strengths and weaknesses. In particular, the convex parts indicate that high scores have been achieved in some policy aspects, while the concave parts mean that low scores have been gained (Kuang et al., 2020). For different policies, the closer the values of the main-variables in the PMC matrix are, the more similar their PMC surfaces will be. According to Figure 1, it is not hard to see that all studied policies actually have certain aspects to be further improved. More specifically, the strengths of China's shipping decarbonization policies are mainly reflected in following three points. First, the policy areas and foci are quite comprehensive. For instance, policy foci generally cover the mainstream methods in the domain of shipping decarbonization such as clean energy applications. Second, almost each policy has its clear policy objectives for different development stages, which implicitly means China aims to achieve its decarbonization goals in a progressive manner rather than a radical way. Third, various measures like financial support, policy supervision and institution building are taken as important tools to guarantee the smooth implementation of relevant policies. Compared to these policy strengths, the weaknesses

TABLE 2 Variables setting for evaluation of China's shipping decarbonization policies.

Main-variables	Sub-variables	Evaluation criteria for sub-variables	References
Policy nature (X_1)	Prediction ($X_{1:1}$)	Whether the nature of policy is predictive.	Estrada, 2011; Li and Guo, 2022; Liu and Zhao, 2022
	Regulation ($X_{1:2}$)	Whether the nature of policy is regulative.	
	Suggestion ($X_{1:3}$)	Whether the nature of policy is recommendation-oriented.	
	Diagnosis ($X_{1:4}$)	Whether the nature of policy is diagnostic.	
	Decision ($X_{1:5}$)	Whether the nature of policy is compulsory.	
Policy timeliness (X_2)	Short term ($X_{2:1}$)	Whether the policy will last less than five years.	Kuang et al., 2020; Yang et al., 2021; Wang et al., 2022
	Medium term ($X_{2:2}$)	Whether the policy will last more than five years, but less than ten years.	
	Long term ($X_{2:3}$)	Whether the policy will last more than ten years.	
Policy issuing agency (X_3)	State Council ($X_{3:1}$)	Whether the policy issuing agency involves the State Council.	Li and Guo, 2022; Lu et al., 2022
	Ministry of Transport ($X_{3:2}$)	Whether the policy issuing agency involves the Ministry of Transport.	
	National Development and Reform Commission ($X_{3:3}$)	Whether the policy issuing agency involves the National Development and Reform Commission.	
	Others ($X_{3:4}$)	Whether the policy involves any other issuing agencies.	
Policy type (X_4)	Development planning ($X_{4:1}$)	Whether the policy can be categorized as a development planning.	Kuang et al., 2020; Tian et al., 2022
	Guidance ($X_{4:2}$)	Whether the policy can be categorized as a policy guidance.	
	Action program ($X_{4:3}$)	Whether the policy can be categorized as an action program.	
Policy topic (X_5)	Shipping ($X_{5:1}$)	Whether the policy covers the topic of shipping.	Li Y. et al., 2021; Liu and Zhao, 2022
	Port ($X_{5:2}$)	Whether the policy covers the topic of port.	
	Comprehensive transportation ($X_{5:3}$)	Whether the policy covers the topic of comprehensive transportation.	
Policy preliminary assessment (X_6)	Clear objectives ($X_{6:1}$)	Whether the policy has clear policy objectives.	Li and Guo, 2022; Wang et al., 2022
	Comprehensive content ($X_{6:2}$)	Whether the policy has comprehensive contents.	
	Adequate basis ($X_{6:3}$)	Whether the policy has an adequate theoretical and practical basis.	
Policy area (X_7)	Economy ($X_{7:1}$)	Whether the policy can be classified into the economic field.	Yang et al., 2021; Wang et al., 2022
	Technology ($X_{7:2}$)	Whether the policy can be classified into the technical field.	
	Environment ($X_{7:3}$)	Whether the policy can be classified into the environmental field.	
	Administration ($X_{7:4}$)	Whether the policy can be classified into the administrative field.	
	International communication ($X_{7:5}$)	Whether the policy can be classified into the international communication field.	
Policy focus (X_8)	Prevention and control of pollution ($X_{8:1}$)	Whether the policy pays attention to the prevention and control of pollution.	Dai et al., 2022; Tian et al., 2022
	Green shipping governance ($X_{8:2}$)	Whether the policy pays attention to improving the governance of green shipping.	
	Optimization of transportation structure ($X_{8:3}$)	Whether the policy pays attention to adjusting and optimizing the transportation structure.	
	Clean energy applications ($X_{8:4}$)	Whether the policy pays attention to the applications of clean energy.	
	Innovation and application of low-carbon technologies ($X_{8:5}$)	Whether the policy pays attention to the use of various low-carbon technologies.	

(Continued)

TABLE 2 Continued

Main-variables	Sub-variables	Evaluation criteria for sub-variables	References
Policy guarantee (X_9)	Financial support ($X_{9:1}$)	Whether the guarantee measures of the policy involve financial supports.	Kuang et al., 2020; Li and Guo, 2022; Lu et al., 2022
	Institution building ($X_{9:2}$)	Whether the guarantee measures of the policy involve institution building.	
	Policy advocacy ($X_{9:3}$)	Whether the guarantee measures of the policy involve policy advocacy.	
	Policy publicity ($X_{9:4}$)	Whether the guarantee measures of the policy involve policy publicity.	
	Policy supervision ($X_{9:5}$)	Whether the guarantee measures of the policy involve policy supervision.	
	Organizational leadership ($X_{9:6}$)	Whether the guarantee measures of the policy involve organizational leadership.	
	Personnel training ($X_{9:7}$)	Whether the guarantee measures of the policy involve personnel training.	

of the studied policies are also relatively obvious by reflecting in three aspects. First, most policies are labeled as development plans or guidance without binding force, the non-mandatory nature to a certain extent erodes the effectiveness of these shipping decarbonization policies. Second, many policies don't pay enough attention to the diagnosis of the current policy situations, which actually are important bases for newly issued policies. Third, personnel training is often neglected by many policies. In practical terms, extensive training for shipping practitioners are very useful for the popularization of the notion of shipping decarbonization.

5 Discussion: China's shipping decarbonization policy beyond the PMC index

The above-mentioned analysis based on the PMC-Index model makes it clear that China's shipping decarbonization policies have an overall good policy consistency with consideration of various policy elements. In addition to the quantitative analysis, we conduct more discussions on China's shipping decarbonization policies by focusing on their apparent characteristics in this section. Reviewing these representative policies in our data collection reveals that more emphasis has been placed by the Chinese government on the development and application of clean energy, coordination between shipping and port industries, and governance mechanism for shipping decarbonisation issues.

5.1 Development and application of clean energy

Currently, traditional fossil fuels such as heavy fuel oil and marine diesel oil provide power for the almost entire shipping transportation (Van Leeuwen and Monios, 2022), although the IMO has introduced a regulation to limit Sulphur in ships' fuel oil to a maximum 0.5% since 2020. Driven by ambitious GHG reduction targets proposed by relevant international organizations and giant shipping companies, the transition towards alternative clean energy has been widely recognized by both academic and industrial professionals (e.g., Peter et al., 2014; Ampah et al., 2021; World Bank, 2021; DNV GL, 2022; Kouzelis et al., 2022). In China, the government is also fully aware of the importance of the clean energy transition in the shipping domain, and emphasizes the development and utilization of clean energy for ship and port operations.

In the early 2010s, the Chinese government mainly focused on the improvement of energy efficiency and took it as a crucial measure to reduce GHG emissions. For instance, the policy P_2, namely "*Guiding Opinions on Accelerating the Development of Green Circular and Low-carbon Transportation*" issued in 2013, even proposed to formulate relevant regulations on energy conservation in transportation industry. The development and use of renewable energy were only slightly mentioned then. However, in recent years, great attention has been paid to energy transition by the Chinese government, particularly after China declared its "double-carbon" strategy (i.e., China plans to reach peak carbon use by 2030 and become carbon neutral by 2060) in 2020. Although energy saving is still considered as a key path toward GHG reduction because of the status quo of energy use in China, Chinese energy strategy has gradually shifted from energy saving to the dual focuses on energy conservation and transition. The strategical role of energy transition has been adequately recognized. Therefore, alternative clean-energy-powered ships and port equipment are significantly encouraged to be developed and deployed. Take the policy P_{13} (i.e., "*The 14th Five-year Development Plan for Green Transportation*") as an example, it clearly advocates the actions to explore the application of hybrid electric, hydrogen fueled, ammonia fueled and methanol powered ships.

5.2 Coordination between shipping and port industries

Compared to the shipping decarbonization, the decarnomization of the port sector has been given relatively less attention to nowadays.

TABLE 3 The multi-input-output table for studied China's shipping decarbonization policies.

Main-variables	Sub-variables	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}
X_1	$X_{1:1}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	$X_{1:2}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{1:3}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{1:4}$	1	0	0	0	1	1	0	0	0	0	0	0	1	1	0
	$X_{1:5}$	1	1	1	0	0	1	1	0	1	0	0	1	0	1	0
X_2	$X_{2:1}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{2:2}$	0	1	1	1	0	0	0	1	0	1	1	1	0	0	1
	$X_{2:3}$	0	0	0	0	0	0	0	1	0	1	1	0	0	0	1
X_3	$X_{3:1}$	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
	$X_{3:2}$	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1
	$X_{3:3}$	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
	$X_{3:4}$	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1
X_4	$X_{4:1}$	1	0	0	0	1	1	0	0	0	0	0	0	1	1	0
	$X_{4:2}$	0	1	1	1	0	0	1	1	0	1	1	0	0	0	1
	$X_{4:3}$	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
X_5	$X_{5:1}$	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1
	$X_{5:2}$	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0
	$X_{5:3}$	0	1	1	1	0	1	1	1	1	1	0	1	1	0	1
X_6	$X_{6:1}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	$X_{6:2}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{6:3}$	1	0	0	0	1	1	0	0	0	0	0	0	1	1	0
X_7	$X_{7:1}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{7:2}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{7:3}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{7:4}$	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0
	$X_{7:5}$	1	1	1	1	1	0	0	1	0	1	1	1	1	1	1
X_8	$X_{8:1}$	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0
	$X_{8:2}$	1	1	1	0	1	1	1	1	1	0	1	1	1	0	0
	$X_{8:3}$	0	1	1	1	0	1	1	1	1	1	0	1	1	0	1
	$X_{8:4}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{8:5}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
X_9	$X_{9:1}$	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1
	$X_{9:2}$	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0
	$X_{9:3}$	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
	$X_{9:4}$	1	1	1	0	0	1	1	1	1	1	1	1	1	0	1
	$X_{9:5}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{9:6}$	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{9:7}$	1	1	0	1	0	1	0	0	0	1	1	1	0	0	0

TABLE 4 The PMC index for studied China's shipping decarbonization policies.

Main-variables	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	Average
X_1	1	0.8	0.8	0.6	0.8	1	0.8	0.6	0.8	0.6	0.6	0.8	0.8	1	0.4	**0.76**
X_2	0.33	0.67	0.67	0.67	0.33	0.33	0.33	1	0.33	1	1	0.67	0.33	0.33	1	**0.60**
X_3	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.5	0.75	0.75	0.25	0.25	0.25	0.5	**0.35**
X_4	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	**0.33**
X_5	0.67	1	0.67	1	0.67	1	1	1	1	0.67	0.67	0.67	1	0.67	0.67	**0.82**
X_6	1	0.67	0.67	0.67	1	1	0.67	0.67	0.67	0.67	0.67	0.67	1	1	0.33	**0.76**
X_7	1	1	0.8	1	1	0.8	0.8	1	0.8	1	1	1	1	1	0.8	**0.93**
X_8	0.8	1	1	0.8	0.8	1	1	1	1	0.8	0.8	0.8	1	0.6	0.6	**0.87**
X_9	0.86	0.86	0.86	0.86	0.71	0.86	0.86	0.86	0.86	0.86	0.86	1	0.86	0.71	0.71	**0.84**
PMC index	**6.24**	**6.58**	**6.05**	**6.18**	**5.89**	**6.57**	**6.04**	**6.71**	**6.29**	**6.68**	**6.68**	**6.19**	**6.57**	**5.89**	**5.34**	**6.26**

TABLE 5 Evaluation criteria for policy consistency based on PMC index scores.

PMC index	0-3.99	4-5.99	6-7.99	8-9
Evaluation	Low consistency	Acceptable consistency	Good consistency	Perfect consistency

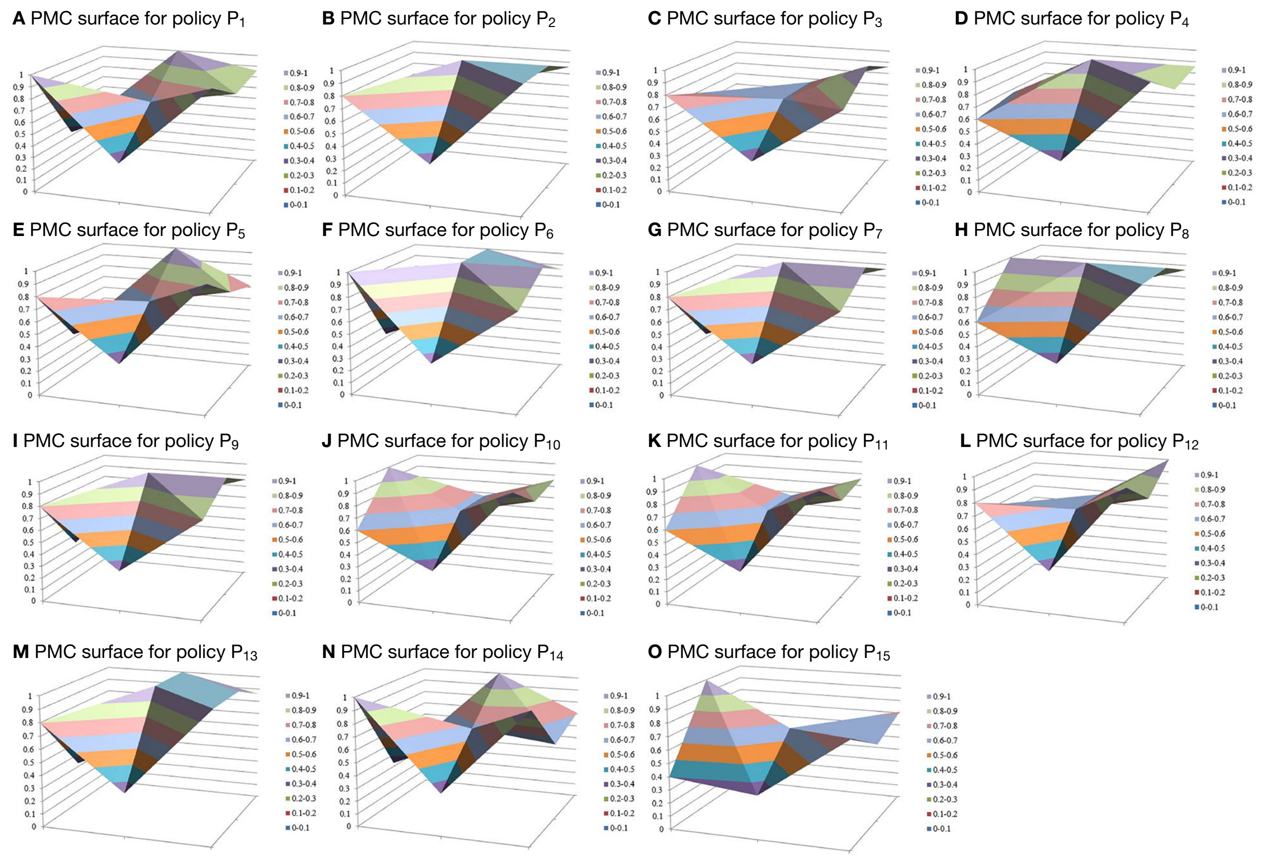

FIGURE 1
PMC surfaces for China's shipping decarbonization policies. **(A)** PMC surface for policy P_1. **(B)** PMC surface for policy P_2. **(C)** PMC surface for policy P_3. **(D)** PMC surface for policy P_4. **(E)** PMC surface for policy P_5. **(F)** PMC surface for policy P_6. **(G)** PMC surface for policy P_7. **(H)** PMC surface for policy P_8. **(I)** PMC surface for policy P_9. **(J)** PMC surface for policy P_{10}. **(K)** PMC surface for policy P_{11}. **(L)** PMC surface for policy P_{12}. **(M)** PMC surface for policy P_{13}. **(N)** PMC surface for policy P_{14}. **(O)** PMC surface for policy P_{15}.

However, ports actually play an indispensable role in maritime decarbonization especially at the ship-port interface, due to the fact that both maritime transportation and port operation are important components of maritime supply chain (Alamoush et al., 2022). In this sense, the coordination between shipping and port industries are very critical to both shipping and port decarbonization. Regarding the ways to reduce GHG emissions at the ship-port interface, there are a number of technical and operational measures such as the use of shore power, automated mooring systems and facilitation of virtual arrival (Alamoush et al., 2020). Among these measures, shore power usage has been greatly promoted by the Chinese government not only because it not only contributes to the decarbonization but also helps to reduce ship-source air pollutant emissions (Yin et al., 2020), but also due to the fact that the commercial applications of shore power equipment are still in the infancy currently (Chen et al., 2021).

Considering that the use of shore power needs the close cooperation between shipping companies and port operators, the Chinese government emphasizes the effective coordination among relevant stakeholders. According to the policy P_{10} (i.e., "*Guiding Opinions on Building World-class Ports*"), collaborative actions are encouraged to improve the utilization rate of shore power for berthing ships, and the shore power usage is chosen as an indicator to evaluate port operational performance. Moreover, the policy P_{11} (i.e., "*Guiding Opinions on Vigorously Promoting the High Quality Development of the Maritime Shipping Industry*") calls on shipping companies to install receiving facilities of shore power for their ships and use shore power during the period of ship berthing. It is worth mentioning that the policy P_{11} further suggests improving the utilization rate of shore power for international seagoing vessels by making full use of the bilateral and multilateral international maritime cooperation mechanisms. Beyond the studied representative policies in this paper, there actually exist several specialized policies on the application of shore power issued by the Ministry of Transport such as "*Port and Ship Shore Power Management Measures*".

5.3 Governance mechanism for shipping decarbonization issues

A sound environmental governance mechanism of maritime transport is critical for dealing with the issue of GHG emissions from ships (Chen et al., 2019; Monios and Ng, 2021). Although IMO has taken various governance measures to promote the process of shipping decarbonization at the global level, constructive actions at the regional level are also needed to address GHG mitigation issues (Wan et al., 2018). In recent years, the Chinese government has placed more emphasis on the establishment of governance mechanism for green transport including decarbonized shipping.

According to the policy P_{13} (i.e., "*The 14th Five-year Development Plan for Green Transportation*"), China will strengthen the construction of green traffic statistics system, and improve the data collection of energy consumption, GHG and pollutant emissions in shipping and other transportation domains, which is beneficial to the effective evaluation and supervision on decarbonization. In addition, the policy P_{14} (i.e., "*The 14th Five-year Development Plan for Waterway Transportation*") puts forward a plan to formulate technical regulations on clean-energy-powered ships with the aim of enhancing the technical standards regarding shipping decarbonization. The policy P_{15} (i.e., "*Implementation Opinions on 'Opinions of the CPC Central Committee and the State Council on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job of Carbon Peak and Carbon Neutralization'*") highlights the role of governmental financial supports in the development of green and low-carbon transportation.

6 Conclusion and policy implications

To better understand China's shipping decarbonization policies, this study adopts the PMC-Index model to quantitatively evaluate 15 representative policies that are dealing with shipping decarbonization affairs to different extents in China. The results show that there exists an overall good policy consistency, but all studied policies have certain aspects to be further improved. In general, the existing China's shipping decarbonization policies are laying emphasis on the development and application of clean energy, coordination between shipping and port industries, and governance mechanism for shipping decarbonisation issues. According to the results of our analysis, the following two policy implications can be draw for policy-makers in China.

First, regarding the studied representative policies in this study, it is not difficult to find that nearly half of them do not merely concentrate on the shipping field but focus on the entire transportation sector with only parts of contents on green shipping issues. Therefore, it is very necessary to issue much more specialized guiding policies on shipping decarbonization such as GHG emission standards for ships, emission monitoring measures. Although China to a certain extent has built up its national macro policy system currently to accelerate the decarbonization process in the shipping domain, the relevant specific regulations are scattered in different policies without clear policy objectives or paths regarding shipping decarbonization. A specialized policy on shipping decarbonization is helpful to show the nation's ambitions for the development of green shipping, and guide the investments from industries in green shipping fuels and infrastructures. It is worth pointing out that Maritime Safety Administration of China promulgated "*Management Measures for Ships' Energy Consumption Data and Carbon Intensity*" in November 2022, which is a specialized regulation on collecting energy consumption data of Chinese ships and foreign ships using Chinese ports and determining Chinese ships' levels of carbon intensity. The implementation of abovementioned regulation is very useful to promote the shipping decarbonization from a technical management perspective.

Second, nowadays most of China's existing shipping decarbonization policies are non-mandatory lacking binding force, this is mainly because the policies formulated by the central government and its subsidiary departments are often in a guiding nature. However, in addition to those guiding policies, the Chinese central government actually has mandatory policy tools such as the formulation of regulations and laws. Compared to the non-mandatory policies, mandatory ones are more authoritative and binding. In this sense, adopting some mandatory policies perhaps is conductive to impel relevant stakeholders such as carriers, port operators to take substantial measures as quickly as possible to reduce GHG emissions. Note that supportive policies including financial incentives from governments and the establishment of carbon emissions trading system are important for shipping companies, which provides more options for them to collect funds.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

QZ and JZ contributed to conception and design of the study. QZ and CC organized the database. CC performed the statistical analysis. QZ and CC wrote the first draft of the manuscript. QZ, CC, JZ, and LC wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Analysis of port pollutant emission characteristics in United States based on multiscale geographically weighted regression

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The huge fuel consumption of shipping activities has a great impact on the ecological environment, port city environment, air quality, and residents' health. This paper uses Automatic Identification System (AIS) data records and ship-related data in 2021 coastal waters of the United States to calculate pollutant emissions from ships in 30 ports of the United States in 2021. After calculating the pollutant emissions from ships at each port, the multiscale geographically weighted regression (MGWR) model is used to analyze the factors affecting the ship pollutant emissions. Geographically weighted regression (GWR) model is used to investigate the spatial heterogeneity of various factors affecting the characteristics of ship pollutant emissions at different scales. This paper mainly compares the effect of models of GWR and MGWR. MGWR may truly reveal the scale difference between different variables. While controlling the social and economic attributes, the coastline length, container throughput, and population are used to describe the spatial effects of ship pollutant emissions in the United States. The results denote that the distribution trend of ship pollutant emissions has a gap based on various ship types and ports. NOx accounts for the highest proportion of pollutant emissions from port ships, followed by SO_2 and CO. The impact coefficients of coastline length and population on pollutant emissions in port areas are mostly positive, indicating that the growth of coastline length and population will increase pollutant emissions in port areas, while the effect of container throughput is opposite. Relevant departments should put forward effective measures to curb NO_x emission. Port managers should reasonably plan the number of ship transactions according to the coastline length of the port.

KEYWORDS
pollutant emissions, coastline length, population, throughput, multiscale geographically weighted regression

1 Introduction

The global shipping industry takes a crucial role in international logistics and the growth of the world economy (Yu et al., 2022). However, increased maritime transport activities have caused severe harm to the marine environment. With the advancement of technology and equipment, including transmission and positioning function, these emerging technical means provide real-time observation information for the daily operation of ships and provide data support for scientific research activities (Jiang et al., 2023). The Automatic Identification System (AIS) has become a critical tool in supporting and maintaining the growth of the shipping industry, which provides real-time monitoring of ship navigation and location information (Shu et al., 2023). Green development is an important development topic in the global port and shipping industry (Magazine, 2018; Xiao et al., 2022).

The International Maritime Organization (IMO) was erected by the United Nations. Its main objectives are to promote shipping technical cooperation among countries, ensure the safety of marine sailing activity, improve the efficiency of ship navigation, and prevent and control pollutants emitted by ships (Zhi, 2021). It can also greatly promote the technical cooperation between countries in shipping and control the consistency of ship pollutant emissions standards. On the premise of maintaining the safety of maritime transport, it improves the efficiency of ship navigation and the quantification and controllability of pollutants generated by ship activities. IMO has formulated a range of criteria for controlling the ship pollutant discharge, and constantly updated these conventions to solve the new problems. The “Sulfur Limit Order” for vessels in 2020 has attracted the attention of relevant enterprises and shipping departments in various countries (Xiao and Cui, 2023). In order to reduce the emission of NO_X, SO_X, and particulate matter during ship operation, IMO has set up ship Emission Control Areas (ECA) internationally, and the EU, the United States, China, and others have also set up ship emission control areas in major sea areas (Xu et al., 2021a). Relevant policies have certain influence on the discharge of pollutants from ships, and the discharge of pollutants from ships has some spatial effects (Chen et al., 2022).

The goals of this study are given as follows. First, the major ports in the United States are taken as the object and the ship pollutant emissions are quantified. Second, the model of Multiscale Geographically Weighted Regression (MGWR) is applied for analyze the spatial heterogeneity of various influencing factors on ship pollutant emission characteristics. Third, the difference of ship pollution emission characteristics between different ports is evaluated.

2 Literature review

In recent years, the number of studies on the ship pollutant emissions has gradually increased, most of which are about the compilation of the pollutant emissions list from ships, the harm of the pollutant discharge caused by vessels to the environment, and the exploration of how to establish more effective policies to curb the excessive emissions of pollutants from ships (Shi et al., 2020). Based on the available studies, the compilation methods of ship discharge inventories in the world mainly include “top-down” method (fuel method and trade method) and “bottom-up” method (statistical method and dynamic method) (Liu et al., 2018). Liu (2020) used the trade data of Qingdao Port between 2005 and 2017 to establish the ship emission inventory through the trade method, mainly including five atmospheric pollutants: NOx, SO_2, CO, PM_{10}, and VOCs. Lee et al. (2021) chose the “bottom-up” approach to create a comprehensive local discharge inventory of ships from the Incheon Port in 2019. The data were collected by the Vessel Tracking Services (VTS). The study indicated that CO_2 emissions dominated, followed by NOx and SOx. Tokuslu (2021) calculated the ships’ exhaust emissions throughout the states of berthing, maneuvering, and cruising in Samsun Port using ship activity-based methods. The results showed that cargo carriers, ro-ro ships, and oil tankers are the top port pollutant emission sources, with these types of ship generating nearly 91% of all port emissions. Meanwhile, the highest pollutant emissions are generated when the ship is in the cruising state, accounting for 86% of the total. In addition, the research results also show that ship pollution emissions will affect the population size of port cities, which was not involved in previous studies. Yang et al (2021). proposed the ship emission inventory according to the AIS data from Tianjin Port with the “bottom-up” method. According to the inventory it can be found that NOx was the main pollutant, followed by SO_2. In terms of temporal distribution, NOx, SO_2, and other ship pollutants will not only affect the air environment in the surrounding areas, but also particularly in summer and autumn. Chen et al. (2021) established a ship discharge inventory estimation method according to operating modes to capture the features of ship pollutant emissions. The operating modes of ships were first classified through AIS data, and then emissions were estimated based on the identified operating modes. Finally, ship emissions in the water of Dalian Port were computed and the research showed that port operators could decrease ship emissions by controlling the sulfur content of marine fuel and requesting tugboats to operate at lower engine loads. Feng et al. (2018) made use of the ship traffic emission model STEAM2 to establish an inventory of ship emissions at four typical cross-sections of the Yangtze River in Jiangsu in 2017, with data derived from AIS data, field observation and research and other data on ship characteristics. And the spatial distribution and temporal variation patterns of vessel pollution source emissions at each section were also analyzed. The results indicated that SO_2 and NOx were the main air pollutant emissions from ships in the Jiangsu section of the Yangtze River; March to April was the peak period of ship emissions, and February and September were the trough periods; the contribution of pollutant discharge from container ships and cargo ships is the highest, exceeding 90% of the total. Lee et al. (2020) analyzed the inventory of non-GHG emissions from ships in Incheon Port. In order to obtain reliable estimates, a “bottom-up” methodology based on operations with real-time ship activity data recorded by the VTS was used. NOx and SOx dominated ship emissions. The study also discussed the necessity for long-term policies, including designating a local emissions control area and establishing an emissions management platform. Toscano et al. (2021) used the "bottom-up" approach to set up a global ship pollutant discharge inventory including the emissions of NOx, SO_2, and PM from ships with 2018 AIS data. The objective of the research is to evaluate the amount of ship pollutant emissions in port and its effects on the atmosphere of contamination. Murcia et al (Murcia González, 2021). assessed port-wide emissions from port-assisted vessels with "bottom-up" method, including estimates of CO_2, NOx, SOx, and PM, by collecting data such as real-time AIS data and IMO-established emission factors.

Shipping activities are the major source of anthropogenic emissions of particulate matter in most parts of the world and can take a major effect on the marine environment, atmospheric quality, and the health of nearby residents. Kuittinen et al. (2020) presented the number of particulate matter particles produced by global shipping activities in 2016, and the spatial distribution showed that the particulate matter emissions from shipping were mainly concentrated near the coastline, but there were also large quantities of emissions in the open ocean. In order to control pollution emissions from ships, IMO had established a series of related conventions and updated them according to the needs of different times, such as the sulfur limit order, the "preliminary strategy for reducing greenhouse gas emissions from ships" formulated for greenhouse gas emissions. Ma et al. (2021) proposed a non-linear integer programming model to solve the problem of concurrently optimizing the route, speed, and bunkering strategy of ship operations under the constraints of the ECA policy.

Some researchers have started to compare and assess the effect of the implementation of policies on decreasing ship emissions. Repka et al. (2021) assessed the changes in SOx and NOx deposition from ship exhaust discharge in 2014 and 2016 of the Baltic Sea regions. The results showed a 7.3% reduction in total SOx deposition in the study area. Shi et al. (2020) evaluated ship pollutant emissions after the implementation of ECA policies in Shanghai Port with 2017 AIS data. The results showed that ECA policies differed obviously between various ship types and waters, and that pollutant emissions from cargo ships, including SO_2 and $PM_{2.5}$, were most affected by ECA policies. However, NOx emissions have not changed significantly under the various ECA policies. The results also suggested that the ECA policy might lead to significant reductions in pollutant emissions from Yangshan and Wusong water areas in the future. Tauchi et al. (2022) evaluated the reduction of the global sulfur cap requirement from 3.5% to 0.5% in 2020, and the research showed that the gaseous sulfur dioxide content in the sea dropped immediately after the regulation took effect. Wang et al. (2021) compiled a series of high spatial and temporal ship discharge inventories from 2016 to 2019 across China to provide an effective and comprehensive ex-post assessment of the policy for ships. SO_2 emissions from ships fell by 29.6% over the three years, as did PM emissions by 26.4%, while the emissions of NOx raised by 13.0%. Yang et al. (2022) calculated the ship discharge in Qingdao based on 2020 AIS data in order to evaluate the environmental benefits of the policy. The results suggested that after the implementation of the policy, the air pollution from ships in various regions was substantially reduced, especially SO_2 and PM. Zhang et al. (2022b) applied to empirical data modelling in the Yangtze River Delta region with the regression discontinuity (RD) approach to assess the impact of the ECA policies. The statistical results suggested that implementation of the ECA policies in Shanghai and Suzhou achieved SO_2 reductions at the 1% level of significance. However, the effect of the policy on SO_2 concentrations in Ningbo and Nanjing is not effective. Zhang et al. (2019) compared the impact of the domestic emissions control area policies on SO_2 and particulate matter in Shanghai from 2015 to 2017. The research results showed that SO_2 decreased significantly by 27–55% after implementing of the policies. Zhou and Fan (2021) used the Difference-in-Difference (DID) model to determine the impact of fuel switching regulations on SO_2 content in port air. The study collected the wind speed, wind direction, and SO_2 concentration, as well as the time of the arrival and departure. Due to the use of high sulfur fuels the effect of increased SO_2 concentration in the air of the port was particularly significant when the wind direction was downwind. Wan et al. (2019) applied the DID model to assess the effect of implementing the ECA policies on sulfur emissions from ships. The results of the study showed that the ECA policies had significant influence on reducing SO_2 concentrations in the Yangtze River Delta and Bohai Rim regions. However, it has no positive impact on the reduction of SO2 content in the Pearl River Delta, which may be related to a series of policies adopted before.

In addition to the effect of technological changes and international policies on the inhibition of ship pollutant discharge, other external factors may also affect pollutant emissions from ships to some extent. Xu et al. (2021b) assessed the effect of the COVID-19 outbreak and measures taken by the government to deal with the epidemic on shipping trade. The results suggested that shipping business would grow to some extent as the outbreak was further controlled. Luigia and Franco (Mocerino and Quaranta, 2022) quantified the SOx emissions, NOx emissions, and CO_2 emissions and estimated their generation and reduction. Then the results for 2020 were compared with the assumed emissions without closure control and with the emissions of the corresponding period of the previous year. Li et al. (2022) studied the effect of ship massification on typical pollutant emissions. The study showed that an increase in average ship tonnage resulted in a significant reduction in ship traffic and a significant increase in cargo volume, resulting in an increase of about 7.7% in pollution reduction compared to a constant average ship tonnage. Shi and Weng (2021) compared AIS data in February of 2019 and 2020 to verify whether the COVID-19 has an impact on merchant shipping trade activities and the influence of the epidemic on pollutant emissions of ships in Shanghai Port. The epidemic was likely to lead to longer turnaround times for ships, with significantly lower emissions of cargo ships, while emissions of tankers and container ships were slightly reduced due to strict COVID-19 quarantine measures. The research also shows that a slow downward trend in SOx and NOx emissions observed. Saliba et al. (2021) analyzed the influence of the COVID-19 on maritime transportation modes and air quality.

Weng et al. (2020) estimated emissions of ships with Yangtze River estuary AIS data with high precision using the STEAM model. This study explored some factors affecting ship emissions such as ship types, modes of operation, and unloading facilities, etc. The findings indicated that many ship emissions were produced during the states of slow steam and cruising, and time and location had significant influence on ship emissions. The spatial data was found to be heterogeneous or non-stationary, which highlights the importance of selecting the appropriate spatial modeling tool to analyze ship emissions. One such tool is the Geographically Weighted Regression (GWR) analysis technique, which is often used to analyze pollution emissions (Lu et al., 2020). Alahmadi et al. (2019) applied a local GWR model to understand and quantify the impact of the emissions form marine transportation department in the Red Sea. The research results showed that the local GWR model outperformed the global Ordinary Least Squares (OLS) regression model. However, the basic GWR model often uses the same bandwidth and a single kernel function to calculate weights, which also causes the spatial variation of all parameter estimates to present the same scale characteristics. The MGWR technique, on the other hand can reveal the scale differences of variable truly. Fotheringham et al. (2017) applied the GWR and MGWR models to two simulated datasets with known attributes and an empirical dataset on the Irish famine, and then compared the regression results of the two models. The results show that MGWR has significant advantages in parameter surface with different spatial heterogeneity levels, and can also provide valuable information about the operation scale of different processes. Zhang et al. (2022a) used MGWR model to analyze the spatial heterogeneity of the influence of tourism development on the urban-rural income disparity and its scaling pattern. The results of the comparative model fitting founded that the MGWR model was closer to the regression results of the actual values. An et al. (2022) controlled for three socio-economic attribute variables. Then the GWR and MGWR models were used to describe Wuhan's built environment by detailing. It was found that the MGWR model worked better to explain all influencing factors than GWR. Tholiya et al. (2022) used OLS, GWR, and MGWR regression to analyze the factors of the water supply distribution and spatial patterns. The study pointed out that MGWR outperforms the GWR model, while the two models significantly outperform the OLS model, and proved how local factors influence variables. At present, there are few studies considering the use of GWR models to analyze ship pollution emissions. And there are few studies on spatial econometrics in ports and most concern industries and regional development in port areas.

In summary, the academic contributions of this paper are about three directions. First, this study calculates the pollutant emissions of 30 ports in the United States, including SO_2, NO_X, and CO emissions, and analyzes the distribution of ship types and ports. Second, the MGWR model is used to explain the impact of pollutant emissions from ports in the United States with the length of coastline, population, and container throughput as independent variables. Third, the regression effects of OLS, GWR, MGWR, and neural network are compared, which proves the superiority of MGWR in interpreting this study.

3 Materials and methods

3.1 AIS data source

The United States Coast Guard collects AIS data through on-board navigation safety equipment, which supports transmission and detection of the position and characteristics of ships in the United States waters in real time. The AIS data source that supplies real-time data feeds back the AIS data set of the current time period, which cannot meet the requirement of simultaneously providing AIS data in different periods. Real-time AIS data is presented for time points, while historical AIS data is more like a collection of real-time AIS data. Real-time AIS data is convenient for relevant departments to supervise marine vessel information and monitor abnormal conditions, and it is also helpful for shipowners and cargo owners to obtain real-time ship sailing progress. Historical AIS data can reflect the development and changes of marine shipping and provide relevant departments to formulate strategies. At the same time, it can also provide a data basis for the calculation of pollutant emissions, which is also the data type selected to build model.

Since the code designation of ship types in AIS datasets from different sources may be different, the user manual on the same website was also searched when acquiring AIS data. In the report "Frequently Asked Questions: AIS Data and Tools," the detailed ship types and their corresponding codes are given, and the version is updated to "Vessel Type Code 2018" (AIS vessel type and group codes used by the marine cadastre project[EB/OL] 2018-05-23).

Different from the general two-digit ship code, its ship code is a value from 0 to 1025, because it leaves a lot of blanks in the ship code for use. A fine distinction is made for each type of ship according to its nature and purpose (AIS vessel type and group codes used by the marine cadastre project[EB/OL] 2018-05-23). The ships are according to their primary classification and are mainly divided into six categories, and the correspondence between ship types and codes is shown in the Table 1 (Repka et al., 2021).

3.2 Model building

This paper calculates ship pollutant emissions based on 2021 American AIS data, and the objective is to use MGWR model to analyze the spatial heterogeneity of ship pollutant emission characteristics of major American ports at different scales. The scope of major ports is divided according to latitude and longitude

TABLE 1 Ship types and code correspondence.

Ship type	Included encoding
Container ship	30, 31, 32, 1003, 1004, 1012-1015
Cargo ship	70-79, 1016
Passenger ship	36, 60-69
Oil tanker	37, 80-89, 1017, 1024
Tugboat	21, 22, 52, 1023, 1025
Others	0-1025 other remaining values

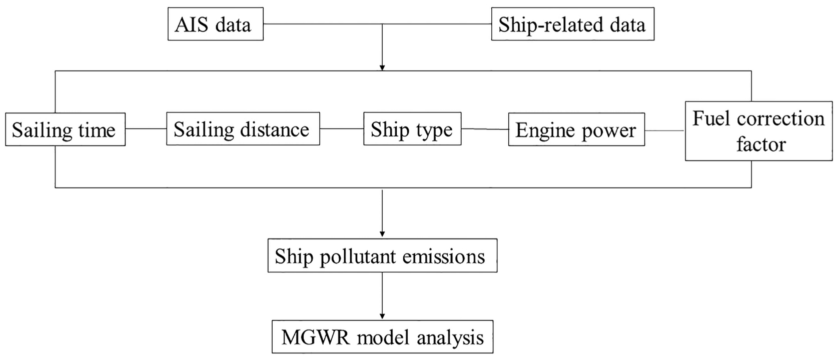

FIGURE 1
Evaluation framework.

and route, and ship pollutant emissions in 2021 are calculated. The framework of this paper is illustrated in the Figure 1.

Based on the port information and related materials consulted, combined with land information and water conditions, 30 ports were finally selected. These ports include major ports in the US-East route, such as the ports of New York and New Jersey, Savannah, Jacksonville, Charleston, etc. Major ports in the US-East route, such as the ports of Los Angeles, Long Beach, Seattle and Tacoma, Oakland, etc. In addition, some American inland ports such as the ports of Wilmington and Hampton Roads also include. The time range of this paper is from January to March in 2021. The calculation of emissions relies mainly on the energy output of the ship's engines. Emissions are calculated from three sources: the main engine, the auxiliary engine, and the auxiliary boiler. The pollutant emission calculation formula is (Kao et al., 2022):

$$E = Energy \times EF \times FCF/10^6 \quad (1)$$

$$Energy = Energy_{me} + Energy_{ae} + Energy_{ab} \quad (2)$$

$$Energy_{me} = MCR \times LF_{me} \times Act \quad (3)$$

$$Energy_{ae} = MCR \times LF_{AE} \times Act \quad (4)$$

$$Energy_{ab} = LF_{ab} \times Act \quad (5)$$

$$LF = \left(\frac{AS}{MS}\right)^3 \quad (6)$$

$$Act = D/AS \quad (7)$$

where E refers the emissions and the unit is ton, $Energy$ refers to the total energy demand and the unit is kW-hrs, $Energy_{me}$, $Energy_{ae}$, and $Energy_{ab}$ represent the energy demand of main engine, auxiliary engine, and auxiliary boiler, respectively. MCR refers to the maximum continuous rating power and the unit is kW. LF_{me}, LF_{ae}, and LF_{ab} denote the load factor of main engine, auxiliary engine, and auxiliary engine, respectively. Act indicates the activity, EF refers to the emission factor, and FCF signifies fuel correction factor. AS is actual speed and MS being maximum speed, whose units are all knots. D refers to the sailing distance. The data about the parameters are shown in the Tables 2, 3 (Kao et al., 2022).

3.3 Emissions calculation results

In this study, the data of the first three months are selected from the AIS data of 2021 provided by Marinecadastre.gov, and the water area records of 30 ports selected in this study are about 16.9 million AIS records in total according to the port location. The number distribution of various ship types is shown in the Figure 2. It can be seen from the results that the pollutant emissions of container ships and oil tankers are higher than other ship types, which may be because the AIS records collected in the main port waters of the two ship types in 2021 account for more relevant records.

In the early stage of development, container ships also had various structures and styles, but in order to facilitate international circulation, containers began the process of developing to

TABLE 2 Parameter defaults for ships.

Ship type	Maximum speed (knot)	Maximum main engine power (kW)	Auxiliary engine power (kW)
Container ship	21	32,082	6,100
Passenger ship	19	21,848	6,752
Cargo ship	13	4,540	1,195
Tanker	14	7,055	2,179
Ro/Ro	19	8,805	1,175
Other	12	4,934	1,455

TABLE 3 Fuel correction factor.

Fuel	SO_2
HFO (2.7%S)	1.000
HFO (1.5%S)	0.555
MGO (0.5%S)	0.185
MDO (1.5%S)	0.555
MGO (0.1%S)	0.037
MGO (0.3%S)	0.111
MGO (0.4%S)	0.148

international standardization in 1961 under the leadership of the International Organization for Standardization (ISO). Up to now, the manufacturing of containers generally follows the specific standards of each region (Shi, 2004). Under the premise of container standardization, container ship transportation has an efficient and economical transportation system, and at the same time, the scale of container ships can be decided according to the capacity of the ship to load containers. Although container ships also have different sizes, the container ships with the largest circulation and the most frequent use are of a fixed dimensions in the world. In this regard, the uncertainty and difference caused by the size and size of ships to ship pollutant emissions are not as good as a cargo ship. Oil tankers generally refer to transportation ships that carry crude oil or refined oil and other petroleum products. The oil tankers active in the waters of the ports are mostly medium-sized ships mainly responsible for the transportation of refined oil and large ships mainly responsible for the transportation of crude oil and heavy oil. The size of these ships also has certain standards, which are mostly in connection with the load of the ship itself.

The top 15 ports with the largest pollutant emission among the 30 ports are shown in the Figure 3. The ship pollutant emissions in the port of Houston, the port of New Jersey and New York, and the port of Seattle and Tacoma far exceed that of other ports. There are many records of Houston Port in AIS records. Houston Port is located on the northwest coast of Galveston, the Gulf of Mexico. It is the second international commercial port in the United States, the second energy and trade port in the United States and the sixth in the world. As joint ports, the port of New Jersey New York, the port of Seattle and Tacoma have more AIS data within their waters. The port of New Jersey and New York are located on the northeastern coast of the United States. The port hinterland is vast and radiates the northeastern region of the United States. This region is the most developed of the three major regions in the economic development of the United States. Most of the ports are located along the Brooklyn coast of New York City and Newark Bay coast of New Jersey (List of ports in the united States[EB/OL]). Seattle port and Tacoma port proposed to merge the marine cargo business in 2014. In 2015, a public development agency, Northwest Seaports Alliance, was established and approved by the Federal Maritime Commission. In terms of container volume, it is the third largest cargo port in the United States after the merger (Port introduction | Northwest seaport alliance: Seattle port and Tacoma Port[EB/OL] Haituo joint supply chain).

From the perspective of pollutant types, the emissions of SO_2 and NO_X are much higher than that of CO, and the emissions of NO_X are the highest among the three. Due to the great harm of SO_2 to the environment, more and more policies aimed at suppressing SO_2 emissions are being introduced. Some measures to inhibit SO_2 emissions, such as establishing ECA and using low-sulfur fuel oil, have been proved to be effective in reducing SO_2 emissions during ship operation. However, the impact of ECA policies on restraining NO_X emission is relatively weak compared with SO_2.

4 Weighted geographic regression analysis

4.1 Variable description and statistics

In this study, the SO_2 emissions of major ports in the United States in the first quarter of 2021 are taken as dependent variables, and the port coastline length, port throughput, and port city population are taken as independent variables to describe the distribution of pollutant emissions from ships of major ports in the United States. The regression results of GWR and MGWR models are compared.

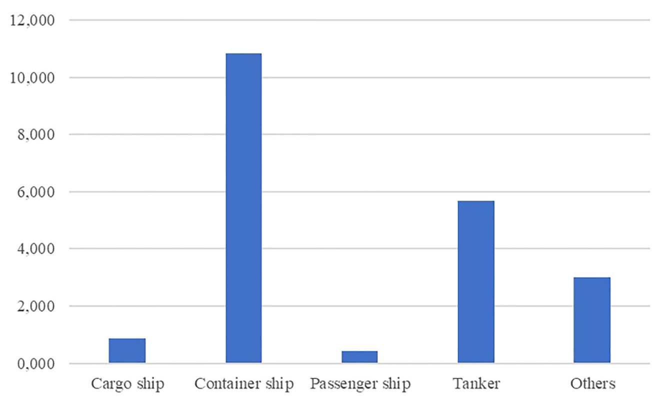

FIGURE 2
The number distribution of various ship types.

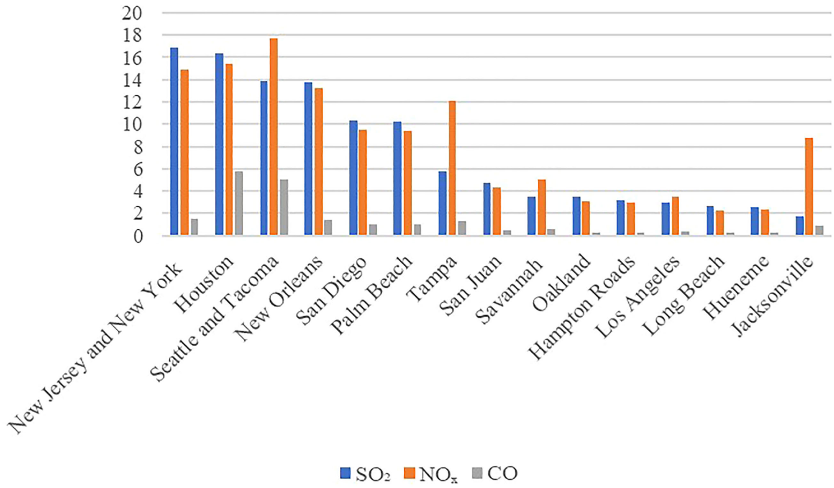

FIGURE 3
15 Ports with high pollutant emissions (unit: ton).

4.1.1 Coastline length

In general, the coastline can be simply regarded as the boundary between sea and land. Natural factors such as coastal erosion and siltation, sea level rise, and factors such as artificial levees and reclamation of land from the sea will lead to changes in sea level. The coastline is long and tortuous, which is more conducive to the development of ports. In addition, socio-economic development and policies are also important driving factors of coastline evolution (Yang et al., 2021). The acquisition of coastline length is mainly determined by consulting relevant data and using measurement tools in ArcGIS.

4.1.2 Population

Ship pollutant emissions to the air environment will ultimately have harm to normal production, daily life, and physical health of people. For example, the sulfur is an important factor that can cause the formation of acid rain, moreover it can ruin and acidify soil, which has seriously affected the development of economics in relevant areas. The port can promote the development of its own city and nearby cities, so the population density in the port area is relatively high. At the same time, because ships take a lot of time to load and unload goods, the pollutants generated while in port will also have an impact on the people living in the port city. The more obvious is that the inhalable particulate matter in the ship pollutant emissions increases the risk of people suffering from cardiopulmonary diseases. Some studies have shown that the particulate matter caused by shipping activities causes about 60,000 deaths every year. Most of the causes of death are related to the common diseases caused by particulate matter emissions (Corbett et al., 2007; Sofiev et al., 2018). The population density will have an impact on the pollutant emission policies formulated by port managers and the government. Relevant policies should minimize the impact of pollutant emissions on human health.

4.1.3 Throughput

Port throughput refers to the total throughput of bulk cargo, liquid cargo, containers, etc. In this study, port throughput mainly refers to the throughput of container ports. Container throughput includes the number of imported containers and exported containers at the port in a period, usually taking TEU as the unit. Container throughput can generally be used to measure the international trade market demand of a port city. As it is difficult to obtain the statistical data of container throughput of major ports in the United States in 2021, the container throughput data in this study is the average of the container throughput data of major ports in the United States from 2013 to 2017 according to the statistics of the American Association of Port Authorities (American Association of Port Authorities[EB/OL]).

4.2 The analysis of the regression results

The data of major ports in the United States, independent variables (coastline length, population, and throughput) and dependent variables (SO_2, NO_X, CO emissions) used in this study are shown in the Table 4.

The distribution of major ports in the United States on the map is shown in the Figure 4. GWR is based on the idea of local regression analysis and variable parameters. Based on the theory of nonparametric methods of local weighted regression such as curve fitting and smoothing, it embeds the spatial position of data into regression parameters to study the regression relationship varying with space. The structure of GWR model is as follows (Li et al., 2022):

$$y_i = \sum_{j=1}^{k} x_{ij}\beta_{bwj}(u_i, v_i) + \epsilon_i \tag{8}$$

where y_i represents the interpreted variable, (u_i, vi) represents the coordinate of the center point at i, bwj represents the bandwidth used for the coefficient of the jth regression variable, and β_{bwj} represents the regression coefficient of the jth variable at i.

TABLE 4 Main variables of the model.

Port	Coastline (km)	Population ($\times 10^4$)	Throughput (TEU)	SO_2 emissions (ton)	NO_X emissions (ton)	CO emissions (ton)
Los Angeles	69	398	8,513,814	2.978	3.539	0.371
Baltimore	28	61	8,29,530	0.502	0.450	0.047
Boston	6	67	233,196	1.509	1.324	0.139
Charleston	24	43	1,908,075	0.289	0.242	0.025
Houston	56	230	2,134,706	16.364	55.476	5.813
Jacksonville	6	88	956,084	1.703	8.776	0.920
Long Beach	40	47	7,012,625	2.642	2.246	0.235
New Jersey and New York	70	853	6,114,828	16.889	14.880	1.559
New Orleans	28	39	504,282	13.748	13.273	1.391
Oakland	33	42	2,361,706	3.443	3.030	0.317
Portland	33	63	122,021	1.578	1.397	0.146
Savannah	40	14	3,561,639	3.446	5.090	0.534
Seattle and Tacoma	75	70	3,545,672	13.848	47.735	5.000
Tampa	58	37	50,495	5.816	12.093	1.267
Wilmington	27	72	270,236	0.743	4.426	0.464
Hampton Roads	24	14	2,532,513	3.203	2.924	0.306
San Juan	10	200	1,263,988	4.763	4.347	0.455
Honolulu	47	35	1,167,543	0.155	0.215	0.022
Everglades	9	25	1,023,103	0.050	0.0457	0.005
Palm Beach	32	11	267,663	10.255	9.360	0.981
Mobile	38	20	256,759	0.284	0.260	0.027
Gulfport	14	7	184,261	0.001	0.0003	3.32×10^{-5}
Hueneme	37	18	99,571	2.555	2.326	0.244
San Diego	36	141	120,424	10.379	9.479	0.992
Kahului	6	15	102,871	0.00005	0.0005	4.78×10^{-5}
Kawaihae	47	35	79,824	0.004	0.003	0.0004
Nawiliwili	15	35	48,551	0.004	0.004	0.0004
Hilo	31	4	39,325	0.0004	0.0004	4.59×10^{-5}
Galveston	46	6	37,546	1.524	1.392	0.146
Manatee	9	26	24,174	1.400	1.279	0.134

Compared with the classical GWR model, the biggest difference of MGWR is that this model is a local model, allowing parameters to change in space, that is, bandwidth specificity. The kernel function and bandwidth selection criteria of the MGWR model still follow the selection criteria of the GWR model. In this paper, the most used quadratic kernel function and the correct Akchi information criterion (AICc) are used. For the estimation of MGWR model, it can be seen as a generalized additive model (Zhang et al., 2022a).

$$y = \sum_{j=1}^{k} f_j + \epsilon \tag{9}$$

$$where\ \ f_j = \beta_{bwj} x_{ij}$$

We conducted spatial autocorrelation analysis, clustering and outlier analysis on the model, and obtained the local Moran's I. We found that the results of some ports, such as Honolulu Port, Galveston

Port were more significant, indicating that there was a certain degree of spatial aggregation of ship pollutant emissions, and the use of MGWR analysis can better explore the characteristics of ship pollutant emissions at the port. First, the collinearity analysis is carried out in the OLS model, and all independent variables are added to the model. The variance inflation factor (VIF) is less than 3 and the tolerance is greater than 0, which indicates that there is no obvious collinearity between independent variables. In OLS model results, R^2 of SO_2, NO_X, and CO are 0.193, 0.081, and 0.081 respectively. The interpretation effect of the model is insufficient. In the MGWR model results, the R^2 of SO_2, NO_X, and CO are 0.421, 0.283, and 0.283 respectively. The effect of R^2 in the results of GWR and MGWR is better than that of OLS. We also used neural network to predict the model. Thirty representative ports were selected as samples for training through analysis. Due to the small sample size, we divided the data into 15 training sets and 15 test sets each according to 1:1. After determining the training set, the training set was normalized. Initially, we set the neural network with three layers, including input layer, hidden layer, and output layer. The input layer includes three neurons, which are three independent variables Coastline, Population and Throughput average (2013-2017). The hidden layer includes four neurons. The output layer consists of one neuron representing the dependent variable. The entire neural network was implemented by MATLAB, and the three model R-squares obtained under the learning rate of 0.01 and the epochs of 4000 were SO_2:0.271 NOx:0.004 CO:0.024. We compare R^2 in the regression results of the four models, and the comparison results are shown in the Table 5.

The Tables 6–8 show the regression results of three types of pollutants. These tables showthe regression results of GWR and MGWR. Then, we compare the bandwidth and regression coefficient of the sink measurement between GWR and MGWR models. The GWR model allocates a fixed bandwidth for all independent variables. In contrast, MGWR sets a different bandwidth for each variable, and the standard deviation of the GWR coefficient of the independent variable is higher than the MGWR coefficient.

TABLE 5 R^2 of regression results of four models.

	SO_2	NO_X	CO
OLS	0.193	0.081	0.081
Neural network	0.271	0.004	0.024
GWR	0.421	0.283	0.283
MGWR	0.424	0.283	0.283

Descriptive statistics of regression coefficients of MGWR model reflect the overall influence of various factors on the port pollutant emissions. In the regression results of the three types of pollutants, among the variables with significant impact, the constant term mainly has an expanding effect on the port pollutant emissions. The impact coefficients of coastline length and population on the port pollutant emissions are mainly positive, indicating that the increase of coastline length and population will increase the port pollutant emissions. However, the impact coefficient of throughput on the port area is mostly negative, and container throughput plays a strong role in inhibiting pollutant emissions from ship in the port area. In general, the impact of coastline length, population, and container throughput on pollutant emissions in port areas is mainly to expand. In the regression results of SO_2, the p-value of the two independent variables of coastline length and population are both less than 0.05, and the results are significant. In the regression results of NO_X and CO, only the P-value of coastline length is less than 0.05. The variable bandwidth reflects the action scale of each variable. A larger bandwidth means that the variable affects the pollutant emissions of the United States ports in a larger range or even in a global range. A smaller bandwidth means that the variable affects the pollutant emissions of the major ship types in the United States ports in a regional or local range. In the GWR model, the control bandwidth is 186.630, the bandwidth of each variable in the MGWR is 188.040, and the bandwidth of the constant term is 30.340, indicating that the core variables such as the length of coastline and population have certain spatial heterogeneity on the pollutant emissions of the United States ports.

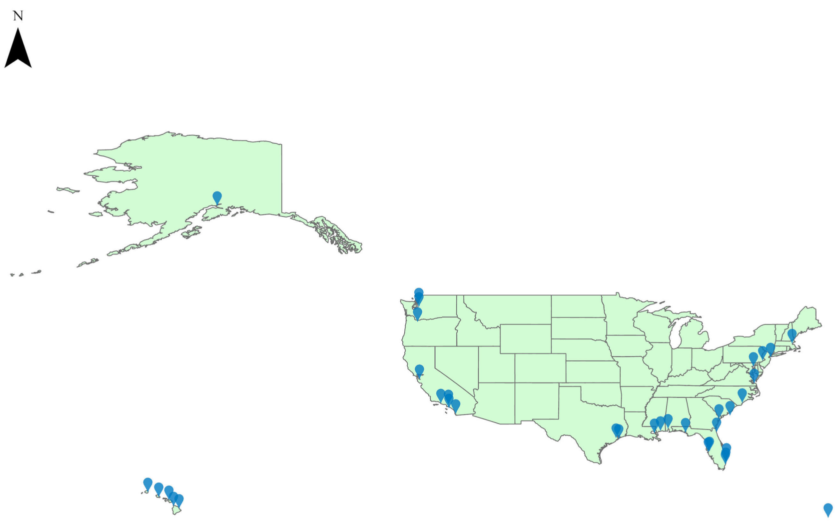

FIGURE 4
The distribution of major ports in the United States.

TABLE 6 Regression results of SO_2 emissions.

	Variable	Intercept	Coastline length	Population	Throughput
GWR/MGWR results	Est	−0.000	0.429*	0.472*	−0.218
	SE	0.149	0.181	0.191	0.200
	t (Est/SE)	−0.000	2.369	2.474	−1.089
	p-value	1.000	0.018	0.013	0.276
Summary Statistics for MGWR parameter estimates	Mean	0.027	0.455	0.448	−0.246
	STD	0.060	0.002	0.448	0.000
	Min	−0.034	0.452	0.000	−0.246
	Median	0.114	0.456	0.448	−0.246
	Max	0.130	0.457	0.449	−0.246
	Bandwidth	30.340	188.040	188.040	188.040

*p-value<0.05.

TABLE 7 Regression results of NO_X emissions.

	Variable	Intercept	Coastline length	Population	Throughput
GWR/MGWR results	Est	−0.000	0.550*	0.095	−0.143
	SE	0.166	0.202	0.213	−0.143
	t (Est/SE)	−0.000	2.720	0.447	−0.641
	p-value	1.000	0.007	0.655	0.522
Summary Statistics for MGWR parameter estimates	Mean	0.003	0.555	0.094	−0.147
	STD	0.004	0.002	0.002	0.002
	Min	−0.006	0.552	0.092	−0.149
	Median	0.005	0.554	0.094	−0.148
	Max	0.007	0.557	0.098	−0.142
	Bandwidth	186.630	186.630	186.630	186.630

*p-value<0.05.

TABLE 8 Regression results of CO emissions.

	Variable	Intercept	Coastline length	Population	Throughput
GWR/MGWR results	Est	−0.000	0.550*	0.095	−0.143
	SE	0.166	0.202	0.213	−0.143
	t (Est/SE)	−0.000	2.720	0.447	−0.641
	p-value	1.000	0.007	0.655	0.522
Summary Statistics for MGWR parameter estimates	Mean	0.003	0.555	0.094	−0.147
	STD	0.004	0.002	0.002	0.002
	Min	−0.006	0.552	0.092	−0.149
	Median	0.005	0.554	0.094	−0.148
	Max	0.007	0.557	0.098	−0.142
	Bandwidth	188.040	188.040	188.040	188.040

*p-value<0.05.

5 Discussions

The innovation of this paper is to calculate the ship pollutant emissions of three different types of pollutants (SO_2, NO_X, and CO) in the 30 ports of the United States. The MGWR model is used to evaluate the influencing factors of these pollutant emissions. The variables studied include the length of the coastline of the port area, the population of the port city, and the throughput of containers at each port. This paper also has some limitations. First, there are errors in the process of data acquisition. The coastline length of each port is measured in ArcGIS, and there are some errors in the measurement process, which may have some effect on the results of the model. Second, due to the AIS data is divided according to port scope, and the port scope is determined according to longitude and latitude, there may be data omission. Third, this paper does not consider the impact of navigation status on the emissions of three types of pollutants, and the location of AIS data points is also related to navigation status, such as berthing status and cruising status. Fourth, because it is hard to acquire the data of container throughput of ports in the United States in 2021, the data of container throughput in the model is based on the average of container throughput from 2013 to 2017, which may have some impacts on the regression results of the model.

From the regression results of the model in this study, among the regression methods of OLS, GWR, MGWR, and neural network, due to the insufficient sample size and possible error, the prediction results of neural network in the model studied are not ideal, and the prediction value differs greatly from the expected value. In the OLS model, the correlation between each variable and the dependent variable can only be judged by the regression results, and the overall impact of each factor on the discharge of pollutants from ships in 30 ports in the United States cannot be known. Both MGWR and GWR models are applicable to explain the spatial heterogeneity of the independent variables of the model on the port pollutant emissions. The model comparison results show that the AICc value of MGWR is lower than that of GWR, and the adjusted goodness of fit R^2 is higher, and the sum of residual squares of MGWR is significantly lower than that of GWR, which indicates that the MGWR is closer to the regression results of the true value. Therefore, MGWR is more suitable for explaining the influence of each variable on the pollutant emissions of ports in the United States.

By calculating the pollutant emissions of 30 ports in the United States, we found that NO_X accounted for the highest proportion of the three pollutant types, followed by SO_2 and CO, and the pollutant emissions in each month in the first three months were roughly the same, and the distribution of pollutant types was also similar. We speculated that the pollutant emissions in different quarters would have different distribution trends. In the distribution of ship types, oil tankers and container ships are the main sources of pollutant emissions from ships, which may be related to the size of ships and the navigation status of ships. In terms of port distribution, the New Jersey and New York Port, Houston Port, Seattle and Tacoma Port are the ports with the largest pollutant emissions. These three ports are large in scale. The first two are the main ports on the US-East route, while Seattle and Tacoma Port is the main port on the US-East route. There are many types of ships for trading and transportation, and the geographical location is favorable for the development of maritime transport business.

The emission of SO_2, NO_X, and CO will have a vital effect on the environment. These pollutants will cause irreversible harm to the environment and human health. As people attach more importance to the treatment of ship pollution, more and more policies and measures have been put forward and implemented by the policy and relevant organizations to curb the emission of ship pollutants. Researches show that ECA policies and the use of low-sulfur fuel can effectively reduce SO_2 emissions. However, some policies have not acted significantly in inhibiting NOx, which accounts for the largest proportion of all kinds of pollutants. In the future, port administrator and local government should consider how to take measures to effectively reduce NOx emissions. The emission of SO_2 is significantly correlated with the length of coastline and population, while the emissions of NO_X and CO are only significantly interrelated with the length of coastline. It is showed that the length of coastline is an important factor affecting the discharge of pollutants from various types of ships. Therefore, port managers and local governments should reasonably control the number of ships parked and traded along the coast according to the length of coastline in the area where the port is located, and reasonably develop the shipping economy to achieve the sustainable development of the port economy.

The navigation status of ships will also have significant influence on the pollutant discharge in the port area. In ports with long coastline and large scope, the number of ships docked will also increase. However, the pollutant discharge of ships in the berthing status is more, so it is necessary to minimize the stay time of ships in the port. Besides the majorization of loading and unloading process, other measures can also be used to alleviate the port congestion and avoid many ships are stranded in ports. In 2020, the Baltic and International Maritime Council (BIMCO) launched the virtual arrival clause, so that when ships face congestion in the port, they can delay the arrival time by reducing the sailing speed on the way, which not only effectively alleviates ship detention problems at the port, reducing the pollutant emission caused by the ship waiting at the berth, but also reducing the cost of the ship operator due to the detention of the ship in the port.

6 Conclusions

This paper takes the pollutant emissions of 30 major ports in the United States as the main research object, and uses the AIS data of American waters from January to March 2021 to compute the discharge of pollutants from ships in ports. (1) The results show that oil tankers and container ships are the main sources of pollutants in various ship types. (2) Among the ports, Houston Port, New Jersey and New York Port, and Seattle and Tacoma Port have far more pollutant emissions than other ports. The distribution difference of ship types may be related to the number of ship types recorded in AIS records. There are many AIS data records within the scope of Houston Port. New Jersey and New York Port, and Seattle and Tacoma Port are joint ports with large port scope. Because there are many AIS data records within the scope of these three ports, the pollutant emissions within the scope of these three ports are relatively high. (3) The distribution trend of pollutant emissions of SO_2, NO_X, and CO in each port is roughly the same, and NO_X emissions are the largest, and the emission distribution of various types of pollutants in each month is also the same.

Taking coastline length, population and container throughput as independent variables and port pollutant emissions as dependent variables, the MGWR is used to analyze the effect of the discharge of pollutants from ships of ports in the United States. The results show that the length of coastline and population promote the pollutant discharge of ports, while the container throughput reduces the pollutant discharge of ports. Among the variables with significant influence, the constant term mainly has a reducing effect on the port pollutant emissions.

Future research can consider taking more ports on the inland ports, the US-East route, and the US-West route as samples to analyze the spatial distribution of pollutant emissions from the ports of the United States, and analyze the influence of factors affecting the pollutant emissions from ships in different regions. In addition, some social and economic factors, such as policies on pollutant emissions and the degree of economic development, can also be considered as independent variables to study their effect on the pollutant emissions of various ship types in the port area. The dynamic ensemble method can be considered to investigate the distribution of pollutant discharge from ships in ports.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

GX: Conceptualization, Methodology, Writing—Review and Editing, Funding acquisition. TW: Conceptualization, Methodology, Writing—Original Draft. YL: Writing—Original Draft, Investigation. DY: Formal analysis. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Evaluation of policy synergy in coastal ocean pollution prevention and control: The case from China

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In recent years, the Chinese central government and coastal provincial governments have promulgated a series of Coastal Ocean Pollution Prevention and Control Programs (COPPCP). Whether the government's COPPCP can achieve policy synergy will affect the level of marine pollution governance. This study constructs a two-dimensional assessment framework of policy "subject department"–"content theme" and conducts a comprehensive evolution of policy synergy from objective, process, and state perspectives. From the subject department dimension, the study used social network analysis to find that interdepartmental collaboration was not done well overall. The policy synergy process is difficult to be guaranteed. Meanwhile, the structure of departmental synergy networks in different provinces shows differences and can be divided into three types of governments with single-core, multi-core, and vertical synergy. In the content synergy dimension, it was found by the Chinese Bidirectional Encoder Representations from Transformers-Whole Word Masking (BERT-WWM) model that the policy content is mainly focused on four themes of marine ecological protection (MEP), marine pollution control (MPC), land-based pollution reduction (LPR), and safeguard measures (SAM). The three types of governments show different performances on the four theme synergies. The governments perform well in the objective synergy; however, it is difficult for them to agree on the policy tool synergy, and the status of policy synergy is difficult to maintain. This paper adopts the BERT-WWM model instead of the manual coding method in the previous policy content analysis, enhancing the evaluation's objectivity. The study results will provide a reference for further improving marine pollution governance systems in developing countries.

KEYWORDS

coastal ocean pollution, marine pollution governance, coastal ocean pollution prevention and control program, policy synergy evaluation, content analysis

1 Introduction

Coastal ocean pollution is an essential theme in marine pollution management. The coastal ocean consists of several distinct but closely linked ecosystems, including rivers, estuaries, tidal wetlands, and continental shelves (Bauer et al., 2013). The coastal ocean is of great interest because it is biologically very productive and most vulnerable to human activities. About 80% of marine litter is widely believed to come from land-based sources and flows mainly to coastal and nearshore areas (Morales-Caselles et al., 2021). The problems of eutrophication, accumulation of toxic substances, pollution from ships (Xiao et al., 2022a), and plastic waste pollution in the coastal ocean are becoming more and more serious. In recent years, the effluent from the Fukushima nuclear power plant has also posed a threat to the environment in coastal oceans around the world (Lu et al., 2021; Men, 2021; Liu et al., 2022). The possibility of ecological species reduction (Kumar and Prasannamedha, 2021) and geological disaster occurrence is increasing (Zhou et al., 2022). Focusing on environmental protection in the coastal ocean is essential to combat marine pollution.

China is one of the largest developing countries in the world. Since the reform and development, the high-speed economic growth and urbanization of coastal areas have caused severe pollution and damage to the coastal ocean environment (Xu and Zhang, 2022). China's central government gradually realized the seriousness of this problem, and in March 2017, it specifically formulated the Coastal Ocean Pollution Prevention and Control Program (COPPCP). COPPCP specifies the objectives of pollution prevention and control in China's coastal ocean and lists essential matters as well. However, the "Bulletin on the State of China's Marine Ecological Environment in 2021" points out that the ecological environment quality of China's coastal ocean still needs to be improved. 21,350 square kilometers of the worst class IV waters are still covered in 2021. One cannot help but doubt the validity of the policies issued by the central government. However, the facts may be more complex. The transboundary nature of marine pollution makes it necessary to achieve policy synergy among coastal governments (Graham, 2022). Policy synergy is significant in China, where government departments face difficulties achieving integration (Li and Ye, 2021; Liu and Wang, 2022). The degree of policy synergy is one factor that influences the pollution control level (Li and Ye, 2021). Following the central government's program, all 11 coastal provincial administrative regions in mainland China have issued local pollution prevention and control programs for the coastal ocean. This leads people to wonder whether there can be synergy between these policies. Measuring the degree of policy synergy will support analyzing the policy effectiveness of COPPCP.

Policy synergy is reflected in the consistency of policy objectives and the non-redundancy of interdepartmental collaboration. Therefore, this paper expects to build a two-dimensional policy synergy evolution framework to measure the synergy between the policy contents and subject departments of COPPCPs issued by various Chinese governments. The study is expected to provide a methodological reference for evaluating the effectiveness of coastal ocean pollution prevention and control policies in other countries. More importantly, it will help to improve the contribution of COPPCP to marine pollution governance.

2 Literature review

2.1 Research on marine pollution management

The marine environment is mainly threatened by marine litter and chemical pollution from human activities. Most of the current marine pollution research themes are focused on plastic litter. The research questions primarily investigate the sources, chemical and physical characteristics of pollutants, and their economic, social, and environmental impacts. Treatment programs for marine environmental pollution have also emerged in recent years. This trend is reflected in the review of studies in developing countries such as India (Sivadas et al., 2022) and Southeast Asia (Omeyer et al., 2022). Regarding the governance of marine pollution, researchers generally make their recommendations in terms of technology, economics, society, and policy. Wu et al. (2023) pointed out that developing countries should learn from the experience of developed countries and actively promote cleaner production technologies to reduce pollution at source. Fadeeva and van Berkel (2021) proposed that promoting the transition to a circular economy is expected to reduce the flow of plastic waste to the ocean. Hartley et al. (2018); Sivadas et al. (2022), and Garcia et al. (2019) unanimously proposed that promoting green environmental awareness through publicity and education is the fundamental way to reduce pollution. Developed countries have developed a body of experience in technology, circular economy, and lifestyle habit development, yet developing countries need help in achieving these governance objectives in a short period. Boom Cárcamo and Peñabaena-Niebles (2022) points out that developing countries are hardly hindered by the huge costs in the early stages of the transition to a circular economy. These difficulties are further compounded by the shortage of infrastructure (Sivadas et al., 2022). The long cycle and high cost of technological innovation make it difficult for developing countries to achieve in the short term. As for the difficulties in awareness and education, they lie in the fact that people cling to their cultural habits, which are difficult to change

Abbreviations: COPPCP, Coastal Ocean Pollution Prevention and Control Program; LLG-x, Lower Level Government; MEP, marine ecological protection; MAB, Marine Bureau; MPC, marine pollution control; MSA, Maritime Safety Agency; LPR, land-based pollution reduction; MSB, Market Supervision Bureau; SAM, safeguard measures; NRB, Natural Resources Bureau; ACB, Agriculture Committee or Bureau of Agriculture; STC, Science and Technology Committee; COO, Coastal Office; TRC, Transportation Committee; DRC, Development and Reform Commission; WAB, Water Bureau; EMB, Emergency Management Bureau; BUB, Business Bureau; EPB, Environmental Protection Bureau; TOB, Tourism Bureau; FIB, Finance Bureau; HEC, Health Committee; FOB, Forestry Bureau; MPB, Marine Police Bureau; HUB, Housing and Urban-Rural Development Bureau; GAB; Greening and Amenities Bureau; ITC, Industrialization and Information Technology Committee; AHB, Animal Husbandry Bureau; BERT-WWM, Bidirectional Encoder Representations from Transformers-Whole Word Masking.

in the short term. Currently, environmental regulation is gaining importance in marine pollution governance. After Sivadas et al. (2022) overviewed the challenges of plastic pollution in India, it was noted that an important step to meet the challenge is to review the existing regulatory approaches. The transboundary nature of marine pollution makes it a regional and global problem. Regional collaboration is necessary to address the issue of marine litter and its transboundary nature through planning and management. Similarly, in the field of nuclear wastewater pollution control research, several researchers have proposed the necessity and feasibility of transboundary collaboration from the perspective of international law (Chang et al., 2022; Chen and Xu, 2022; Wang and Li, 2022). Holistic management policies with shared objectives are an important first step towards a unified and cooperative approach to marine waste at all levels(Graham, 2022).

2.2 Research on policy synergy

The transboundary nature of pollution has interested researchers in the theme of policy synergy among different levels of government. Policy synergy can be defined from three perspectives: objective, process, and state. The objective of policy synergy is to make inter-policy collaboration produce effects that are higher than the sum of each policy performance and reduce interdepartmental conflicts (Bai et al., 2018). From the perspective of process, Bai et al. (2018) argued that policy synergy is the process by which two or more policies coordinate to achieve a common objective. Dinges et al. (2018) considered policy synergy as the collaboration among different organizational departments. Both definitions specify the meaning of policy synergy from the perspective of the process. In terms of the status in which the policies are located, policy synergy refers to the existence of consistency in content between two or more procedures (Bolleyer, 2011).

Research on policy synergy has transitioned from simple descriptive answers to the "what" question to the more complex "evaluation of policy synergy" question. In recent years, policy synergy was evaluated mainly by observing the effects produced by policy synergy. Most researchers have collected real-world data to demonstrate the effects of implementing policy synergy (Lu et al., 2022; Ouyang et al., 2022). However, the confounding nature of other factors and the reliability of the data call into question the scientific validity of these empirical studies. Starting from the policy text itself, examining whether the state of policy synergy exists has become a study that has been gradually promoted in recent years. Liu and Wang (2022) used a combination of content analysis and social network approaches to analyzing the degree of synergy in coal de-capacity policies at all levels of government in China. The degree of close interdepartmental collaboration, the consistency of policy themes across all levels of government, and the degree of thematic change over time was considered. Ye and Wu (2022) also used a content analysis approach to analyze the synergy between demand-side and supply-side policy instruments at different stages of the green value chain. Similar studies using content analysis methods to explore policy synergy from the perspectives of objectives, processes, and states are emerging (Hills et al., 2021). However, most of these studies use policy codes, policy concept word lists, or mapping relationships between policies and semantics for automatic identification and automatic processing of policy concepts in their content analysis methods. An intuitive parsing framework from policy text to policy semantics is constructed, on the basis of which the analysis of policy text and its connotation is carried out (Grimmer and Stewart, 2013; Bunea and Ibenskas, 2017). This type of method is still a semi-computational and subjective analysis tool, although computer software is introduced for conceptual extraction and quantitative statistics of policy texts and has automatic statistical and relationship identification methods for text data. This is because the concept extraction method still uses traditional content analysis methods and processes, but relies heavily on manual extraction by the researcher in the data processing aspect.

From the above, it can be seen that the current research in the field of marine pollution governance, and the study of evaluation of policy synergy has more practical applications, especially for developing countries. In terms of policy synergy research, the assessment of policy synergy from the perspective of the definition of policy synergy itself has gained the attention of scholars. Evaluating policy synergy effects utilizing content analysis has become a well-established method. However, the issue of policy synergy in pollution prevention and control policies for coastal ocean waters has not been discussed. Moreover, the methods often used in policy synergy evaluation studies are mostly biased toward subjectivity analysis. Therefore, this study establishes a policy synergy evaluation framework of policy subject department - policy content theme based on the previous work. The COPPC's policy synergy is evaluated using social network analysis and Bidirectional Encoder Representation from the Transformers (BERT) model. Among them, the BERT model can accurately enumerate the semantic information of words, making the words computable with each other (Mikolov et al., 2013), thus greatly reducing the errors caused by manual coding. Therefore, this study is expected to provide a reference for the evaluation ideas of marine pollution governance policies in developing countries, and it is also hoped further to improve the scientific quality of policy synergy evaluation.

3 Methodology

3.1 Research framework

In this study, an x-y two-dimensional theoretical analysis coordinate system was first established, as shown in Figure 1. The degree of collaboration between the policy subject departments and the consistency of policy content themes are used as evaluation indicators of policy synergy. The x-coordinate represents the subject departments of the policy, and the y-coordinate represents the types of themes that the policy focuses on. In the second step, we will observe the performance of each government in the department synergy dimension by each government that implements the policy. At the same time, the degree of synergy among governments in the content dimension is calculated by observing the focus of each government on different themes. Policy synergy can be divided into

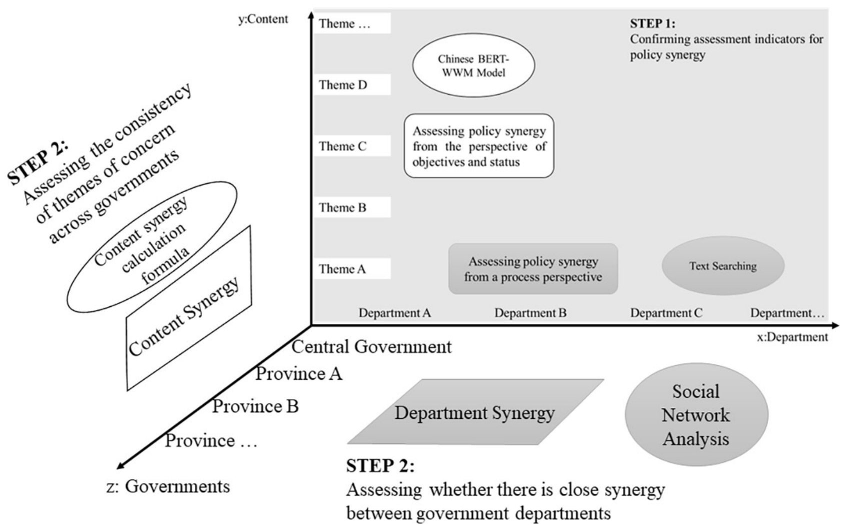

FIGURE 1
Research Framework.

intra-organizational synergy and inter-organizational synergy (Meijers and Stead, 2004). When we take the government as the organization, the departmental synergy dimension is then an evaluation of intra-organizational synergy and the content synergy is an evaluation of inter-organizational synergy.

The subject departments are the policymakers and implementers. The closeness of collaboration between policy subject departments will be related to whether the policy synergistic process can be carried out smoothly. In this study, the social network approach is used to observe the closeness of interdepartmental collaboration. This paper draws on the research idea of Liu and Wang (2022) to reflect the degree of synergy among policy subject departments using the network density indicator in social networks.

The degree of policy theme consistency captures whether all governments are working toward the same objective. At the same time, the redundancy status of policy content is also assessed. The policy theme is a high-level summary of the core content, basic thrust, and achievement of the policy text. It can reflect the allocation of attention to the policy (Xiao et al., 2022b). Pollution externalities allow governments to be consistent in their policy themes. This study first generates policy themes using the BERT model, and then draws on the synergy calculation method of (Liu and Wang, 2022) to derive the degree of policy theme content synergy among governments.

3.2 Quantitative criteria of department synergy evaluation

This study uses the social network analysis method to analyze the degree of policy department synergy. Social network analysis is a commonly used research method for the construction and analysis of interdepartmental collaboration networks (Liu and Wang, 2022; Ye and Wu, 2022). First, we extract the policy promulgator from the policy text by constructing regular expressions, count the frequency of pairwise collaboration among policymakers and implementers, and construct the co-occurrence matrix of the subject department. Second, we use Gephi to analyze the co-occurrence matrix and illustrate the policy structure of the subject departments. Gephi is a software for social network analysis. Due to its excellent visualization capabilities (Deng, 2014), Gephi is widely used to analyze the relationships between network nodes (Shen et al., 2021; Yao et al., 2023).

In the indicator of policy structure, network density represents the ratio of the number of relationships to the total number of possible relationships between nodes in the network. The greater the network density, the more likely it is to be considered a cohesive community (Wise, 2014), and the higher the department synergy. So, we use the network density (ED) index to measure the degree of department synergy, and the calculation formula is shown in Equation (1).

$$ED = f/n \times (n+1) \tag{1}$$

Where n represents network size and f represents network link frequency.

At the same time, we use node degree centrality and eigenvector centrality to measure the importance or influence of a single department in the network. The former assumes that the importance of a single department depends on the number of departments that it works with (Zhang and Luo, 2017), and the latter assumes that the importance of a single department depends not only on the number of departments it cooperates with, but also depends on the importance of departments it cooperates with (Ruhnau, 2000). The node degree centrality d_i is as Equation (2), and the node eigenvector centrality $EC(i)$ or x_i is as Equation (3).

$$d_i = \sum_{j=1}^{n} a_{ij} \tag{2}$$

$$EC(i) = x_i = c\sum_{j=1}^{n} a_{ij}x_j \quad (3)$$

Where a_{ij} indicates node i is connected to node j , c is a constant.

3.3 Quantitative criteria of content synergy evaluation

Third, we explore the content synergy between local government and central government. Generally, a person's cognitive tendency is mainly reflected in the words they often use. The change in the frequency of word use reflects the change in a person's attention to specific things (Liu and Wang, 2022). Similarly, the direction of focus on policy content is always reflected in the vocabulary used by the publisher. Furthermore, in computational linguistics, the semantics of words are usually embedded into word vectors according to their co-occurrence relationship (Hamilton et al., 2016) and the encoding process is called word embedding. Therefore, in this paper, we use the word embedding model combined with the clustering method to calculate the words contained in different themes and then calculate the synergy of the same theme between different provinces and the central government.

3.3.1 Theme generation

The starting point of the content synergy evolution is to establish the mapping relationship between policy themes and words with the help of natural language processing methods. In the past, most researchers used the Latent Dirichlet Allocation (LDA) topic clustering method (Blei et al., 2003; Hills et al., 2021) to analyze the policy content, and obtained the corresponding words contained in each topic by assuming that each policy text was represented by a multinomial distribution of themes. The disadvantage of this method is that it uses bag-of-words to represent policy text, ignores the order of words and deep semantics, and has limited semantic representation ability (Le and Mikolov, 2014). To optimize this drawback, this paper uses the word embedding model to characterize the semantic information of the text. The core idea of the word embedding model is the distributional hypothesis proposed by (Rumelhart and McClelland, 1987), which means the semantics of a word are characterized by its context. As a result, the vector representation corresponding to each word is obtained with the help of the word embedding model. Semantically close words are also more intimate in the vector space. In other words, words with similar semantics have smaller vector distances. Furthermore, the vector distance between two words can be calculated, following the computational principle of "the distance between words within a cluster is as close as possible, and the distance between clusters is as far as possible" to obtain semantically similar word clusters, i.e., text themes. The above is the computational idea of clustering (Sinaga and Yang, 2020). Therefore, the paper uses the method of "word embedding + word clustering" to calculate theme clusters on words. The whole process of numerical calculation is led by the semantics of words, thus greatly reducing manual errors.

For the Natural Language Processing (NLP) task of Chinese word embedding, the current commonly used language representation learning models, such as Word2Vec (Church, 2017), Glove (Pennington et al., 2014), ELMO (Peters et al., 2018), cannot sufficiently represent the word polysemy in the Chinese language. With the emergence of pre-trained language models, the representation of word embeddings has been improved to be more accurate. Among them, the most representative is the BERT (Bidirectional Encoder Representation from Transformers) model (Devlin et al., 2019), which can learn general language representation from a massive corpus without manual labeling, and capture the potential grammatical and semantic information in the text. However, the BERT model is more prominent in the word embeddings of English than in Chinese. The semantic understanding in the Chinese field is different from that in English. Therefore, we choose the BERT-WWM (Bidirectional Encoder Representations from Transformers-Whole Word Masking) pre-trained language model (Cui et al., 2021) that is more suitable for Chinese to obtain Chinese word embeddings.

Next, through the method of "word embedding" combined with "K-means clustering" to obtain the "theme-vocabulary" correspondence. Each cluster contains different words and represents a policy theme. Then, draw all the groups into a word cloud map conducive to manual screening, summarize each theme into several major themes, and discard themes with poor clustering effect. The overall process is shown in Figure 2. In particular, the "sub-topic" in the graph is obtained by the following "theme cluster" method, and the higher-level topics are obtained by manual summarization.

3.3.1.1 Word embedding

To get word embeddings more suitable for the Chinese language style, the Chinese BERT-WWM model performs [MASK] action on the phrase during the training process. The model consists of the Embedding layer and the Transformer layer. The training process mainly includes the following steps:

Firstly, define the input sentence of the model as $e=(e_1,e_2,\dots,e_n)$, where e_i represents the i_th word of the sentence, and n represents the length of the sentence.

Second, calculate the Token Embeddings, Segment Embeddings, and Position Embeddings of the sentence e in the Embedding layer, and then sum the above three to get the input sequence $T=(t_1,t,\dots,t_n)$.

Finally, input the sequence $T=(t_1,t,\dots,t_n)$ into the Transformer layer to extract features, and obtain the output sequence $h=(h_1,h_2,\dots,h_n)$ with rich context semantics as the subsequent word embeddings for theme clustering. The Chinses BERT-WWM model framework is shown in Figure 3.

The research used the Chinese RoBERTa-wwm-ext-large pre-trained language model to further improve the effect of word embedding. Based on the Chinese BERT-WWM model, the model has further increased the amount of training data, and finally trained the model on a 5.4B vocabulary including Chinese Wikipedia. At present, it is in SOTA in many Chinese NLP tasks (Cui et al., 2021) and can obtain word vectors with richer semantic information.

3.3.1.2 Theme cluster

Then, we use the K-means algorithm to perform cluster analysis on the word vector results generated by the Chinese BERT-WWM model. Suppose the input sample set of the K-means algorithm is

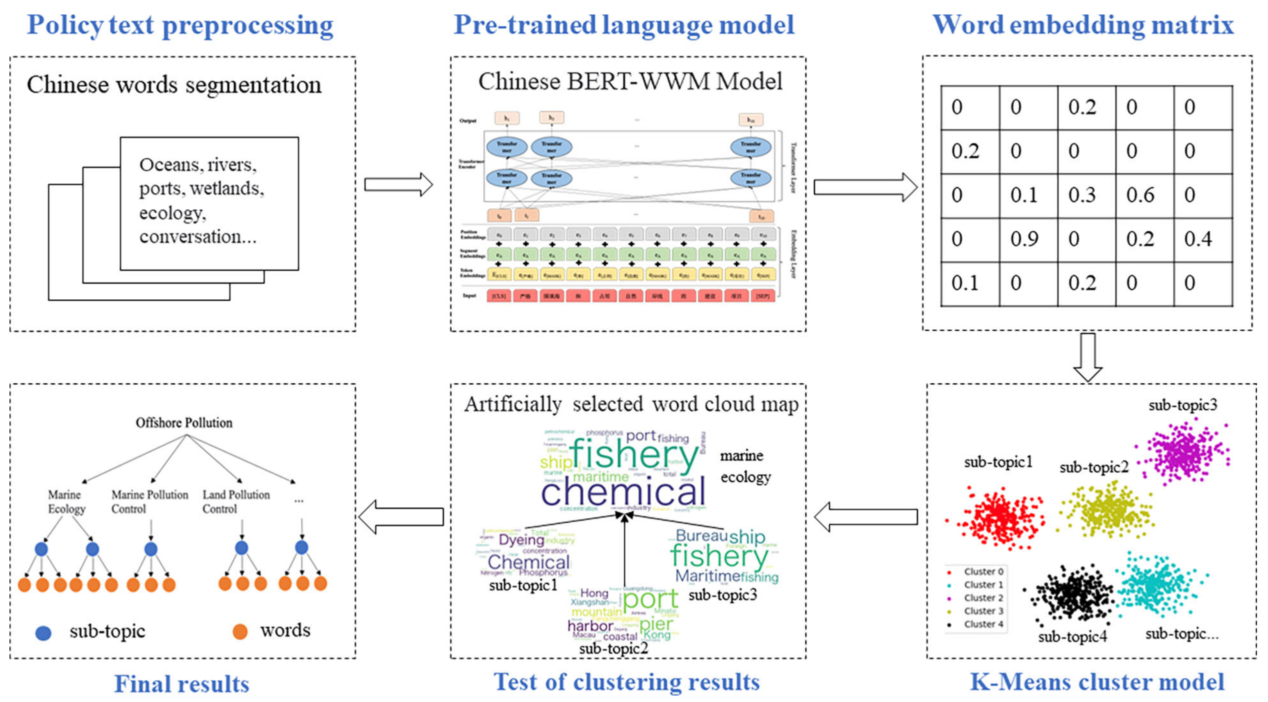

FIGURE 2
The process of generating different themest.

$K=\{K_1,K_2,\ldots,K_m\}$, the number of clusters is k , and the algorithm stops after N iterations. The specific operation steps are as follows:

Step 1: k samples are randomly selected from the data set K as the initial k centroid vectors $\{v_1,v_2,\ldots,v_k\}$;

Step 2: For each iteration $n=1,2,\ldots,N$, perform the following operations:

(i) Initialize the entire cluster C to subcluster $C_t=\{c_t\}(t=1,2,\ldots,k)$.

(ii) For $i=1,2,.,m$, calculate the distance $d_{i,j}=K_i-v_j$ between the sample K_i and each centroid vector $v_j(j=1,2,\ldots,k)$ respectively, and mark the smallest distance $d_{i,\ j}$ as K_i belong to category j, then update $V_j=V_j\cup\{K_i\}$.

(iii) For $j=1,2,\ldots,k$, recalculate the new centroid $v_j=\frac{1}{|v_j|}\sum_{x\in V_j}K$ for all samples in V_j .

(iv) If the positions of the k centroids have not changed, then end the algorithm and go to Step 3.

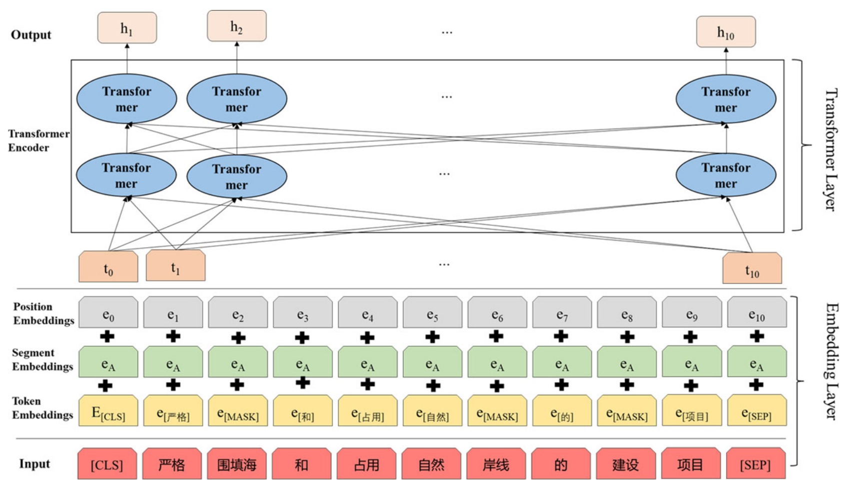

FIGURE 3
The Chinese BERT-WWM model framework.

Step 3: The output cluster is divided into $V=\{V_1,V_2,\ldots,V_k\}$.

Step 4: According to the silhouette coefficient metric, we choose the number of clusters with the best clustering effect.

Thus, the subtheme corresponding to each word is obtained. Then it needs to be manually organized into major categories of themes.

3.3.2 Calculation of content synergy degree

We classify government policy texts by government to form a database for the content synergy evaluation. The content synergy degree is calculated based on the proportion of keywords in the total word frequency(Liu and Wang, 2022), as follows in Equation (4), Equation (5):

$$S_{wyp} = \frac{\sum_{w=1}^{n} n_{wyp}}{\sum_{w=1}^{\infty} n_{wyp}}, \quad w \neq 0, \quad y \in [1,2,3,\ldots,m] \tag{4}$$

$$Z_{wyp} = \prod_{y=1}^{m} \frac{S_{wyp}}{S_{wy}}, \quad w \neq 0, \quad y \in [1,2,3,\ldots,m] \tag{5}$$

where w represents the keywords of the policy, y represents a policy theme dimension (i.e., safeguard measures). m represents the number of policy theme dimensions, p represents the government. n_{wyp} represents the total frequency of the policy keywords of dimension y of the government p , S_{wyp} represents the intensity of policy of dimension y of government p , S_{wy} represents the intensity of the policy for dimension y in all governments. S_{wyp}/S_{wy} characterizes the content synergy of that government p on dimension y , reflecting how much that government's focus on that dimension is consistent with the nation as a whole. Z_{wyp} represents the total content synergy degree of government ps.

4 Empirical research

4.1 Data collection

This paper focuses on the policy synergy of COPPCP in China. The COPPCPs of the central government and 11 coastal provinces were collected. China's mainland coastline is over 18,000 km (Figure 4). The coastal provinces have issued similar policies in their respective provinces after the COPPCP of the central government was promulgated. The governmental structure of each Chinese province varies, and each has a different list of tasks. The problem of scattered department structures is representative of developing countries and at the same time brings to light the need to evaluate the degree of policy synergy. Most of these policies were enacted under the guidance of the COPPCP issued by the Chinese central government in 2017. The standardized structure of the texts makes it feasible to evaluate the degree of policy synergy in these 12 texts.

4.2 Analysis of department synergy degree

After constructing the synergistic network of policy subject departments in the 12 COPPCPs, three types of synergistic networks with different structural characteristics were observed, as shown in Figure 5. The node size in the figure represents the value of the eigenvector centrality. A darker color means that the node is connected to more other nodes and the node has a greater degree. The three synergistic networks are represented by the department synergy networks of Shandong, the central government, and Shanghai. Shandong's synergy network has only

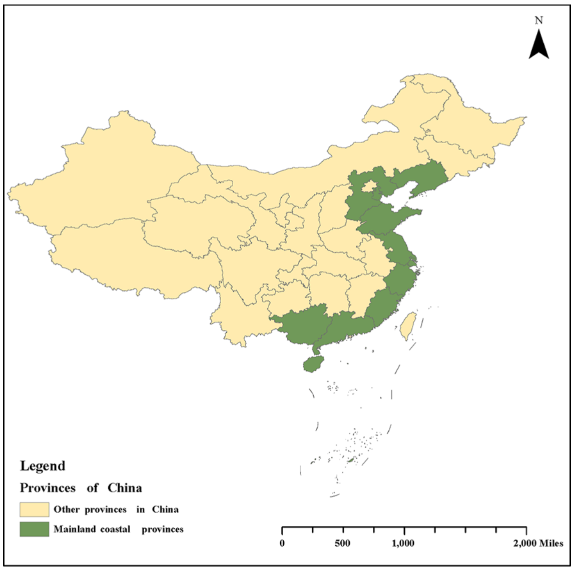

FIGURE 4
Coastal provinces in mainland China.

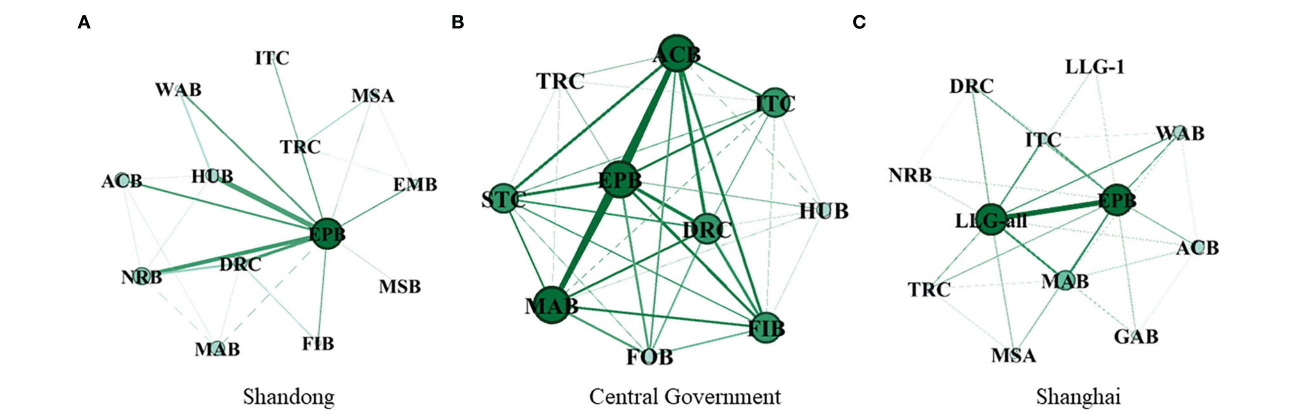

FIGURE 5
Three types of synergy networks: **(A)** Single-core government, **(B)** Multi-core government, **(C)** Vertical synergistic government.

the Environmental Protection Bureau (EPB) as the core, and the others are in a position to be led. The central government's synergy network is polycentric in nature, with the EPB, the Agricultural Commission & Bureau (ACB), and the Marine Bureau (MAB) occupying the network's central position. On the other hand, the synergistic network in Shanghai emphasizes the centrality of the lower-level government (LLG), and vertical synergy between the upper and lower levels features prominently.

According to the characteristics of the network structure, we can call the governments similar to the synergistic networks in Shandong, the central government, and Shanghai as single-core government, multi-core government, and vertical synergistic government, respectively. The synergistic networks of other provinces all belong to these three types respectively, and due to the limited space of the article, the synergistic networks of other provinces are presented in the Supplementary Image.

The types of collaborative networks can also be distinguished under network density, as shown in Table 1. The central government shows the highest density of department synergy networks. On the one hand, it reflects more cores in the network, and on the other hand, it reflects the close collaboration relationship between departments. It can be seen that the central government of China attaches importance to the COPPCP synergistic process, emphasizing the joint action of multiple departments. Hebei and Shandong fall into the same category. The network is centered on the environmental protection department, resulting in a single core government with low density. There needs to be stronger interdepartmental synergy among policy subject departments. The single core government is mostly in the northern provinces of China. Most of the northern provinces are manufacturing concentrated provinces, and pollution is more serious. Environmental protection has always been an important government work that the northern provinces are concerned about. This is the real reason why the EPB is getting attention. The network density of vertical synergistic government lies between that of the central government and that of Shandong province. The extent to which responsibilities are assigned to the next level of government affects the density of the synergistic network. For example, in Shanghai, most of the tasks of marine pollution prevention and control are assigned to the next level of government as well as the Environmental Protection Bureau, which is only a dual-core structure with a low network density. However, in Guangxi, each task is assigned to the next level of government as the responsible unit, with provincial departments assisting. This has resulted in a higher network density in Guangxi.

4.3 Analysis of content synergy degree

4.3.1 Theme analysis

We build a database of policy texts to be analyzed based on 12 policies. First, tokenize the policy text with Jieba Chinese word segmentation tool to obtain a list of all the words it contains. Then, input the sentence into the Chinese RoBERTa-wwm-ext-large pre-

TABLE 1 Departmental synergy network density.

Government	Network Density	Government	Network Density
Central Government	0.844	Zhejiang	0.567
Guangdong	0.742	Shanghai	0.500
Guangxi	0.705	Hainan	0.500
Liaoning	0.667	Hebei	0.489
Tianjin	0.667	Fujian	0.341
Jiangsu	0.667	Shandong	0.321

trained language model to get the word vector corresponding to the vocabulary list.

After obtaining the word vectors corresponding to each word, input it into the K-Means algorithm to obtain the category corresponding to each word. Subsequently, we conduct experiments in the range of the number of clusters [20-100] and select the cluster with the highest silhouette coefficient as the final number of themes. According to the performance in Figure 6, the clustering effect after the number of categories is 75 has little improvement, so we select the category 75 corresponding to the maximum silhouette coefficient as the final number of themes.

After filtering out clustering topics that do not cluster well or are too semantically broad or have no clear semantics, the above 75 categories were manually filtered to finally get 24 categories of keywords and summarized to get four major categories of themes. The four categories of themes are Marine Ecological Protection (MEP), Marine Pollution Control (MPC), Land-based Pollution Reduction (LPR), and Safeguard Measures (SAM). The characteristic words in each of the four categories of themes are shown in Figure 7. The four categories correspond exactly to the standardized framework of priority task safeguards in COPPCP. This illustrates the accuracy of the automatic theme clustering method. The keywords of MEP, MPC, and MPR are primarily words that characterize the problem objects and policy objectives. Observing these keywords can give us a glimpse of each government's objectives, expectations, and requirements in policy formulation. For example, MEP contains keywords such as oil well, wetland, and other marine ecological focus, MPC contains chemicals and other common pollutants in the ocean, and LPR includes target words such as environmental quality. SAM is a collection of keywords that can characterize policy tools and policy measures, such as monitor, register, network platform, etc. The four themes are identified so that the content of China COPPCP can be abstractly and precisely expressed.

Since each major category contains different subthemes, the frequency of the words contained in different subthemes varies. When selecting theme words based on frequency or ranking alone, it would result in the overall lower frequency subthemes being ignored. Therefore, we took the top 10 keywords of each subtheme as the nationally focused policy content. The main keywords for each theme are presented in the word cloud image, as shown in Figure 8. The size of the words in the cloud image is determined by word frequency. On the theme of MEP, there is a general national focus on resources, wetlands, and other words that characterize ecology. For MPC, there is a general national focus on ships, ports, and chemicals. For the LCR theme, the nation is generally concerned with land-based pollution from industries and companies. For SAM, most of the government's attention is focused on the terms of monitoring, license, and other command-and-control policy tools.

4.3.2 Theme synergy calculation

To fully demonstrate the content synergy, this study uses the change in the proportion of high-frequency words to reflect changes in policy concerns. Equation (1) and Equation (2) are used to quantify the degree of content policy coordination, and the results are listed in Figure 9. In this figure, the synergy among governments on the four content themes and the overall content synergy make up the five dimensions of content synergy evaluation. The value represents the degree of synergy in that dimension, and a value of 1 means that the policy content can be consistent with the overall national situation. On the whole, the policy contents of all governments can be consistent in the three themes of marine ecological protection, marine pollution control, and land-based pollution reduction. However, on the theme of SAM, the individual governments reflect different degrees of synergy. This, on the one hand, indicates the different degrees of importance attached to the safeguards of COPPCP among governments. On the other hand, it may also indicate the different policy tools used among governments. These two scenarios are the reasons for the variability in the degree of synergy.

In connection with the three government categories divided by the synergy network's characteristics in section 4.2, we conduct a comparative analysis of the content theme synergy situation. The three categories of governments show different distributions of theme synergy. The single-core government can keep in line with the overall national situation in MEP, MPC, and LPR, and the synergy degree is

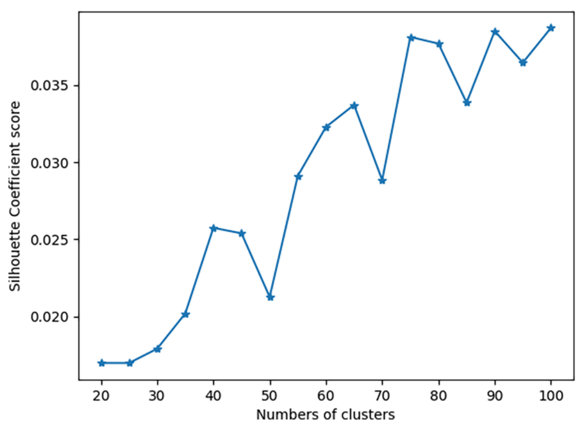

FIGURE 6
K-means clustering experiment process.

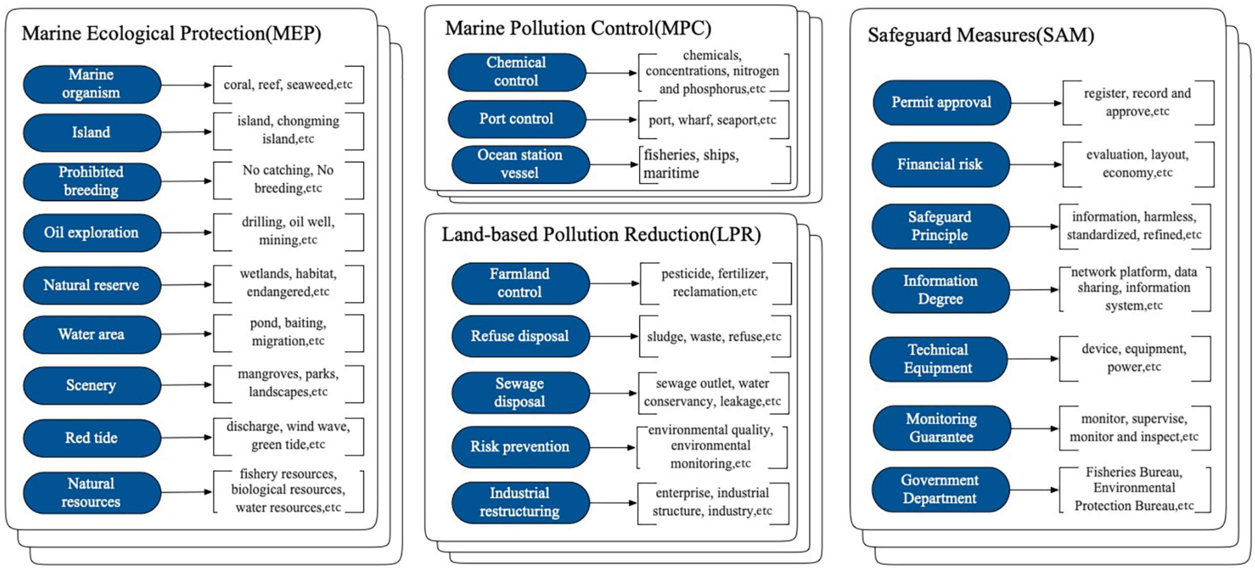

FIGURE 7
Theme Clustering.

close to 1. However, the attention to the theme of SAM is much greater than the overall national situation, and the synergy degree is higher than 1. The multi-core government is completely opposite to the single-core government. Regarding the SAM theme, the multi-core government was not able to align with the national picture as a whole. On the MEP, MPC, and LPR themes, the multi-core governments are able to align with the nation and even have an enhanced level of concern. The vertical synergistic governments show differentiation among themselves. Although these governments are able to align with the overall national picture on the MEP, MPC, and LPR themes, they show differences in the degree of synergy on the SAM theme. This differentiation draws our attention to the fact that provinces with different geographic locations have different concerns about policy themes. Liaoning is more similar to the governments around Bohai Bay, such as Hebei and Shandong, in terms of policy content, and focuses more on SAM. The SAM theme is mostly reflected in the command-and-control policy tools, which are in line with the reality of northern China that focuses more on the enforcement role of policies. Shanghai delegates responsibility for coastal ocean pollution prevention and control to lower levels of government, and the excessive focus on SAM provides a guarantee for this. Guangxi and Jiangsu pay less attention to SAM than the

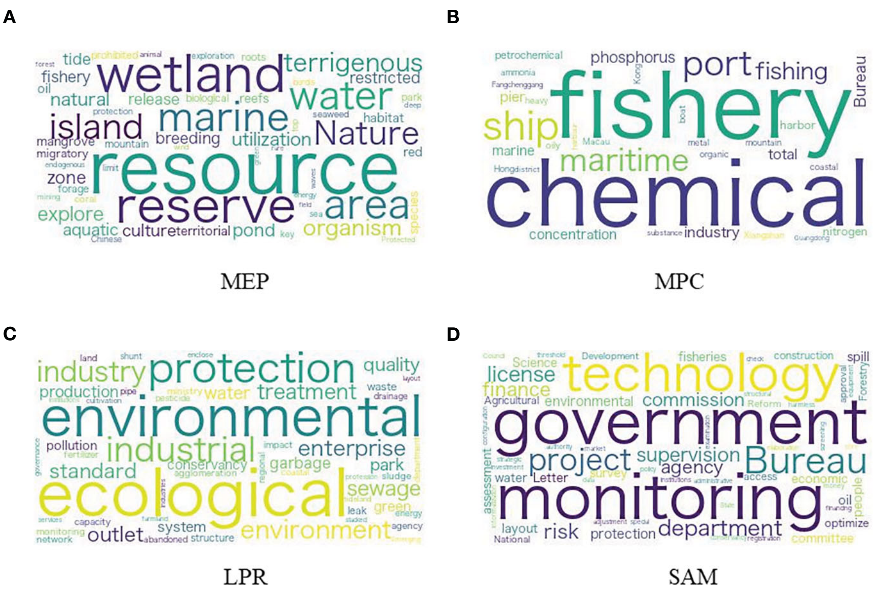

FIGURE 8
Cloud map of high-frequency words in the policy texts of governments: **(A)** High-frequency words in the MEP theme, **(B)** High-frequency words in the MPC theme, **(C)** High-frequency words in the LPR theme, **(D)** High-frequency words in the SAM theme.

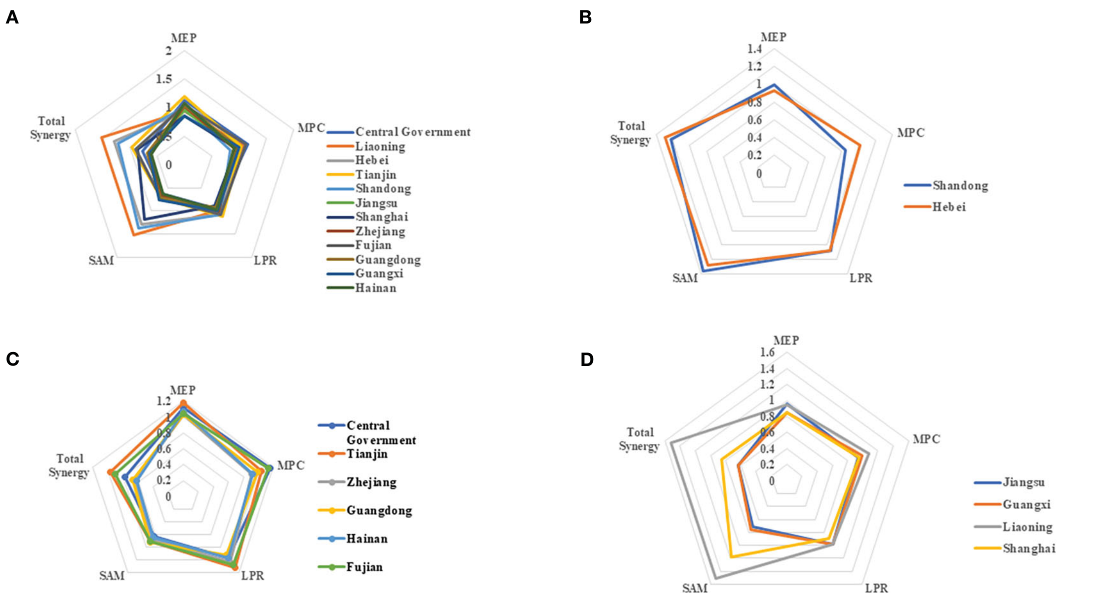

FIGURE 9
Content Synergy Distribution: **(A)** the degree of all governments, **(B)** the degree of single-core governments, **(C)** the degree of multi-core governments, **(D)** the degree of vertical synergistic governments.

country as a whole. This makes us aware that the two provincial governments may need more follow-up on the implementation of policy objectives, handing over both tasks and difficulties to lower levels of government.

5 Discussion

The policy synergy of COPPCP is an important component of marine pollution governance. In this paper, we use methods such as social network analysis and the Chinese BERT-WWM model to evaluate policy synergy in two dimensions: subject department and content theme.

Through the construction of the department synergy network, we evaluated the policy synergy from a process perspective. This study finds that the overall degree of department synergy of COPPCP in China is low. The results are similar to previous studies on the synergistic measurement of haze pollution management policies (Li and Ye, 2021), which indicates that the environmental governance structure in China still needs to be improved. The current policy synergy process of China's COPPCP still needs to be improved. The characteristics of the inter-governmental department synergy network structure vary widely, and the consistency of actions is weak. According to the synergy network structure, governments can be divided into three types: single-core governments, multi-core governments, and vertical synergy governments. The coexistence of multiple government types reflects the current reform of China's governmental governance system toward polycentric governance (Yu and Cui, 2021). The policy synergy process of polycentric governance will cross the administrative limits of the domain and is consistent with integration from an ecosystem perspective (Soma et al., 2015). At the same time, by drawing on the studies of ship transportation optimization problems that have fully taken into account regional synergy factors, it is foreseen that the process of future policy synergy will also need to take into account the economic demands of enterprises in different regions, the coast, and port conditions (Xu et al., 2021a; Xu et al., 2022a; Xu et al., 2022b). Meanwhile, the popularity of COVID-19 also intensifies the complexity of the policy synergy process (Xu et al., 2022c). In addition, the structure of the synergy network can reflect the COPPCP focus of each location. Northern governments are mostly synergy networks with EPB as a single core, which is a result consistent with the current reality of more serious pollution in Bohai Bay.

Through the clustering of content themes and the calculation of content synergy, we evaluated the policy synergy from the objective and status perspectives. Through objective quantitative calculations of the BERT model, we derived four major themes. The four major themes fit with the COPPCP standardized framework, which can prove the reliability of the method. In the synergy calculation, Chinese coastal provinces were able to maintain synergy in the MEP, MPC, and LPR themes. These themes mostly contain keywords that reflect the policy objectives. It can be seen that the objectives of the Chinese government regarding COPPCP are able to achieve synergy. However, regarding the SAM theme, it is difficult to reach an agreement among the various governments. The keywords in SAM reflect more the type of policy tools. Therefore, it is difficult for governments to agree in policy tool synergy and the status of policy synergy is difficult to maintain. In addition, single-core governments, multi-core governments, and vertical synergy governments show different characteristics in terms of policy content synergy. Single-core governments have higher synergy in SAM compared to the other two types of governments. This partly indicates that the concentration of power can better leverage the power to solve problems rather than just setting objectives (Luo et al., 2019). It can be seen that each government is choosing different policy tools according to its own situation. Drawing on research in other fields (Xu et al., 2021b), we believe that the establishment of information platforms or specialized integrated governance departments for pollution prevention and control in the coastal ocean will be necessary to maintain the state of policy synergy.

The contribution of this paper is to highlight the study of policy synergy in the coastal ocean for pollution prevention and control, which is not available in previous marine pollution governance studies. This study evaluates policy synergy from the objective, process, and status perspectives, which is more credible than previous empirical studies under the outcome perspective. In addition, the BERT-WWM model is used to replace the manually coded content analysis method in previous policy synergy studies, and the advantage of methodological objectivity is obvious.

6 Conclusion and insights

The issue of policy synergy evolution is highlighted as a necessity in current research on marine pollution governance in developing countries. This study uses a two-dimensional evolution framework of policy subject department and policy content theme to analyze the policy synergy degree for COPPCP in China. The objectives, status, and process of policy synergy are observed. This study finds that the current degree of synergy among Chinese coastal provinces and central government departments is poor overall, and the policy synergy process lacks vitality. Consistent policy objectives can be established among governments in marine ecological protection, marine pollution control, and land-based sources of pollution reduction. However, it is difficult to achieve synergy in the policy tools reflected in the safeguard measure theme. The content themes are not fully consistent across governments making the state of policy synergy poor. Both inside and outside the organization faces obstacles to policy synergy. This may be an impediment for the current COPPCP to play a greater role.

The synergy network of subject departments and the degree of content theme synergy obtained from the evaluation of this study can help the Chinese government to further improve COPPCP.

(1) The degree of interdepartmental linkages within the single-core government is weak and should be strengthened. Environmental protection departments in Shandong and Hebei have been effective in leading the fight against pollution but should take into account both economic and environmental benefits. If the transition to a circular economy is promoted, the economic department should take more responsibility for the prevention and control of pollution in the coastal ocean in the future.

(2) The degree of policy tool synergy among governments is weak. The traditional governance concept of relying only on the control-command tool should be abandoned. With the concept of service-oriented government being advocated today, coastal provinces should try more fundamental solutions to marine pollution. Policy tools such as technology, awareness, and education should be promoted.

(3) The objectives are consistent, but there is a need for a sound mechanism to ensure that these objectives are achieved. Chinese provinces are able to achieve objective synergy in marine ecological protection, marine pollution control, and land-based sources of pollution reduction. And some provinces already have a department synergy network with polycentric governance. This is a good starting point. Next, a joint marine governance department can be considered between different regions, which will help further the integration of resources and guarantee the smooth achievement of objectives.

This study still has limitations. This study provides an evolution method of policy synergy. In the field of coastal ocean pollution prevention and control, issues such as policy synergy mechanisms and influencing factors of policy synergy still need to be explored by subsequent researchers.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Official websites of China's coastal provinces and the central government, such as "The notice on the issuance of ' Coastal Ocean Pollution Prevention and Control Program' (2017) Official website of the Ministry of Ecology and Environment of the People's Republic of China. Ministry of Ecology and Environment of the People's Republic of China. Available at: https://www.mee.gov.cn/gkml/hbb/bgth/201704/t20170419_411769.htm (Accessed: October 12, 2022).

Author contributions

CY: Conceptualization, Data Curation, Formal analysis, Visualization, Writing - original draft. MS: Methodology, Writing - original draft, Writing - Review & Editing. LL: Conceptualization, Supervision, Validation. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1131590/full#supplementary-material

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International cruise research advances and hotspots: Based on literature big data

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This paper makes a systematic visual analysis of cruise research literature collected in science network database from 1996 to 2019. The results show that: the overall number of published literatures on cruise research are growing; North American states, Europe, and Asia are the main regions of cruise research. The evolutionary of theme development of cruise research has three stages, and the current hot topics of cruise research can be summarized as cruise tourism, luxury cruises, cruise passengers, destination ports, environmental and biological conservation, and cruise diseases. Future research in the cruise field is in the areas of cruise supply chain, technology in cruise, children's cruise experience, itinerary design, planning and optimization, brand reputation and luxury cruises, public transportation in destinations, environmental responsibility of passengers and corporate social responsibility, optimization of energy systems, climate change in relation to the cruise industry, the Chinese cruise market and risk management of cruise diseases.

KEYWORDS

cruise ship, Citespace, low carbon, sustainability, cruise tourism market

1 Introduction

As the fastest growing sector of the global tourism industry, Cruise tourism has drawn extensive attention. Over the past 40 years, although the global economy has experienced many economic recessions and fluctuations triggered by various factors, the number of cruise passengers has maintained an average growth of about 7%. According to data provided by the Cruise Lines International Association (CLIA), the number of passengers carried by the cruise industry has increased 9.9 million in 2001 to 28.5 million in 2018 (China.com, C, 2019; Hong, 2019). The cruise industry plays an important role in the global economy, creating 1,177,000 jobs, sending out $50.024 billion in payroll and generating $150 billion in global revenue in 2018 (China.com, C, 2019).

In 2020, the wide-spread of the novel coronavirus has resulted in the loss of about 1.1 billion international tourists, a drop in export earnings of between $91 billion and $1.1 trillion and the loss of between 100 million and 120 million jobs (Personal and Archive, 2020). Although the novel coronavirus pneumonia has caused the global cruise market to temporarily suspend, it has not changed the long-term upward trend of the global cruise market. The Cruise Lines International Association (CLIA) is optimistic about the prospects of the cruise tourism market. It predicts that the global cruise market will reach 37.6 million in 2025, with good development prospects and market potential (Hong, 2020).

In terms of specific destinations, the Caribbean and the Mediterranean are still the two most popular cruise destinations in the world (Wondirad, 2019). On the other hand, Asia, Australasia and the Pacific are the fastest growing cruise destinations in the world (Wondirad, 2019). In recent years, the cruise tourism industry has shown extraordinary growth, and gradually become popular among Asian tourists (Chen, 2016). Due to its rich tourism resources and huge potential tourism market, cruise tourism has gained rapid development momentum in Asia (Ma et al., 2018). The direct economic contribution of cruise industry to Asian economy reached 3.23 billion US dollars (Wondirad, 2019). Nevertheless, this rapid growth has been tested by huge challenges such as infrastructure constraints, lack of expertise, inadequate marine expertise, insufficient government commitment and environmental sustainability issues (Sun et al., 2014; Ma et al., 2018).

The cruise industry involves a wide range of sectors and industries, including manufacturing, tourism, finance, commerce, shipping and logistics, and is connected by cruise routes and ports to form a vast regional and global network economy, a process that has far-reaching social, economic and environmental impacts on both source and destination regions (Vega-Muñoz et al., 2020). Cruise research has developed a diverse range of research centers from various levels and perspectives. A review of the research literature in the cruise field reveals that, for the time being, no scholars have conducted systematic bibliometric research on the cruise field as a whole.

To this end, this study aims to comprehensively analyze the global references related to cruise research in the WOS database from 1996 to 2019. Specifically, this systematic review study intends to:

1) Examine the research trends in the field of cruise ships;
2) Analyze the pre-existing knowledge according to the research background of the literature, the author, the organization and the country to which it belongs;
3) Explore the leading cruise research topics in the past 24 years;
4) On the basis of literature analysis in the past 24 years, discuss future research trends in the cruise field, and provide reference for in-depth research.

2 Data sources and methodology

2.1 Data sources

The source of literature data is Web of Science Core Collection. The WOS Core Collection is a collection of authoritative and influential academic journals from around the world, covering a wide range of disciplines, and is characterized by high quality, large quantity and time span, and complete documentation (Moreno-Guerrero et al., 2020). The data retrieval is carried out by using the fields of "TI = cruise ship* \cruise* \cruise line*, etc. and TS = cruise ship* \cruise* \cruise line*, etc." In order to ensure the representativeness of documents, "Document Types = ARTICLE OR REVIEW" is set to refine and articles unrelated to cruise research and whose authors are unknown are removed. After that, 437 valid documents between 1996 and 2019 are obtained. The above search was conducted before January 1, 2020.

2.2 Methodology

CiteSpaces is a widely used tool in bibliometric research. It is written by a java program developed by Dr. Meichao Chen (Chen, 2006) to generate a visual knowledge graph composed of different lines and nodes, such as countries, organizations, authors, cited authors, and keywords. The CiteSpace software requires the setting of relevant queues before the data can be visually analyzed. In this study, the time span is set to 1996-2019, the time division is set to one year, the data extraction object is selected as Top50, and the other options remain in the default state. Citations, countries, authors, institutions, keywords and other options are selected to perform bibliometric visualization analysis.

3 Statistical results of cruise research literature

3.1 Trend of the number of publications

Figure 1 shows the regression model of the number of articles published from 1996 to 2019 established by using STATA software. It can be seen from the model that the number of articles published in the cruise field has increased significantly, and the time series of articles published in WOS has been adjusted by 69.7%. As can be seen from the scatter on the graph, there is a reasonable fluctuation with an upward trend in the number of publications. The fitted trend line shows that the growth in the literature was at a low level from 1996 to 2004, with an annual average of less than four articles; the number of publications grew slowly from 2005 to 2012, with an annual average of nearly 11 articles; and grew rapidly from 2013 to 2019, with an annual average of nearly 47 articles.

3.2 Analysis of countries and organizations

The network map of the co-author's country/region contains 80 nodes and 104 lines (Figure 2A). A total of 437 articles were published in 80 countries/regions from 1996 to 2019, with contributions ranging from 118 articles (27.0%) to 1 article (0.2%). The United States not only has a high volume of publications (27.0%), but also a high centrality (0.96). This

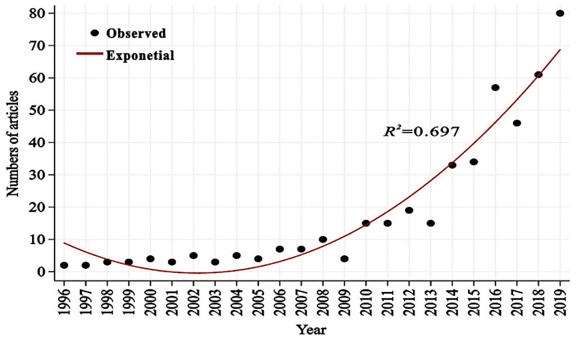

FIGURE 1
The number of articles in international cruise research published in 1996-2019.

indicates that the US maintains extensive collaborations with many countries (such as China, Italy, Spain) and American researchers have achieved some significant achievements and made important contributions to the field. Both Italy and China have higher publication volumes than Korea, but both have lower centrality than Korea. The volume of publications is not positively correlated with centrality in most countries. According to the centrality, Canada and Greece should strengthen international academic cooperation with other countries.

As far as the regional distribution of research publications is concerned (Figure 3), the countries to which the published literature belongs are mainly concentrated in Europe, and the countries with more publications are concentrated in North America and Asia, which is consistent with the market phenomenon of the global cruise industry. The global cruise market is mainly concentrated in the Caribbean, Asia & Pacific, Mediterranean, Northern Europe, Western Europe, Australia, Alaska and other regions, with these six regions accounting for 85% of the market share. According to the intercontinental division, the six regions can be divided into North America, Europe, Asia and other regions (Hong, 2019; Vega-Muñoz et al., 2020).

Creating and analysing a knowledge map of an organization's network not only provides valuable information, but also helps organizations to build and develop collaborative relationships.

The following organizations have made important contributions to the research in the entire field: University of Genoa (20 articles), University of Sejong (13 articles), and University of Valencia (11 articles). From Table 1, we can see that the centrality of these organizations is low. From Figure 2B, it can be seen that there are only four sub-networks in the cooperation network of research organizations, with a low network density, a loose overall structure and a high cooperation degree gap. The largest collaborative network is made up of 12 research organizations, including Sejong University and Hanyang University. Of these, Sejong University (Centricity = 0.07) is the organization with the highest network centrality, which has promoted academic cooperation in this field and has become the main force in promoting the development of cruise research.

3.3 Analysis of author collaboration networks and author co-citation networks

Figure 4A vividly maps the author's collaboration network in cruise research. The authors who excelled in terms of publications are Heesup Han (11 articles), Sunghyup Sean Hyun (10 articles), Silvia Sanzblas (8 articles), Daniela Buzova (8 articles) and Juan Gabriel Brida (8 articles), whose tireless efforts have contributed to the depth of cruise research. The author collaborative network consists of 13 collaborative groups. Among them, the two largest collaborative networks is a sub-network with 6 people including Heesup Han and a sub-network of 6 people including Juan Gabriel Brida, while the other collaborative relationships are mostly composed of 2-4 people.

Although there are multiple collaborative networks, the nodes do not have a purple outer circle, which indicates that these authors have low centrality and lack extensive collaboration with other scholars.

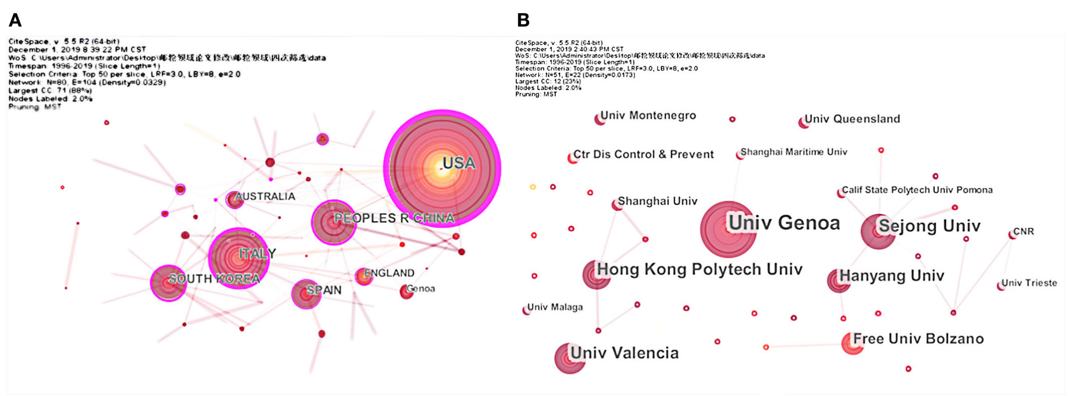

FIGURE 2
A visual map of countries/organizations in the cruise research: **(A)** the main countries in the cruise research; **(B)** the organizations in the cruise research.

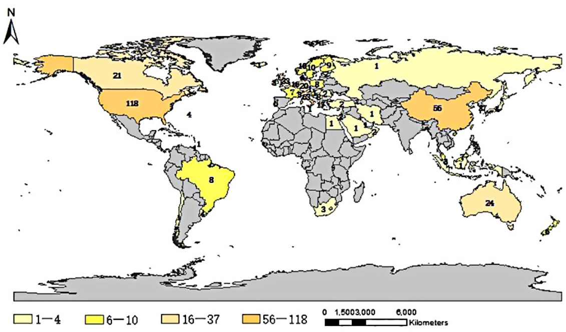

FIGURE 3
Global cruise research productivity contribution.

Table 2 summarizes the top 10 most cited authors. The larger nodes in Figure 4B have fewer peripheral links, indicating that the number of publications by cited authors is not proportional to centrality. Based on 437 articles, it is easy to find that the author who is widely cited by other scholars in this field is Brida JG, he applied three-step multivariable market segmentation analysis to study the characteristics and preferences of cruise passengers and the overall experience of passengers at the port of call, providing a reference for local managers to formulate policies (Brida et al., 2013). The second author, Petrick JF, conducted a meta-analysis of the direct economic impact of cruise tourism, with significant positive coefficients between the direct economic impact and: number of passengers, number of crew, number of cruise lines, expenditure per passenger, and expenditure per cruise line. It was further found that cruise lines have a significant mediating effect on expenditure per passenger and per crew member in port destinations. Compared with the North American market, the direct economic impact of cruise tourism on the Caribbean market and other emerging market ports is significantly lower (Chen et al., 2019). The third author, Hung K, explores the differences between Chinese and British cruise tourism literature by reviewing 62 articles published in top English-language tourism and hospitality journals and 26 articles in leading Chinese journals, and discusses important research themes, methodological trends and future research fields (Hung et al., 2019). Most of the inner circles of these authors are from orange to dark red, indicating the rapid increase in citations of these authors in recent years. Their articles are more likely to provide ideas for some basic research and to guide scholars in establishing new perspectives on cruise research.

4 Content level dimension analysis of cruise research

4.1 Analysis of disciplines in cruise research

Figure 5 is a time zone view of the cruise research disciplines from 1996 to 2019, involving 47 disciplines. hospitality, leisure, sport & tourism, environmental science & ecology, business & economics, engineering, environmental sciences and environmental studies are the main disciplines of cruise research, accounting for 47% of the total. The year of the discipline in Table 3 indicates the time of the first concentration. As can be seen from Table 3 and Figure 5, Medicine, general & internal and infectious diseases were the basic disciplines in the early stage of cruise research. In recent years, cruise research has begun to involve marine engineering, environmental engineering, green & sustainable technology, energy & fuels, etc., which may be emerging disciplines for future research.

4.2 Analysis of references

Burst detection is an effective analysis tool that can be used to detect emergencies or important information within a specific period of time. Figure 6 shows the top 10 strongest citations detected by CiteSpace from 1996 to 2019.

In terms of time, the first two references highlight emerging trends in cruise research in 2005 and 2008, and the remaining

TABLE 1 Top ten countries and organizations in cruise research.

Rank	Count	TP [a]	Centricity	Country	Count	TP	Centricity	Organization
1	118	27.0%	0.96	USA	20	4.6%	0	Univ Genoa
2	63	14.4&	0.33	Italy	13	3.0%	0.07	Sejong Univ
3	47	10.8%	0.28	Peoples R China	11	2.5%	0	Univ Valencia
4	37	8.5%	0.4	South Korea	9	2.0%	0.01	Hong Kong Polytech Univ
5	33	7.6%	0.13	Spain	8	1.8%	0.02	Hanyang Univ
6	25	5.7%	0.11	England	7	1.6%	0	Free Univ Bolzano
7	24	5.5%	0.23	Australia	4	0.9%	0	Univ Montenegro
8	21	4.8%	0.06	Canada	4	0.9%	0	Univ Queensland
9	20	4.6%	0.14	Germany	4	0.9%	0	Ctr Dis Control & Prevent
10	17	3.9%	0.05	Greece	4	0.9%	0	Shanghai Univ

a: Total percentage.

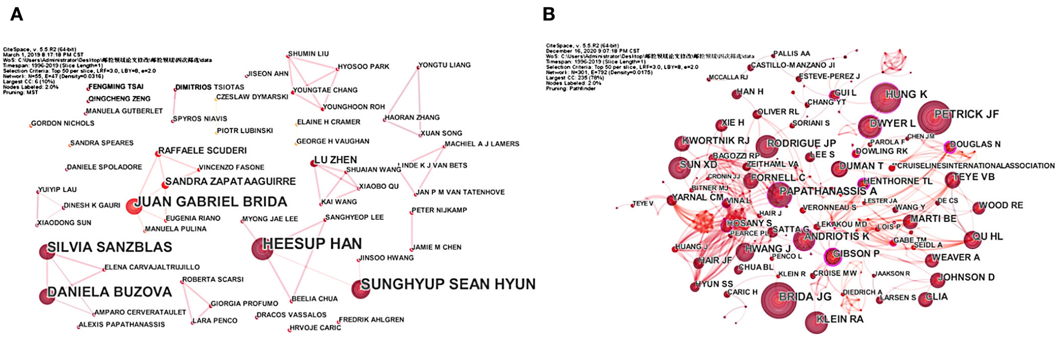

FIGURE 4
Visualization of authors in cruise research: **(A)** Collaborative network of lead authors in cruise research; **(B)** Cited authors in cruise research.

references highlight emerging trends in cruise research from 2012 to 2014. In 2005 and 2008, the most noticeable burst intensity of 4.6625 was written by Cramer EH. The outbreak started in 2008 and ended in 2014. This article assessed the correlation between the incidence of gastroenteritis on cruise ships and its outbreak frequency, and found that environmental programs cannot adequately predict or prevent common risk factors and the transmission of diseases between people (Cramer et al., 2006).

The three most cited strong citation burst intensities from 2012 to 2014 include Gabe TM (4.7849), Duman T (4.3353) and Petrick JF (4.3353). The subjects of the three literatures are cruise passengers, and they study the factors that affect the intention of cruise passengers to revisit the port community (Gabe et al., 2006); they segment the market based on the price sensitivity of cruise passengers to determine whether a price-sensitive market is needed (Petrick, 2005); In the context of the cruise vacation experience, they study the role of passengers' emotional factors (i.e. enjoyment, control and novelty) on value and the role of customer satisfaction in emotional value relationships (Duman and Mattila, 2005).

Overall, of the 10 references cited between 2005 and 2016, the longest citation time is 7 years, and the shortest is 2 years. However, there are no new strong citations on cruise research from 2017 to 2019.

5 Analysis of hot spots and their evolution in cruise research

5.1 Analysis of hot spots in cruise research

Since keywords are an accurate summary of the literature, analyzing high-frequency keywords can directly reflect the subject

TABLE 2 Top ten authors, cited authors and his high-frequency citations.

Rank	Count	Author	Frequency	Centricity	Cited author	High citation
1	11	Heesup Han	82	0	Brida JG	Cruise Passengers In A Homeport: A Market Analysis
2	10	Sunghyup Sean Hyun	78	0.05	Petrick JF	A Meta-Analysis Of The Direct Economic Impacts Of Cruise Tourism On Port Communities
3	8	Silvia Sanzblas	67	0.13	Hung K	An Overview Of Cruise Tourism Research Through Comparison Of Cruise Studies Published In English And Chinese
4	8	Daniela Buzova	55	0.12	Papathanassis A	Cruise Tourism Management: State Of The Art
5	8	Juan Gabriel Brida	54	0.11	Dwyer L	Economic Significance Of Cruise Tourism
6	4	Sandra Zapataaguirre	54	0.07	Rodrigue JP	The Geography Of Cruises: Itineraries, Not Destinations
7	4	Lu Zhen	52	0.13	Andriotis K	Cruise Visitors' Experience In A Mediterranean Port Of Call
8	3	Raffaele Scuderi	52	0.03	Sun XD	The Cruise Industry In China: Efforts, Progress And Challenges
9	2	Alexis Papathanassis	52	0.01	Klein Ra	Responsible Cruise Tourism: Issues Of Cruise Tourism And Sustainability
10	2	Spyros Niavis	43	0.1	Qu HL	A Service Performance Model Of Hong Kong Cruise Travelers' Motivation Factors And Satisfaction

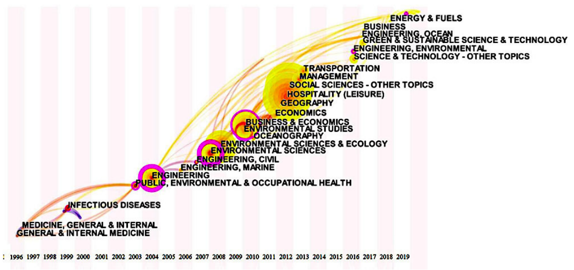

FIGURE 5
Time zone view of the cruise field disciplines. Purple means the node has good centrality; the time demonstration from 1996 to 2019 is represented by a blue to yellow gradient.

content and topical issues in the academic field. The bibliometric data shows that a total of 150 thematic keywords were covered in the cruise research. As shown in Figure 7A, the keywords with a high frequency are cruise ship, tourism, cruise tourism, satisfaction, model, impact, experience and port. The keywords with high centrality are ship, emission and intention.

In order to more clearly reflect the branch composition of cruise research, a cluster analysis of subject terms was performed, and the cluster view was selected on the basis of the original operation to form 8 clusters (Figure 7B). The Q = 0.7345 and S = 0.7553 of this cluster indicate that this cluster is significant and convincing.

Based on the above statistical analysis and the relevant literature, the hot topics of cruise research are classified into the following categories (Table 4).

5.1.1 Cruise tourism

The wide range of possibilities in music tourism, party tourism, hotel management and local city tourism and etc. form a comprehensive sailing experience (Hefner et al., 2014; Cashman, 2016; Paananen and Minoia, 2019). Cruise tourism is one of those tourism phenomena that has experienced significant growth but has not attracted much attention, a claim supported by the growing turnover, the number of passengers, the number of ships or ports in operation and the number of countries in operation (Vega-Muñoz et al., 2020). Cruise tourism has a double impact on the economy of the destination. On the one hand, the direct impact is generated by passengers, crew activities and land-based consumer spending, as well as revenues received by cruise lines and local suppliers that provide services to ports and ships (Chua et al., 2015). On the other hand, the indirect impact is the income generated by the increase in consumption within the scope of the tourism economy that is caused by the purchase of consumables and services from local suppliers and the increase in income generated from cruise tourism activities (Castillo-Manzano et al., 2015). In addition, there are also positive and negative impacts on local communities. Although theoretically increasing employment has led to income growth, little evidence of improvement has been found. On the contrary, cruise tourism has had a significant negative impact on the local environment, and local residents have also suffered from a large number of tourists invaded, and tourists often do not respect local customs, traditions and beliefs (MacNeill and Wozniak, 2018). Cruise tourism can also be studied in terms of the environmental impact of the increasing number and scale of ships, destination ports and cruise passengers, which are covered in the following themes due to cross-cutting and overlapping content.

5.1.2 Luxury cruises

With huge growth potential, luxury cruises are considered to be one of the most promising target markets. Factors such as perception of crowding, food quality, service quality and cabin quality have an impact on brand prestige, which in turn affects customer perception of well-being, brand recognition and loyalty (Hwang and Han, 2014; Hyun and Kim, 2015). In the brand community, the cruise brand, cruise products and the relationship with other cruise ships have a positive impact on the uniqueness of the brand (Shim et al., 2017). Brand tribalism has a positive effect on the formation of passengers' perceived consumer power, passengers' perception of consumer power influences their engagement, and engagement has a moderating effect on passengers' satisfaction, loyalty and perceived happiness (Han and Hyun, 2018; Lee and Kim, 2019). Satisfaction, loyalty, and the "conspicuousness" of product use affect travelers' purchase behavior

TABLE 3 Top 20 disciplines in cruise research.

Rank	Count	Year	Category	Rank	Count	Year	Category
1	133	2012	Hospitality, Leisure, Sport & Tourism	11	26	2016	Science & Technology - Other Topics
2	95	2007	Environmental Sciences & Ecology	12	23	2016	Green & Sustainable Science & Technology
3	74	2010	Business & Economics	13	22	2006	Engineering, Marine
4	66	2004	Engineering	14	22	2012	Economics
5	60	2007	Environmental Sciences	15	16	2006	Engineering, Civil
6	49	2010	Environmental Studies	16	16	2010	Oceanography
7	42	2012	Management	17	11	1996	General & Internal Medicine
8	34	2013	Transportation	18	10	2012	Geography
9	29	1999	Infectious Diseases	19	10	2016	Business
10	28	2003	Public, Environmental & Occupational Health	20	9	1996	Medicine, General & Internal

References	Year	Strength	Begin	End	1996 - 2019
WIDDOWSON MA, 2004, J INFECT DIS, V190, P27, DOI	2004	3.4038	2005	2008	
CRAMER EH, 2006, AM J PREV MED, V30, P252, DOI	2006	4.6625	2008	2014	
GABE TM, 2006, JOURNAL OF TRAVEL RESEARCH, V44, P281, DOI	2006	4.7849	2012	2014	
DUMAN T, 2005, TOURISM MANAGE, V26, P311, DOI	2005	4.3353	2012	2013	
SEIDL A, 2007, TOURISM ECONOMICS, V13, P67	2007	3.8147	2012	2015	
SEIDL A, 2006, PASOS, V4, P213	2006	4.2497	2012	2014	
PETRICK JF, 2005, TOURISM MANAGE, V26, P753, DOI	2005	4.3353	2012	2013	
LEKAKOU MD, 2009, TOURISMOS INT MULTID, V4, P215	2009	3.9348	2013	2015	
BRIDA JG, 2012, OCEAN COAST MANAGE, V55, P135, DOI	2012	3.5961	2014	2015	
KWORTNIK RJ, 2008, INT J CULT TOUR HOSP, V2, P289, DOI	2008	3.5977	2014	2016	

FIGURE 6
The ten most cited references in cruise research. The blue indicates the time interval, the red indicates the time period when the document is cited.

of products, and happiness perception affects travelers' willingness to pay for price premiums (Han et al., 2018; Yu, 2019).

5.1.3 Cruise passengers

The pleasure that cruise travel brings to cruise passengers is created primarily through emotional and relational experiences in the short term, with much of the long-term impact coming from the experience of thinking (Lyu et al., 2018). The difference of passenger culture is reflected in behavioral intention, satisfaction, emotional value, service quality, and etc. (Sanz Blas and Carvajal-Trujillo, 2014; Forgas-Coll et al., 2016; Li and Fairley, 2018). It is necessary for cruise lines or destination ports to reduce the gap between marketing and actual experience in order to increase passenger arrivals and increase revenue. Studying the relationship between elements such as passenger satisfaction, loyalty, and behavioral intentions, factors influencing the decision-making process, the volume and structure of passenger expenditures, and factors influencing willingness to pay (Sanz Blas and Carvajal-Trujillo, 2014; Chua et al., 2015; Chen et al., 2016; Lee et al., 2017; Bahja et al., 2019), and thus segmenting the market according to elements such as nationality, gender, age, satisfaction, perceptions of safety, and consumption patterns (Brida et al., 2013), can help planners and managers increase the likelihood of repeat visits and positive word-of-mouth. The design of the ship, the quality of the guide service and the design of the land excursions also affect the passenger experience (Oklevik et al., 2018; Dai et al., 2019; Buzova et al., 2019b). In addition, attitudes towards cruise travel are gradually shifting by age, with Gen Xers and Millennials becoming more optimistic about cruise travel (Wang et al., 2018; Cooper et al., 2019).

5.1.4 Destination ports

In a mature market, looking for new destinations to expand the catalogue offered by cruise lines to potential customers means that most new ports correspond to port areas in developing countries (Vega-Muñoz et al., 2020). In view of the positive impact of tourism on the ports of call and hinterland, it is necessary to analyze the factors of lines in port site selection (Vega-Muñoz et al., 2020). It is necessary for the cruise lines to evaluate the port's traffic, performance, safety risks and other factors before planning the itinerary (Kofjač et al., 2013; Vidmar and Perković, 2015). The studies of regional port focus on the Mediterranean. The port/terminal serves as a bridge between cruise lines, global operators, and local businesses and infrastructure. The study of port class, concentration, tourist satisfaction, cooperative competition, forms of governance, structure, strategy and other elements within the Mediterranean region (Kofjač et al., 2013; Vidmar and Perković, 2015; Cusano et al., 2017; Esteve-Perez and Garcia-Sanchez, 2018;

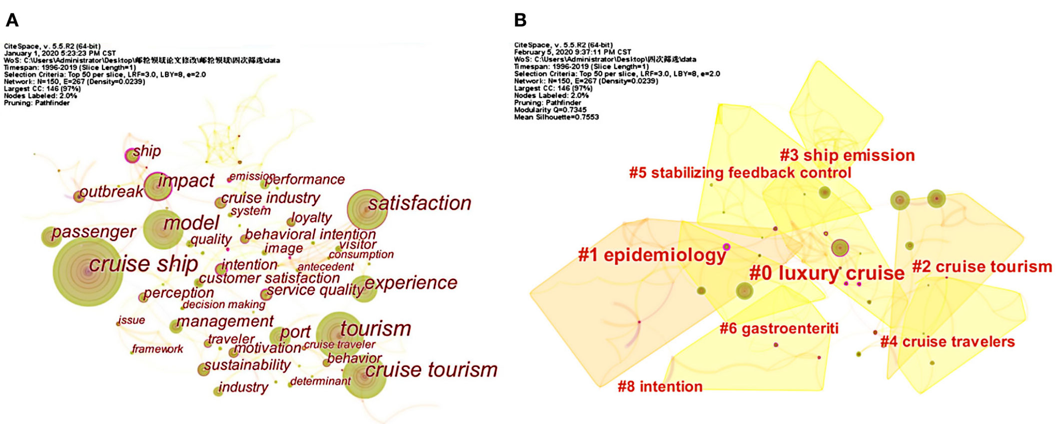

FIGURE 7
A visual map of keywords in cruise research: **(A)** the main keywords in cruise research; **(B)** the cluster map of keywords.

TABLE 4 Hot topics in cruise research.

No.	Hot themes	Composition	Frequency
1	Cruise tourism	market segmentation; cruise passengers; satisfaction; passenger behavior; residents; community media; countries; multivariate analysis of variance; cruise development; design; impact; economic benefits; environment; cruise line; consumption; safety risks; itinerary planning; energy efficiency; optimization; service marketing; luxury cruises; ports; destination attributes	34 (23%)
2	Luxury cruise	well-being; brand recognition; brand awareness; brand reputation; brand loyalty; self-image consistency; face awareness; behavioral intentions; cruise tourism; push-pull motivation; destination attributes; canonical correlation analysis	26 (17%)
3	Cruise passengers	behavioral intention; other customers; experience economy; consumption model; luxury cruise; cruise tourism; interaction; mission statement; cruise lines; stakeholders; cruise vacation; shore excursion; service quality	24 (16%)
4	Port of destination	developing countries; impact; site selection; itinerary planning; region; public transportation; transportation; energy; sustainable management; cooperation; competitiveness; governance model; cost; passenger satisfaction	23 (15%)
5	Environmental and biological protection	ship emissions; air pollution; exhaust emissions; fuel quality; particulate matter; seals; cruise transportation; fuel consumption; emission control areas; optimization; cruise lines; mission statement quality	22 (14%)
6	Cruise diseases	epidemiology; emergency medicine; risk assessment and management; passenger behavior; influenza a/b; norovirus; varicella; legionella; water safety plan; foodborne disease	17 (11%)
7	Other themes		4 (3%)
8	Total		150 (100%)

Pallis et al., 2018; Sanz-Blas et al., 2019), provides port authorities and potential investors with a basis for decision making and facilitates port operators to address the challenge of cruise traffic seasonality and thus achieve sustainable port management. In order to reduce the pollution level of the port, the port implements cost differentiation, and proposes to use (electric) bicycles as public transportation for tourists from the port of call to inland scenic spots (Bardi et al., 2019; Mjelde et al., 2019).

5.1.5 Environmental and biological protection

In 2017, 449 cruise ships were put into service, 27 more in 2018, and 24 more in 2019. The passenger capacity of these ships ranged from 3,000 to 5,000, causing significant environmental impacts on the world, including polar regions (Vega-Muñoz et al., 2020). The emissions of carbon dioxide and sulfur particles during cruise transport lead to air pollution; the incineration of garbage and the generation of organic waste lead to certain economic impact, social costs as well as water pollution, such as coastal waters polluted by high levels of oil, detergents, plastic residues and bacteria (Mölders et al., 2013; Rumpf et al., 2018; Wang et al., 2018; Suneel et al., 2019). In addition, cruise ships have caused serious impacts on living things. For example, the invasion of alien species, engine noise and collisions lead to the death of birds and affect the ecosystems of many marine species, especially cetaceans (Bocetti, 2011; Casoli et al., 2016; Halliday et al., 2018). Growing international concern about environmental issues has prompted many major cruise lines to invest in green technology and fulfill their social responsibility in the marine environment, while optimizing the design of ship energy systems and cruise itinerary planning (Rivarolo et al., 2018; Armellini et al., 2019; Wang et al., 2019; Yan et al., 2019).

5.1.6 Cruise diseases

The international composition of the cruise population and its semi-enclosed environment are conducive to the outbreak of infectious diseases, such as vaccine-preventable diseases (chickenpox), respiratory diseases (A/B influenza), diseases caused by norovirus, and Legionella disease (Mouchtouri et al., 2009; Cramer et al., 2012; Payne et al., 2018). Researches have shown that timely vaccination before sea travel can prevent the outbreak of related diseases (Mitruka et al., 2012). Respiratory diseases usually cause large-scale influenza outbreaks and occur outside the traditional flu season. A comprehensive epidemic prevention and control plan, including timely antiviral treatment, may reduce the impact of the flu epidemic (Millman et al., 2015). Norovirus is prone to gastroenteritis, and individuals in crew cabins and restaurants face the highest risk of infection (Millman et al., 2015). Vigorously promoting good hand-washing habits and increasing the ventilation rate of some or all locations can effectively reduce the risk of infection for passengers (Millman et al., 2015). Isolating sick passengers and cleaning the cabin are also beneficial (Towers et al., 2018). Legionnaires' disease has a significant relationship with water supply systems. The application of water treatment systems in ship water supply systems is expected to improve ship water management and reduce the incidence of passengers (Mouchtouri et al., 2012).

5.2 The evolution and future trends of cruise research hotspots

Figure 8 is a time zone map of the co-occurrence of keywords in cruise research from 2005 to 2019. Since there are fewer keywords from 1996-2004, they are not shown in the map. Keywords such as cruise, cruise tourism, motivation, influence, satisfaction, disease, management, and etc. are shown in Figures 8A, B. The keywords co-occurrence broke out in from 2013 to 2019, indicating that cruise research has entered a boom period at this stage. The research topics are becoming more and more detailed and intersecting with

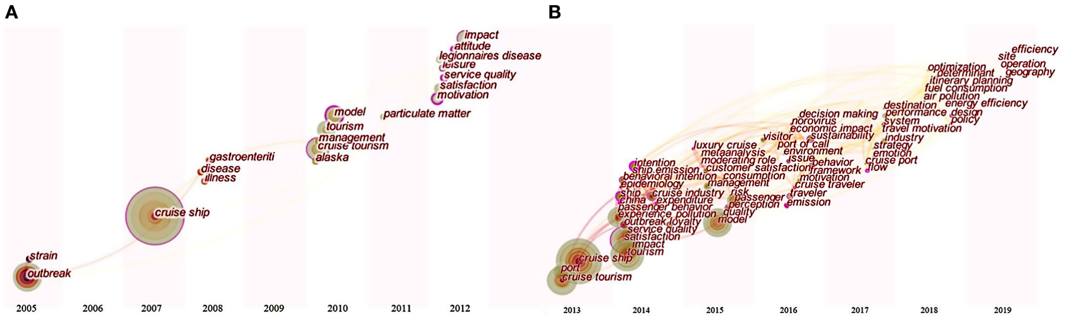

FIGURE 8
Keywords co-occurrence time zone map for the cruise research from 2005 to 2019: **(A)** Keywords co-occurrence time zone map from 2005 to 2012 **(B)** Keywords co-occurrence time zone map from 2013 to 2019.

more disciplines. Many new keywords have emerged, such as optimization, itinerary planning, fuel consumption, efficiency, system sustainability, luxury cruises, pollution, and so on.

The publications collected by this research are divided into three stages to further understand the evolution of the paradigm and theme of cruise research (Figure 9).

Phase I: In this stage, injuries and epidemics on cruise ships are more prominent, such as gastroenteritis (Cramer et al., 2006), Legionnaires' disease (Pastoris et al., 1999), influenza A/B (Brotherton et al., 2003). There are few researches on cruise tourism and cruise performance.

Phase II: Cruise researches have gradually increased by 244% over Phase 1. The scope of research on cruise diseases has expanded, with the emergence of chickenpox, hepatitis E, norovirus, etc., and delves into disease prevention measures. People begin to realize the economic importance brought by the growth of cruise tourism. The cruise market is gradually expanding, and there are more development ideas for terminals or ports. With the development of cruise tourism, research topics such as the design of ships, the payment level of passengers, the employment, experience and operation of cruise ships have emerged.

Phase III: Cruise researches have entered a period of prosperity, by 279% over Phase II. The research area is no longer limited to North America and Europe, but expanded to Asia and even the world, and a new cruise market has emerged. Cruise disease is still the theme of research, but it is more to evaluate the risk and impact through models to find the source of the disease and preventive measures. The scope of impact of tourism or cruise tourism extends to the economic, social and environmental impact of destination ports or communities, with research methods or solutions shifting to novel Internet of Things, such as electronic word of mouth (EWOM), electronic cabin (E-cabin) systems (Barsocchi et al., 2019; Sanz-Blas et al., 2019; Buzova et al., 2019a). Sustainable development is an important research theme at this stage. People are acutely aware of the environmental pollution caused by cruise ships. Environmental responsibility should not be confined to cruise lines and governments, but should extend to port development plans, community residents and every cruise passenger. In addition, various research agendas have been observed, including understanding children's cruise experience, brand reputation, luxury cruises, itinerary planning, musical performances on board, passenger decision-making behavior, sustainability, and the use of technology to better understand the behavior and mobility trends of cruise passengers in cruise destinations.

Although there are already a large number of cruise research publications, there is a lack of liberating research on some important topics in the cruise industry, including the research themes in red in Figure 8, which have gradually emerged in recent years and will continue to be of interest to scholars in the future. It is mainly reflected in the following aspects:

5.2.1 Cruise supply chain

One important research topic that has been overlooked in existing cruise researches is the cruise supply chain. From the perspective of the global value chain of the cruise industry, cruise operations account for 50% of the output value, with the highest added value, and cruise supply is a key link in cruise operation management and has considerable economic benefits (Huang and Yang, 2020). Due to the short replenishment time of the cruise ship, there may be conflicts of interest with the supplier, which will affect the customer experience. Therefore, it is necessary to do in-depth research on the cruise supply chain to promote the establishment of long-term and reliable relationships between cruise lines and service providers.

5.2.2 The use of technology in cruise ships

In addition to the following two items, one is to use GPS technology to track the behavior of cruise passengers at their destinations (De Cantis et al., 2016), and the other is to use GIS to study the mobility of cruise passengers (Paananen and Minoia, 2019).According to Naci Polata, no research technology has been found to reduce the negative impact of the cruise industry or promote the sustainable development of the cruise industry.

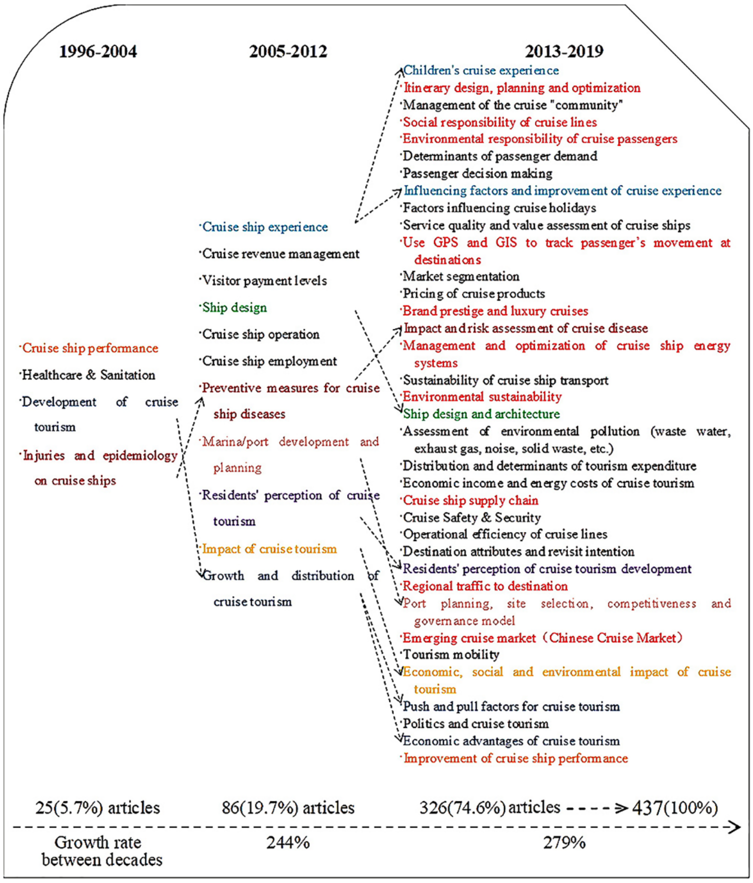

FIGURE 9
The evolution of hot spots in cruise research.

5.2.3 Children's cruise experience

The importance of children in the family's choice of cruise line was identified. While on board, they demanded a certain amount of autonomy so that they could create their own memorable cruise experience (Radic, 2019). Cruise tourism increasingly attracts millennial and generation X family vacations. Children play a decisive role in shaping the future consumption pattern of cruise travel (Radic, 2019). Therefore, with the rapid increase in family cruise travel packages, it is extremely important to understand children's cruise travel experience (Wondirad, 2019).

5.2.4 Itinerary design, planning and optimization

According to the survey, more and more tourists will stay at or near the cruise port. In fact, 65% of cruise passengers spend a few more days in the ports of departure and arrival (China.com, C, 2019). The new generation of cruise passengers has seen a shift in journey schedule, with many passengers looking for shorter trips. The traditional cruise itinerary has been completely unable to meet the needs of passengers. Cruise itinerary planning needs to focus not only on passenger satisfaction, but also on the impact of emission control zones on cruise traffic (Zhen et al., 2018). It is a big challenge for cruise lines to plan, design and optimize a highly attractive, low-polluting itinerary (China.com, C, 2019).

5.2.5 Brand reputation and luxury cruises

Luxury cruises are considered to be one of the most promising target markets due to the huge growth potential (Jeong and Hyun, 2019). However, as the service is expensive, a reasonable pricing strategy is required (Jeong and Hyun, 2019). Reputation plays a certain role in the operation of luxury cruises and can influence passenger perceptions of happiness and loyalty (Hwang and Han, 2014). Research on brand reputation helps cruise lines to better develop their luxury cruise business.

5.2.6 Public transportation at the destination

The increase of cruise activities in port cities has caused a certain degree of traffic congestion to the local tourism resources and historical centers, and hindered the flow of passengers from the port of call to inland tourist attractions (Rosa-Jiménez et al., 2018). The mobility of tourists is an important criterion for cruise destinations as well as the city's economic resources (Perea-Medina et al., 2019). Therefore, it is necessary to analyze the potential public transportation modes of cruise passengers entering the mainland.

5.2.7 Environmental responsibility of cruise passengers and corporate social responsibility

The global growth of the cruise shipping industry has had a strong impact on the ecological environment. The cross-regional and multi-participant nature of cruise routes and the trend towards larger ships have led to a wider environmental impact. Environmental sustainability has always been a hot spot in cruise research, but the research branch rarely involves the environmental responsibility of cruise passengers and corporate social responsibility. Cruise passengers and companies should jointly participate in environmental protection actions.

5.2.8 Optimization of energy systems

The cruise industry is facing more and more challenges due to the strict regulation of anthropogenic emission limits, new targets to reduce carbon emissions and potential carbon pricing (Trivyza et al., 2019). In addition, it is imperative for the cruise industry to discover new technologies and clean energy and promote development. The performance of cruise energy systems needs to be continuously optimized to meet the comprehensive goals of life cycle cost and life cycle carbon emissions.

5.2.9 The relationship between climate change and the cruise industry

Causing changes in the ecosystems of sensitive areas such as the polar regions climate change has brought serious consequences to humans and requires immediate response measures (Dawson et al., 2016; Lamers and Pashkevich, 2018). Although the number of tourists in sensitive areas such as Antarctica seems to be relatively small compared to other destinations, recent trends show that the number of tourists in these areas has increased sharply, with no signs of decrease, especially the emergence of large cruise ships (Wondirad, 2019). Cruise tourism has a great impact on climate change, and the industry itself is also affected by extreme weather due to climate change. Therefore, the relationship between cruise industry and climate change should be one of the most thematic research areas in the next few years (Bender et al., 2016; Wondirad, 2019).

5.2.10 Chinese cruise market

In recent years, the growth rate of emerging cruise market in Asia & Pacific region is higher than the average level (Sun et al., 2014). As one of the core elements of the Asian cruise market, China is growing rapidly in terms of cruise visits (Sun et al., 2014). However, there is currently a lack of research on the development of China's cruise industry to enable stakeholders in cruise tourism to understand the characteristics of the Chinese market. This means that it is necessary to carry out relevant scientific research into this budding and promising area of cruise passenger generation (Wondirad, 2019).

5.2.11 Risk management of cruise diseases

The outbreak of COVID-19 has caused a serious negative impact on the global cruise industry, and it also highlights that international epidemic prevention is still weak (McAleer, 2020). Since the worldwide suspension of cruises, the international cruise industry has carefully analyzed the lessons of the infection incidents of cruise tourists in Yokohama, Japan in the early stages of the epidemic, and has actively studied safety and health measures and risk prevention mechanisms for the resumption of cruises. Some countries and regions around the world have resumed cruise ships. However, among the cruise ships that have resumed sailing around the world, some cruise ships have been suspended due to the epidemic. Therefore, the research of cruise disease risk management is still worth discussing.

6 Conclusion

In this bibliometric study, 437 valid articles on cruise research were analyzed. These documents are recorded in the core collection of Web of Science from 1996 to 2019. This paper uses CiteSpace software to visualize the data of effective articles on cruise research, and analyzes the research status and dynamic frontiers. There is an overall increasing trend in the amount of published literature on cruise research, with reasonable local fluctuations. In recent years, the average number of publications per year has exceeded 40, indicating that cruise research has attracted widespread academic attention.

The United States, Italy, and China are the main countries for cruise research, and the United States maintains extensive cooperation with many countries. The number of published documents and high-quality academic results reflect the important position of the United States in cruise research. In terms of regional distribution, North America, Europe and Asia are the main regions of cruise research. This is consistent with the market phenomenon of the global cruise industry. The University of Genoa, the university of Sejong and the university of Valencia are highly productive organizations whose research has a significant impact. The organizations engaged in research in this area are predominantly independent, with fewer opportunities for collaboration with each other, and the intensity of collaboration needs to be strengthened.

The more prominent of the authors' collaborative network are Heesup Han, Sunghyup Sean Hyun, Silvia Sanzblas, Daniela Buzova and Juan Gabriel Brida. They have contributed to the in-depth research and application in the cruise field. However, the author's centrality is low, and there is a lack of extensive cooperation with other scholars, which leads to the low cooperation intensity of the author. The more prominent of the cited authors are Brida JG, Petrick JF and Hung K. They have provided some basic research and guided others in establishing new perspectives on cruise research.

The hot spots of cruise research can be summarized as cruise tourism, luxury cruises, cruise passengers, destination ports, environmental and biological protection and cruise diseases. The development and change of cruise discipline are related to its hot spot evolution. In recent years, environmental engineering, green sustainable technology, energy and fuel have emerged in the background of cruise research, which indicates that the relationship between cruise industry and ecological environment is the focus of sustainable development in the future. Based on this idea, this paper summarizes some future research trends in the field of cruise, including the environmental responsibility of cruise passengers and corporate social responsibility, the optimization of energy system, and the relationship between climate change and cruise industry. These research topics should be widely concerned by the academia and the government.

In 2020, the global outbreak of the novel coronavirus pneumonia caused the cruise industry to withstand unprecedented impacts and challenges. The epidemic on cruise ships such as "Diamond Princess" severely affected market confidence, causing more than two-thirds of the world's cruise ships to be suspended. This study found that the topic of research on cruise diseases has been lasting for a long time and has always been a hot spot and focus of research. The awareness of prevention and control and related technologies have been improved but not received due attention compared with the speed of cruise industry and market development. In particular, the epidemic prevention and management capabilities in the design, construction and operation of cruise ships need to be improved. Therefore, it is predicted that this area of research will be a key area in the near future.

Author contributions

SM: Conceptualization, writing - review & editing. HL: Investigation, methodology, formal analysis. XW: Supervision, resources. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Hybrid dynamic modeling and receding horizon speed optimization for liner shipping operations from schedule reliability and energy efficiency perspectives

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Uncertainties in port handling efficiency can cause port delays in the liner shipping system. Furthermore, policies on carbon emission reduction, such as EEXI standards, restrict the potential for speed optimization in liner shipping operations. Traditional tactical planning speed optimization is unsuitable for operational-level decision making, leading to unreliable schedules. From a schedule-reliability and energy-efficiency perspective, we propose a real-time speed optimization method based on discrete hybrid automaton (DHA) and decentered model predictive control (DMPC). We use a dynamic adjustment of sailing speed to offset the disturbance caused by port handling efficiency uncertainties. First, we establish a DHA model that describes each ship's hybrid dynamics of state switching between sailing and berthing; then, we develop a prediction model for the DMPC controller, which is analogous to the DHA model. The schedule is transferred into time–position coordinates as controller reference trajectories in the receding horizon speed optimization framework. We consider determining tracking errors, carbon emissions, and fuel consumption as our objectives, and we carry out engine power limitation (EPL) analysis for the sample ship, which turns the EEXI standards into constraints. We attain the recommended speed by solving a mixed-integer optimization. We carry out a case study, and our results indicate the effectiveness of our proposed DHA-DMPC scheme in lowering port delays and achieving the best trade-off between schedule reliability and energy efficiency. Additionally, we conduct further experiments to analyze the impacts of various carbon reduction policies on the performance levels of liner shipping operations.

KEYWORDS

liner shipping, speed optimization, model predictive control, discrete hybrid automaton, Energy Efficiency Existing Ship Index (EEXI)

1 Introduction

Ships operated by container shipping lines follow published schedules and travel along fixed routes with regular port rotations. However, the schedule reliability of liner shipping is often influenced by uncertain factors at ports. For instance, a labor strike would lead to decreases in the pace of port handling, while port congestion would lengthen the time ships are required to wait before berthing. These uncertain factors result in schedule unreliability and port delays, reducing the competitive advantages of liner shipping lines and disturbing the regularity of the global supply chain (Zheng et al., 2021). Ship speeding up is the most common approach to reduce port delays. Moreover, IMO has imposed new technical measures, such as the Energy Efficiency Existing Ship Index (EEXI), which will come into force on January 1, 2023, attempting to achieve long-term goals to reduce greenhouse gas emissions (ABS, 2021). Shipping companies may need to implement solutions such as engine power limitation (EPL) on their fleets to comply with the EEXI standard. However, EPL lowers the top limit of the adjustable ship speed, which has an impact on the controllability of reducing port delays through ship speeding up. Therefore, real-time speed optimization for liner shipping operations is required to eliminate port delays caused by unpredictable port handling efficiency, improve schedule reliability while complying with the EEXI standard, and maintain low operating costs.

Speed changes have a significant impact on fluctuations in fuel consumption and carbon emissions, which are proportional to the third power of sailing speed. As a result, determining the ideal sailing speed is crucial (Leaper, 2019; Dunn et al., 2021); therefore, speed optimization has become a hot topic in research on liner shipping operations (Jimenez et al., 2022). Speed optimization is used in tactical planning to determine the service speed between adjacent ports, and is carried out in combination with other tactical decisions, such as fleet deployment and schedule design (Notteboom, 2006; Brouer et al., 2017; Karsten et al., 2017; Chen et al., 2022). Traditional tactical-level planning often considers minimizing operating costs, fuel consumption, and carbon emissions as objectives, with the problem formulated as a mixed-integer programming (MIP) model (Fagerholt et al., 2010; Wang and Meng, 2012a). Some studies have expanded the model's application scenarios, taking into account more tactical decisions, such as cargo allocation and bunker policy, transforming the model into an integrated decision support system. Psaraftis and Kontovas (2014) considered various factors affecting speed decisions, such as load, fuel price, market condition, etc. Wen et al. (2017) studied the speed optimization of heterogeneous fleets. In addition to voyage duration, cost, and emissions, the satisfaction of shippers is also an objective. Based on statistical data from a shipping line, Xia et al. (2015) fit the relationship between load, sailing speed, and fuel consumption. Both cargo allocation and speed optimization are included in the optimization model. Guericke and Tierney (2015) established an MIP model to maximize shipping lines' profits and designed a decision support system that can recommend the optimal speed, freight rate, and cargo allocation plan. Sheng et al. (2015) combined ship refueling problems with speed determination. Pasha et al. (2021) proposed an integrated optimization model that addresses all the major tactical liner shipping decisions for heterogeneous fleets.

While the aforementioned studies are capable of figuring out tactical plans, they fail to take into account uncertain factors that might affect how effective the plan is. Some scholars attempted to quantify the level of the uncertainties using a probabilistic model, allowing the uncertain factors to be measured and balanced out by adding buffer time to the schedule (Wang and Meng, 2012b; Meng et al., 2014; An and Lo, 2016). Qi and Song (2012) used simulation-based stochastic approximation methods to consider uncertain port times and created a robust schedule aimed at maintaining a high service level. Aydin et al. (2017) developed a speed optimization model with stochastic port times and time windows and then determined the service speed using dynamic programming. Liu et al. (2020) studied speed optimization and bunker policy under uncertain demand conditions. Tan et al. (2018) proposed a joint ship schedule design and sailing speed optimization problem for a single inland shipping service considering uncertain dam transit time.

A robust tactical plan can be generated by quantifying uncertain factors in the optimization model. However, some uncertainties, such as labor strikes and weather conditions, are hard to predict and cannot be measured properly. It is impossible to consider these factors in the tactic-level optimization model. Furthermore, the service speed in tactical plans remains a fixed value for the voyage in adjacent ports and there are no indications for a ship to adjust sailing speed during a voyage. As a result, operational-level speed management incorporating real-time optimization is needed. In operational-level speed optimization studies, the voyage is typically broken into multiple legs, and the sailing speed on each leg is then computed using dynamic programming. (Perera and Mo, 2016; Lee et al., 2018; Wang et al., 2017; Li et al., 2018). Wang et al. (2018) proposed a nonlinear model predictive control framework based on real-time updated environmental information and applied a particle swarm optimization algorithm to compute the optimal speed. Therefore, the sailing speed can be adjusted to consider varying environmental factors and remain optimal throughout the whole voyage. Huotari et al. (2021) presented a novel convex optimization model for ship speed profile optimization under varying environmental conditions and timetable constraints. Tzortzis and Sakalis (2021) proposed a dynamic speed optimization problem, transforming the optimization problem into several sub-problems for improved weather forecasting by segmenting the full time horizon into smaller time regions.

Although the above optimization models can effectively balance uncertainties, they are only able to represent a single voyage with a single ship. A predominant characteristic of liner shipping operations is that the ships' motions repeatedly switch between sailing and berthing. Such a characteristic complicates the modeling process for liner shipping operations; hence, a more detailed optimization model that describes this hybrid dynamic phenomenon is required. In this paper, we model a discrete hybrid automaton (DHA), and then a decentered model predictive control (DMPC) framework is designed. As we focus on operational-level speed management, we assume that the service speed, the fleet deployment, and the schedule have already been determined. Real-time speed optimization is realized through the receding horizon optimization method with the objectives of operating the ships on predetermined schedules while complying with the EEXI standard and maintaining high energy efficiency.

We present the contributions of our paper as follows:

(a) We formulate the hybrid dynamic phenomenon of liner shipping operations by a DHA model constructed using a mixed logical dynamical (MLD) approach, which precisely captures ships' motions and state switching rules;

(b) For real-time speed optimization against uncertain port handling efficiency, we design a DMPC controller based on a receding horizon optimization strategy, in which the prediction model is built analogous to the DHA model and the schedule is transferred into a tractable reference trajectory. Ships' sailing speeds can be adjusted to reduce possible port delays;

(c) Our optimization model incorporates the EEXI standard and converts it into a constraint to guarantee that the emission policy is met while maintaining schedule reliability.

The remainder of our paper is organized as follows: In Section 2, we construct the DHA model and design the DMPC framework. We present our case study and extend experiment results in Section 3. We discuss our findings in Section 4 before concluding our paper in Section 5.

2 Method

There are two motions for ships in liner shipping operations: sailing state and berthing state. These two states switch between each other in circles, reflecting a hybrid dynamical phenomenon that involves both continuous states (sailing states and berthing states) and logic rules (judging when will the state switch happen). While sailing, a ship's positions are updated in real time, and the ship switches into a berthing state when it reaches the corresponding ports. Container handling is done during berthing while the ship's position remains unchanged. In this section, a DHA model is constructed to characterize the dynamics of the ships in liner shipping operations. The real-time dynamical states of each ship in the liner shipping fleet can be calculated. The DHA model serves two purposes: (a) The DHA model functions as a system plant to represent the reality of liner shipping operations and test the proposed sped optimization method. (b) A prediction model in the DMPC framework is established, analogous to the DHA model. As a key component of the DMPC system, the prediction model forecasts the future states of the ships based on their present states. The control effect is determined by the degree of forecast accuracy.

The DMPC controller is designed in Section 2.2. Real-time speed optimization is realized through the receding horizon optimization scheme. Moreover, the decentralized controller arrangement mode reduces individual controllers' computing capacity and improves the system's overall computing efficiency. The DMPC controller is supposed to timely adjust the ships' sailing speed against uncertain port handling efficiency to reduce port delays and keep the liner shipping system in optimal performance.

2.1 Modeling

We propose a DHA model based on a discrete-time framework constructed using the MLD modeling approach to formulate the hybrid dynamics of liner shipping operations (Sirmatel and Geroliminis, 2018). A discrete hybrid automaton (DHA) consists of four modules: a switched affine system (SAS), an event generator (EG), a mode selector (MS), and a finite state machine (FSM). The SAS module describes the continuous dynamics of the liner shipping operations and the FSM module represents the logical rules. The EG and MS modules realize the interconnections between continuous dynamics and logic rules. Continuous state variables in different ranges trigger corresponding discrete events through the EG module, while the MS module alters the continuous variables' evolving modes following indications generated by the FSM module (Bemporad and Morari, 1999).

2.1.1 Switched affine system module

The SAS module describes how the continuous states of each ship evolve in different modes: sailing, berthing, and reset. Each ship is in a specific mode at any instant. In sailing mode, the ship's position changes while the quantities of handled containers remain 0; however, the situation is reversed in the berthing mode. The ship enters reset mode when it accomplishes a round-circle voyage; then, its position is reset to 0 for a new voyage.

We consider a liner shipping system with a fleet of $n_v$ships. The number of calling ports is $n_p$and the total number of sailing legs is n_l. The distance between adjacent ports in the rotation is called a leg.

(a) Position dynamics can be described as follows:

$$x_i(t+1) = \begin{cases} x_i(t) + T_s v_i(t) & \text{if } M_s \text{ True} \\ x_i(t) & \text{if } M_b \text{ True} \\ 0 & \text{if } M_r \text{ True} \end{cases} \quad (1)$$

where T_s is the sampling time; $x_i(t)$ (n mile) represents the position of ship i at instant t ; and $v_i(t)$ (knots) is the sailing speed of ship i at instant t. M_s, M_b, and M_r represent three modes of sailing, berthing, and resetting, respectively.

(b) The dynamics of container handling can be expressed as follows:

$$n_{i,j}(t+1) = \begin{cases} n_{i,j}(t) + T_s h_j(t) & \text{if } M_b \text{ True} \\ 0 & \text{if } M_s \text{ True} \end{cases} \quad (2)$$

where $n_{i,j}(t)$ denotes the quantities of handled containers of ship i at port j, which is the total number of containers being loaded or unloaded, or any other terminal operations; furthermore, $n_{i,j}(t)$is set to 0 when the ship is sailing. $h_{i,j}(t)$expresses the container handling efficiency of port j at instant t. The port handling efficiency is defined as an average container handling rate at port, which is calculated through dividing the total quantities of handled containers by the total observable time at port.

2.1.2 Event generator module

Binary events are triggered when the EG module detects that the continuous state variables reach certain ranges. In the liner shipping system, the events are triggered by the values of ships' positions and the quantities of their handled containers.

(a) Event triggered by position dynamics is as follows:

$$e_{i,j}^{x}(t) \triangleq \begin{cases} True \ \text{if}\ x_i(t) \geq \sum_{m=1}^{j-1} l_{j-1} \\ False \ \text{otherwise} \end{cases} \tag{3}$$

where $e_{i,j}^{x}(t)$ describes whether ship i has reached port j or not. At instant t, if ship i has reached port j, then $e_{i,j}^{x}(t)$is true; otherwise, $e_{i,j}^{x}(t)$is false.

(b) Event generated when ship i finishes a round-circle voyage is as follows:

$$e_{i}^{cir}(t) \triangleq \begin{cases} True \ \text{if}\ x_i(t) \geq \sum_{m=1}^{n_l} l_m \\ False \ \text{otherwise} \end{cases} \tag{4}$$

where$e_{i}^{cir}(t)$ describes whether ship i has finished a circle voyage or not.

(c) Event triggered by container handling dynamics is as follows:

$$e_{i,j}^{h}(t) \triangleq \begin{cases} True \ \text{if}\ n_{i,j} \geq H_{i,j} \\ False \ \text{otherwise} \end{cases} \tag{5}$$

where $e_{i,j}^{h}(t)$ describes whether ship i has finished container handling at port j or not. $H_{i,j}$ is the container quantities to be handled for ship i at port j, which is acquired through observation. $e_{i,j}^{h}(t)$ is triggered when the already-handled container quantities exceed the due quantities.

2.1.3 Mode selector module

In the MS module, different modes are activated by certain binary states and events, changing patterns as the continuous states evolve. The three modes of liner shipping operations are defined as follows:

For $j = 1, \ldots, n_p$, $m = 1, \ldots, n_l$

$$M_s(t) \triangleq \begin{cases} True \ \text{if}\ \exists\ s_{i,m}(t)\ True \\ False \ \text{otherwise} \end{cases} \tag{6}$$

$$M_b(t) \triangleq \begin{cases} True \ \text{if}\ \exists\ b_{i,j}(t)\ True \\ False \ \text{otherwise} \end{cases} \tag{7}$$

$$M_r(t) \triangleq \begin{cases} True \ \text{if}\ e_{i}^{cir}\ True \\ False \ \text{otherwise} \end{cases} \tag{8}$$

where binary state variable $s_{i,m}(t)$ represents at instant t that ship i is sailing on leg m; furthermore, binary state variable $b_{i,j}(t)$ represents at instant t that ship i is berthing at port j. If ship i is sailing on a certain leg, then the sailing mode of this ship is activated; if ship i is berthing at any port, then the berthing mode is activated; and if ship i has finished a circle voyage, then the reset mode is activated. When ship i finishes sailing on the last leg and reaches the first port, its position will be reset to 0 at the same time it enters the berthing state and a new circular voyage begins. Therefore, sailing and berthing modes are mutually exclusive, while berthing and reset modes are compatible.

2.1.4 Finite state machine module

The FSM module describes the evolution of binary states. At every instant, the current binary states are calculated on former states and events generated in the EG module.

(a) The logical rules judging whether ship i is sailing on leg m are defined as follows:

$$s_{i,m}(t+1) \triangleq B_{i,m}^{s}(t) \vee C_{i,m}^{s}(t) \tag{9}$$

$$B_{i,m}^{s}(t) \triangleq b_{i,j}(t) \wedge e_{i,j}^{h}(t), \ \ j = m \tag{10}$$

$$C_{i,m}^{s}(t) \triangleq s_{i,m}(t) \wedge \neg e_{i,j}^{x}(t), \ \ j = m+1 \tag{11}$$

where $B_{i,m}^{s}(t)$ and $C_{i,m}^{s}(t)$ are auxiliary Boolean variables and function as events in the FSM module. $B_{i,m}^{s}(t)$ denotes that ship i begins sailing on leg m; furthermore, $C_{i,m}^{s}(t)$ denotes that ship i is still sailing on leg m. Ship i is deemed to be sailing on leg m if it finishes port handling at port j ($j = m$) or it is sailing on leg m and has not reached the next port.

(b) The logical rules judging whether ship i is berthing at port j are defined as follows:

$$b_{i,j}(t+1) \triangleq B_{i,j}^{b}(t) \vee C_{i,j}^{b}(t) \tag{12}$$

$$B_{i,j}^{b}(t) \triangleq s_{i,m}(t) \wedge e_{i,j}^{x}(t), \ \ j = m+1 \tag{13}$$

$$C_{i,j}^{b}(t) \triangleq b_{i,j}(t) \wedge \neg e_{i,j}^{h}(t) \tag{14}$$

where $B_{i,j}^{b}(t)$ and $C_{i,j}^{b}(t)$ are auxiliary Boolean variables and function as events in the FSM module. $B_{i,j}^{b}(t)$ denotes that ship i reaches port $j(j = m+1)$ and begins to berth at port j; furthermore, $C_{i,j}^{b}(t)$ denotes that ship i is still berthing at port j. Ship i is deemed to be berthing at port j if it reaches port j or it is still berthing at port j and port handling has not finished yet.

Figure 1 shows the state flow in the FSM module.

2.2 Controller design

2.2.1 Transfer schedules into trackable reference trajectories

A liner shipping schedule is a plan that combines time and space factors. Ships serving a certain shipping route are required to reach the corresponding port within the specified period. The importance of schedule reliability is reflected in two ways: (a) Container shipping is a key link in international cargo transportation. A liner shipping schedule provides an important

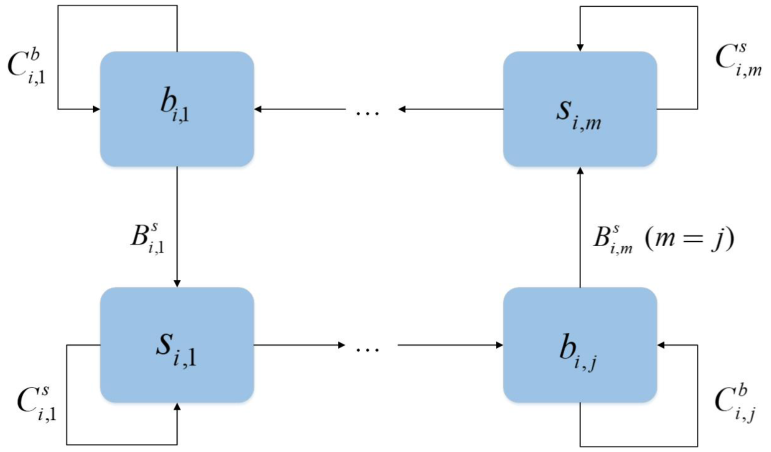

FIGURE 1
FSM module of liner shipping system.

basis for planning by other participants in the global supply chain, such as shippers, inland carriers, and marine container terminal (MCT) operators; therefore, any schedule delays would affect the subsequent logistics chain. (b) Schedule reliability reflects the service level a shipping line can achieve for customers; therefore, maintaining high levels of schedule reliability is beneficial for improving customer satisfaction and gaining competitive advantages.

Schedules published by shipping lines contain estimated times of arrival (ETA) and departure (ETD) for all ports they serve. In the liner shipping schedule, ETA and ETD are sequences of days, meaning that ships have to arrive or leave a port on a certain date, with the exact time (hours) not announced. For example, if the ETA for a certain port is 10, then the ship is supposed to arrive at the port within the period from 00:00 to 24:00 on the 10th day after the voyage starts—there is no requirement regarding the exact time (hours) of arrival. Such a practice allows some schedule flexibility.

However, at an operational level, more detailed instructions for arrivals and departures should be made; therefore, the ETA needs to be accurate to hours. An accurate ETA is key to the coordination between ships and MCT operators (Tao et al., 2023). As such, we transform the schedule into a series of position–time coordinates to obtain a tractable reference trajectory—the time series is in hours and the ships have reference positions at any instant.

In the w_{th} voyage, the estimated time of arrival and departure of ship i at port j (denoted separately by $ETA^w_{i,j}$ and $ETD^w_{i,j}$) can be calculated by predetermined service speed v^{ser}_i (knots), estimated average port handling efficiency $\hat{h}_j$ (TEU/hour), and estimated due quantities of containers to be handled $\hat{H}_{i,j}$ (TEU). Then, $ETA^w_{i,j}$ and $ETD^w_{i,j}$ are set as relay points; therefore, we can derive all the position–time coordinates. Algorithm 1 shows the detailed process for generating the reference trajectories. We minimized the difference between the reference trajectories and the ships' actual trajectories, which is called a tracking error, using a receding horizon scheme in Section 2.3 so that the ships follow the reference trajectories.

```
Input: v_i^ser, ĥ_j, Ĥ_{i,j}, l_m
InitializeETA^w_{i,j}, ETD^w_{i,j} and x_i(k)
setETA^1_{i,1} = 0, x_i(0) = 0
whilei ≤ n_v do
 for each w do
  for each j do
  calculate ETA^w_{i,j} and ETD^w_{i,j} based on v_i^ser, ĥ_j, Ĥ_{i,j}, l_m
  end for
end for
for k = 1 : T_stop
  if ETA^w_{i,j} ≤ k ≤ ETD^w_{i,j} then
     x_i(k + 1) = x_i(k)
  else if k = ETA^w_{i,j}, (w ≥ 2) then
     x_i(k) = 0
  else x_i(k + 1) = x_i(k) + v_i^ser T_s
  end if
 end for
end while
```

ALGORITHM 1
Reference trajectory generator

2.2.2 Fuel consumption and carbon emissions

Minimizing fuel consumption and carbon emissions are additional objectives when operating the liner shipping system in an energy-efficient way. Therefore, we calculate a formula for fuel consumption and carbon emissions as follows:

$$N^e_i(t) = 0.7355\frac{D_i^{2/3}v_i(t)^3}{C} \tag{15}$$

$$G_i(t) = g^e_i N^e_i(t)10^{-6} \tag{16}$$

$$O_i(t) = G_i(t)T_s \tag{17}$$

$$E_i(t) = C_F O_i(t) \tag{18}$$

where $N_i^e(t)$ is the indicated power (kW) of ship i; D_i is the ship's deadweight tonnage (DWT); C is the admiralty coefficient; $G_i(t)$ is the fuel consumption per unit time (t/h); $O_i(t)$ and $E_i(t)$ are the fuel consumption (t) and carbon emissions (t) in the time period $[t, \ t+1]$; and C_F is the conversion factor between fuel consumption and CO_2 emissions.

For calculation convenience, we transformed the fuel consumption and carbon emissions into linear expressions of speed. We used the cubic root of fuel consumption and carbon emissions as performance indicators of ship energy efficiency. The formulas are as follows:

$$O_i(t)^{1/3} = \sqrt[3]{0.7355 \frac{g_i^e D_i^{2/3} T_s 10^{-6}}{C}} v_i(t) \tag{19}$$

$$E_i(t)^{1/3} = \sqrt[3]{0.7355 \frac{C_F g_i^e D_i^{2/3} T_s 10^{-6}}{C}} v_i(t) \tag{20}$$

2.2.3 EEXI limitation as constraints

The EEXI standard is introduced in the 2021 Marine Environmental Protection Committee meeting MEPC76, which acts as an expansion of the Energy Efficiency Design Index (EEDI) and covers existing ships. The attained EEXI for ships in liner shipping lines should be calculated and meet the required EEXI (IMO, 2022). Our calculation formulas for attained EEXI are as follows:

For ship i,

$$R_X = \frac{(1-Y)}{100} R_D \tag{21}$$

$$A_X \le (1-Z) R_X \tag{22}$$

$$A_X = \frac{E_{ME} + E_{AE} + (PTI - Eff_{AE}) - Eff_{ME}}{DV_{ref} f_R} \tag{23}$$

where R_X is the required EEXI $(g/t \cdot nm)$, R_D is the reference line of EEDI $(g/t \cdot nm)$, and A_X is the attained EEXI $(g/t \cdot nm)$. Y is the reduction factor and Z is the safety margin, which are decided by the shipping lines themselves. V_{ref} is the service speed under the EEXI draft. f_R is the correction factor and its value is 1. E_{ME} and E_{AE} are the carbon emissions of the main and auxiliary engines (g); PTI is the emissions of the shaft generator (g); and Eff_{AE} and Eff_{ME} are the carbon emissions reduced by the innovative energy efficient devices in the auxiliary and main engines (g). Our calculation formulas for the carbon emissions of various devices are as follows:

$$E_{ME} = \left(\prod_{j=1}^{n} f_i\right)\left(\sum_{i=1}^{n_{ME}} P_{ME(i)}\right) C_{FME(i)} SFC_{ME(i)} \tag{24}$$

$$E_{AE} = P_{AE} C_{FAE} SFC_{AE} \tag{25}$$

$$PTI = \left(\prod_{j=1}^{n} f_i \cdot \sum_{i=1}^{n_{PTI}} P_{PTI(i)}\right) C_{FAE} SFC_{AE} \tag{26}$$

$$Eff_{AE} = \left(\sum_{i=1}^{n_{eff}} f_{eff(i)} P_{AEeff(i)}\right) C_{FAE} SFC_{AE} \tag{27}$$

$$Eff_{ME} = \left(\sum_{i=1}^{n_{eff}} f_{eff(i)} P_{MEeff(i)}\right) C_{FME} SFC_{ME} \tag{28}$$

$P_{ME(i)}$ is the effective power of the i_{th} main engine (kW), which is 75% of the maximum continuous rating (MCR); P_{AE} is the auxiliary engine power; $P_{PTI(i)}$, $P_{AEeff(i)}$, and $P_{MEeff(i)}$ are the effective power of the shaft motor, and auxiliary and main engine power reductions due to energy efficient technology. f_i and $f_{eff(i)}$ are correction factors and $f_i = f_{eff(i)} = 1$. $C_{FME(i)}$and C_{FAE} are the carbon converting factors; furthermore, here, we assume $C_{FME(i)} = C_{FAE} = C_F$.

If the ship's attained EEXI cannot meet the EEXI standard then adjusting measures should be carried out for EEXI compliance. Among various EEXI improvement solutions, EPL has been proven the most common choice by shipowners due to its effectiveness and economic feasibility. Therefore, our solution is to apply engine power limitation (EPL) to improve the ship's EEXI.

2.2.4 Decentered model predictive control framework

Using the DHA model in Section 2.1 as the system plant, we created a DHA-DMPC framework, which is depicted in Figure 2. There is a local controller on each ship in the liner shipping fleet. The prediction model in the local MPC controller is a hybrid dynamical model built analogously to the DHA model from

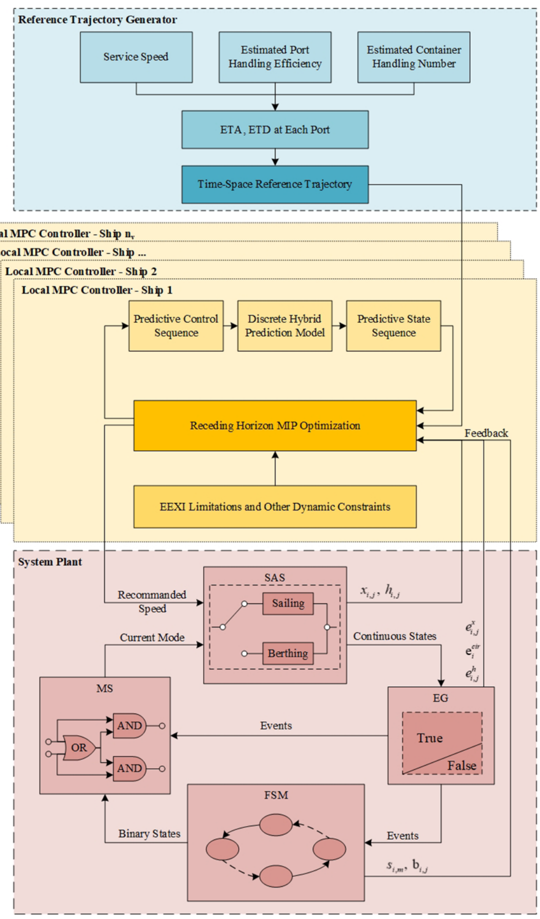

FIGURE 2
DHA-DMPC framework.

Section 2.1. We present the prediction model as follows:

$$x_c(k+1) = A_M(k)x_c(k) + B_M(k)u(k) + C_M(k)d(k) \quad (29)$$

$$\delta_e(k) \triangleq \begin{cases} True & \text{if } A_e(k)x_c(k) + B_e(k)u(k) \leq W_e \\ False & \text{otherwise} \end{cases} \quad (30)$$

$$M(k) \triangleq f_M(x_l(k)) \quad (31)$$

$$x_l(k+1) = f_B(x_l(k), \delta_e(k)) \quad (32)$$

where (29) is analogous to the switched affine system in (1) and (2); A_M, B_M, and C_M are the corresponding coefficients in mode M; the continuous state vector $x_c(k)$ consists of the ship's position $x(k)$ at instant k and handled container quantities $n_j(k)$ at port j; the control vector $u(k)$ contains the ship's sailing speed $v(k)$ at instant k; and the disturbance vector $d(k)$ contains the port handling efficiency $h_j(k)$ and due quantities of containers to be handled H_j at port j. Formula (30) is analogous to the event generator in (3)-(5); event vector $\delta_e(k)$ consists of $e_j^x(k)$ (the ship reaches port j and container handling at port j finishes) and $e^{cir}(k)$ (the ship accomplishes a round-circle voyage); and W_e denotes the condition that triggers various events. Formula (31) is analogous to the mode selector in (6)-(8); the mode vector $M(k)$ contains the sailing, berthing, and reset modes; the binary state vector $x_l(k)$ consists of $s_m(k)$ (the ship is sailing on leg m) and $b_j(k)$ (the ship is berthing at port j); and f_M represents the Boolean operation between the binary variables. Formula (32) is analogous to the finite state machine in (9)-(14); furthermore, in addition to those events in (30), event vector $\delta_e(k)$ in (32) also consists of $B_m^s(k)$ (the ship begins to sailing on leg m), $C_m^s(k)$ (the ship is still sailing on leg m), $B_m^b(k)$ (the ship begins to berth at port j), and $C_j^b(k)$ (the ship is still berthing at port j); and f_B represents the Boolean function, which consists of logical rules in the FSM module. Unlike the system plant, which includes all the ships in the fleet, the prediction model only considers a single ship; therefore, it involves fewer binary variables compared with the system plant and, thus, its computation capacity is much lower. This decentralized arrangement increases the computing speed of a local controller and enables real-time optimization of the ships' speed (Negenborn and Maestre, 2014; Zheng et al., 2017; Wang et al., 2020).

Formula (33) is the optimization model in the DMPC controller, which considers minimizing tracking errors, fuel consumption, and carbon emissions as objectives. Q_1, Q_2, and Q_3 are the weights of the three performance indicators (Q_1 = 4, Q_2 = Q_3 = 1). The control variable is the sailing speed of each ship. We executed (33) using a receding horizon method to compensate for the uncertainties in the disturbances; moreover, binary variables are involved, such as the binary state variables and events in (30)-(32). Therefore, (33) is a mixed integer programming (MIP) problem.

In the receding horizon scheme, the prediction models predict future states in the prediction horizon after observing the current states; then, they calculate the tracking errors, resulting in every local controller computing the MIP optimization problem in (33) to obtain the control sequence in the control horizon. At each step, only the first element of the control sequence is implemented and the rest are ignored. Then, a new control sequence is obtained in the next step. We repeatedly execute this operation to realize online rolling optimization (Algorithm 2).

$$\min J(k) = \sum_{p=0}^{N-1} \left\| Q_1(x_i(k+p) - x_i^{ref}(k+p)) \right\|_\infty + \sum_{p=0}^{N-1} \left\| Q_2(O_i^{1/3}(k+p) \right\|_\infty + \sum_{p=0}^{N-1} \left\| Q_3(E_i^{1/3}(k+p) \right\|_\infty \quad (33)$$

subject to
for $i = 1, \ldots, n_v; j = 1, \ldots, n_p$:
initial states $x(0)$, $n_j(0)$, $s_m(0)$, $b_j(0)$;
predictive model dynamics (29), (30), (31), (32);
EEXI limitations (22);
$x_{i,j}, v_{i,j} \geq 0$.

```
Initialize the system state x_i(0), n_{i,j}(0), s_{i,m}(0), b_{i,j}(0)
for each ship i do
  Calculate the attained EEXI A_X
  if A_X ≤ (1 − Z)R_X do
    employ EPL for the respect ship
  end if
  while k ≤ T_stop do
    Get reference trajectory x_ref(k:k+N−1)
    through Algorithm 1
    Input h_j(k:k+N−1) as disturbance
    Measure the current state x_c(k) and x_l(k)
    by (1)-(14)
    Predict the future state x_c(k:k+N−1) and
    x_l(k:k+N−1) by (29)-(32)
    Calculate the tracking error by
    x_ref(k:k+N−1) − x_c(k:k+N−1)
    Calculate fuel consumption and carbon
    emission by (19) and (20)
    Solve MIP optimization (33), and obtain
    the recommended speed for the prediction
    horizon u(k:k+N−1)
    Implement the first element in u(k:k+N−1)
    to (1)
  end while
end for
```

ALGORITHM 2
DHA-DMPC simulation.

3 Experiments and results

3.1 Numerical experiments design

We carried out a series of comparison studies to confirm the effectiveness of the suggested DHA-DMPC controller. In addition to the reference trajectory generated by Algorithm 1, we considered another reference trajectory to explore the performance of the controller. We introduce this new reference trajectory in Section 3.1.2. Furthermore, we expanded the EEXI standard into four phases with progressively higher reduction factors. We performed

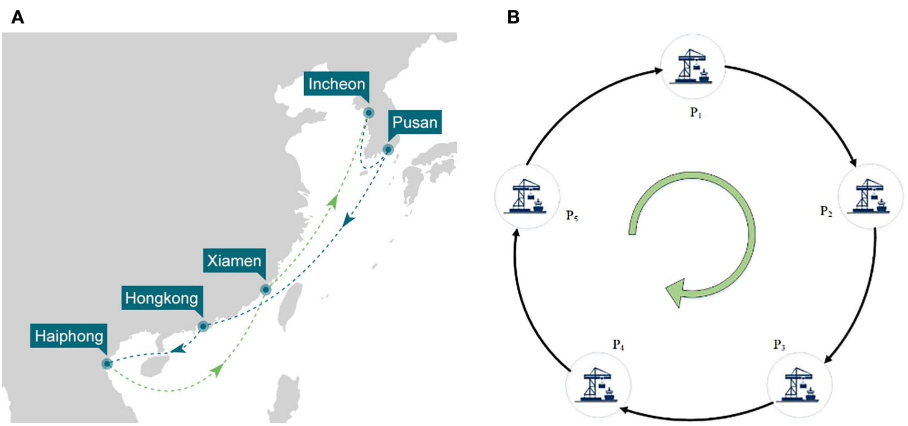

FIGURE 3
(A) real shipping route; (B) concept of circle voyage.

TABLE 1 Shipping route parameters.

Parameters	Value
Projected fleet speed	13.5 kts
Service interval	93 h
Number of serving ships	4
Distance of leg 1	393 nm
Distance of leg 2	1147 nm
Distance of leg 3	468 nm
Distance of leg 4	742 nm
Distance of leg 5	927 nm

TABLE 2 Container handling numbers at different ports (TEU).

Ship	Port 1	Port 2	Port 3	Port 4	Port 5
First voyage					
Ship 1	413	1012	796	1482	984
Ship 2	399	1006	802	1498	1005
Ship 3	405	1014	809	1502	1018
Ship 4	412	993	812	1487	1009
Ship 5	402	1008	802	1510	990
Second voyage					
Ship 1	395	1009	803	1498	1002
Ship 2	419	998	812	1503	1002
Ship 3	398	1004	810	1492	998
Ship 4	407	1003	802	1507	1014
Ship 5	400	987	**811**	1502	1004

a sensitivity analysis to explore the impact of different carbon policies on liner shipping operations.

3.1.1 Liner shipping route

Various types of liner shipping routes exist, such as end-to-end, pendulum, and circular services (Notteboom, 2004). We choose the classical circular service for our case study, which is commonly used in practical liner shipping route design. Figure 3A shows the actual shipping route layout, and Table 1 displays the route's parameters. The route can be abstracted as a concept of the circular voyage shown in Figure 3B, which means the ship visits a fixed port rotation on a pre-published schedule repeatedly. This route is served by four ships, and we assume that the fleet consists of four sister ships with the same technical conditions. Our calculations and solutions to improve the ships' EEXI are shown in Section 3.1.3. All the data on shipping routes and sample ships are provided by CU Lines. The simulation period is the time for the fleet to accomplish two circle voyages, which is 1050 steps. The sampling time is 1h; furthermore, both the prediction and the control horizon are 10 steps. Table 2 shows the data from customer booking platform containing the due quantities of containers to be handled.

Table 3 displays the anticipated port handling efficiency used by shipping lines for tactical planning. The port handling efficiency is not the actual operation rate of the container terminal equipment; instead, it is an average handling efficiency rate, which is obtained by dividing the total number of containers handled by the total time that ships stay at port. However, in practice, port handling efficiency

TABLE 3 Estimated port handling efficiency.

Port	Efficiency (TEU/h)
Port 1	40
Port 2	50
Port 3	40
Port 4	50
Port 5	80

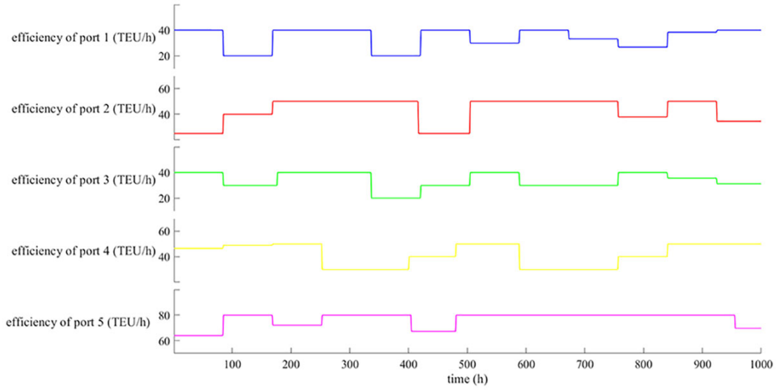

FIGURE 4
Real-time handling efficiency of each port.

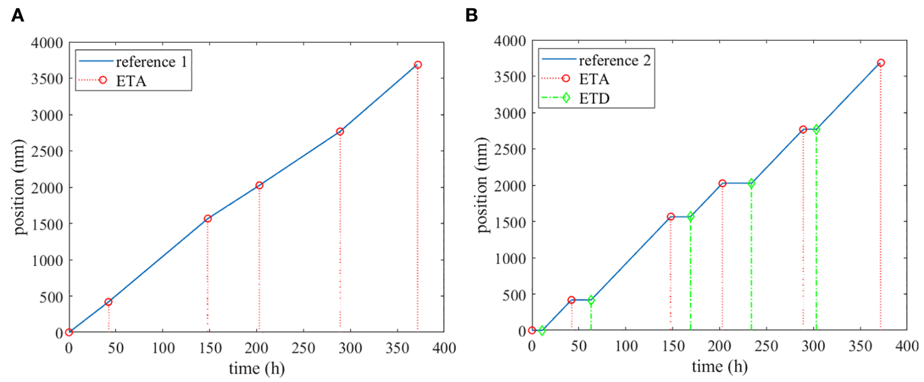

FIGURE 5
(A) Reference 1; **(B)** Reference 2.

TABLE 4 Parameters for calculating EEXI.

Parameters	Description	Value
D	Deadweight	24336 DWT
MCR	Maximum continuous rate	12268 kw
P_{ME}	75% of the main engine MCR	9201 kW
P_{AE}	Auxiliary engine power	304 kW
Q_{ME}	Quantity of main engine	1
Q_{AE}	Quantity of auxiliary engine	3
Q_{PTI}	Quantity of shaft generator	0
Q_{MEeff}	Quantity of energy-saving devices in main engines	0
Q_{AEeff}	Quantity of energy-saving devices in auxiliary engines	0
SFC_{ME}	Specific fuel consumption of the main engine	218.96 g/kW
SFC_{AE}	Specific fuel consumption of the auxiliary engine	235.4 g/kW
C_F	Conversion factor	3.206
Z	Margin	5%
Y	Reduction factor	20%

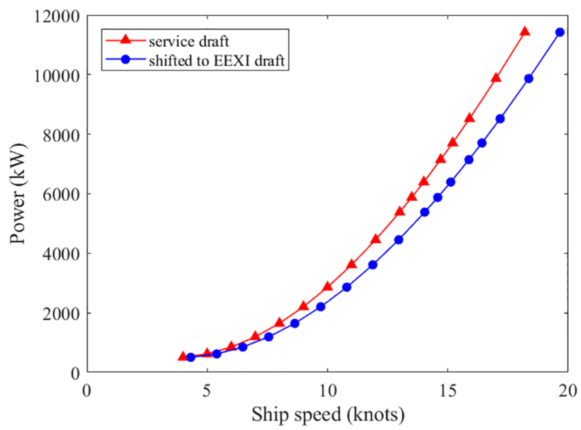

FIGURE 6
Power–speed curve.

can fluctuate because of unpredictable factors, such as extreme weather, which makes loading and unloading operations difficult; port congestion, which increases the waiting time for ships to berth; or strikes, which result in low handling efficiency. Figure 4 shows the actual port handling efficiency during the simulation period, which we input into the optimization model as disturbances.

3.1.2 Reference trajectories

We designed two reference trajectories and compared their performances: (a) Reference 1 ignores the berthing process. We set only $ETA_{i,j}^{w}$ as relay points to calculate the position–time coordinates. Algorithm 3 in Appendix A shows the detailed method to generate Reference 1. (b) Reference 2 considers the berthing process and is generated by Algorithm 1. Figure 5 illustrates the two reference trajectories.

3.1.3 EEXI improvement of the sample ship

Table 4 shows the ship's parameters, which we used to calculate EEXI.

The relationship between main engine power and speed can be described in a power–speed curve. The power–speed curve should be converted from the service draft to the EEXI draft. Figure 6 shows the transferred power–speed curve. The calculation equation is as follows:

$$v_{ref} = (\frac{\Delta_{service}}{\Delta_{EEXI}})^{2/9} \cdot v_{ser} \tag{34}$$

where v_{ref} is the speed at EEXI draft, v_{ser} is the speed at service draft, $\Delta_{service}$ is the displacement at service draft, and Δ_{EEXI} is the displacement at EEXI draft. For container ships, the service draft is the summer draft; furthermore, the EEXI draft is 70% summer draft.

The required EEXI/reference line is based on the below formula:

$$R_X = ab^{-c} \tag{35}$$

where $a = 174.22$, $c = 0.201$, and $b = D$.

The attained EEXI is 17.50 g/t · nm while the required EEXI with a 5% margin is 17.38 g/t · nm; thus, the EPL has to be employed to limit the main engine power. We calculated the MCR after limitations as follows:

$$MCR_{lim} = P_{ME}/0.83 \tag{36}$$

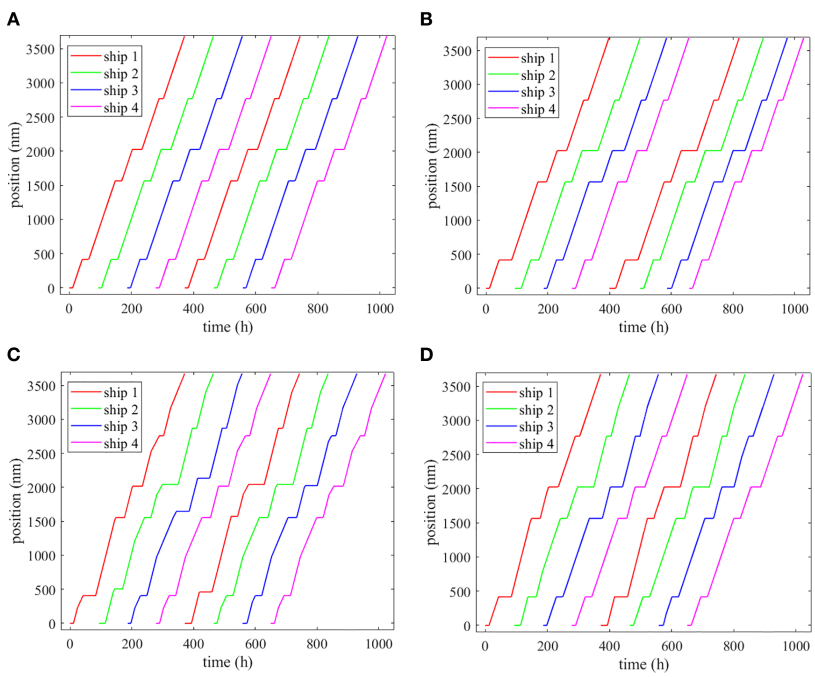

FIGURE 7
(A) Ideal trajectory; **(B)** uncontrolled; **(C)** controlled with Reference 1; **(D)** controlled with Reference 2.

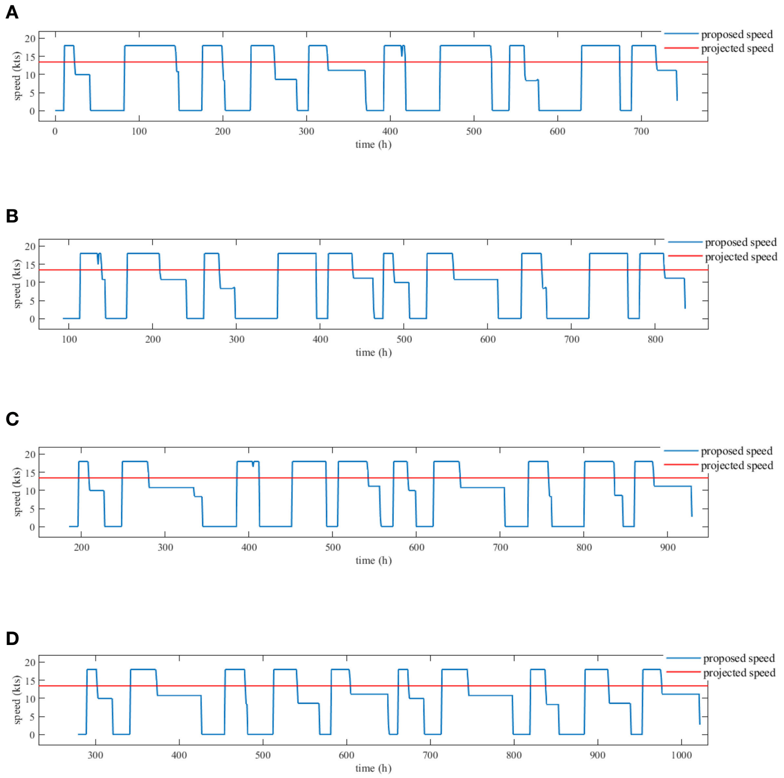

FIGURE 8
Speed of each ship under Reference 1: **(A)** ship 1; **(B)** ship 2; **(C)** ship 3; **(D)** ship 4.

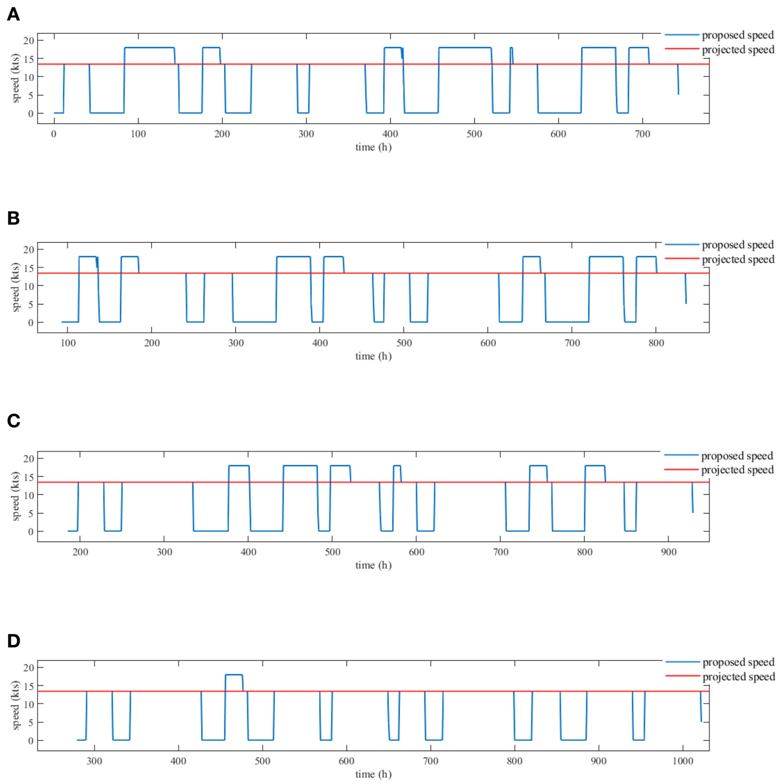

FIGURE 9
Speed of each ship under Reference 2: **(A)** ship 1; **(B)** ship 2; **(C)** ship 3; **(D)** ship 4.

The limited MCR is 10787.9 kW, and the maximum speed under this limited MCR is 18 knots.

3.2 Comparative experiment results

We created four scenarios to evaluate the controller's effectiveness and assess how the two reference trajectories performed: (a) the ideal scenario, where the port handling efficiency retains the anticipated value throughout the simulation period; (b) the uncontrolled scenario; (c) the controlled scenario with Reference 1; and (d) the controlled scenario with Reference 2. Figure 7 shows the ships' actual trajectories in the four scenarios, and the raw data are collected in Appendix B. Figure 7B shows that port delays and schedule disruptions are caused by uncertain port handling efficiency when no control actions are implemented. The intervals between the trajectory of ship 4 in its second voyage and that of ship 1 in the first voyage are larger compared to Figure 7A; in the second voyage, the trajectory of ship 3 is quite close to that of ship 4, and a bunching phenomenon (two ships stay at the same port at the same time) nearly happens at port 4. Figures 7C, D show the controlled results. We found that ships' trajectories can be adjusted in time when a port delay happens to keep a steady ship delivery frequency.

Figures 8, 9 display the real-time sailing speed throughout each ship's simulation period. The controller can increase the ship's sailing speed with either reference trajectory whenever a delay is detected. We discovered differences between the performances of the two reference trajectories by comparing Figures 8, 9. After the delay is offset by the ship's speed-up strategy, the ship's speed will be reduced and maintained at a level lower than the projected service speed when controlled with Reference 1; however, when controlled with Reference 2, the ship's speed will be turned back to the service speed after the speed-up strategy ceases.

Figure 10 demonstrates the delays (arrival time deviations) at each port of each ship under various scenarios. Figure 10 shows that compared with the uncontrolled scenario, the controller is capable of reducing port delays and maintaining high schedule reliability. When no control measures are taken, port delays cannot be corrected on time and will lead to progressively larger delays in subsequent ports. Take ship 1 as an example: Figures 10A, B demonstrate how port delays worsen over time. On the second voyage, the delay at port 5 reached 77 hours. Figures 10G, H depict

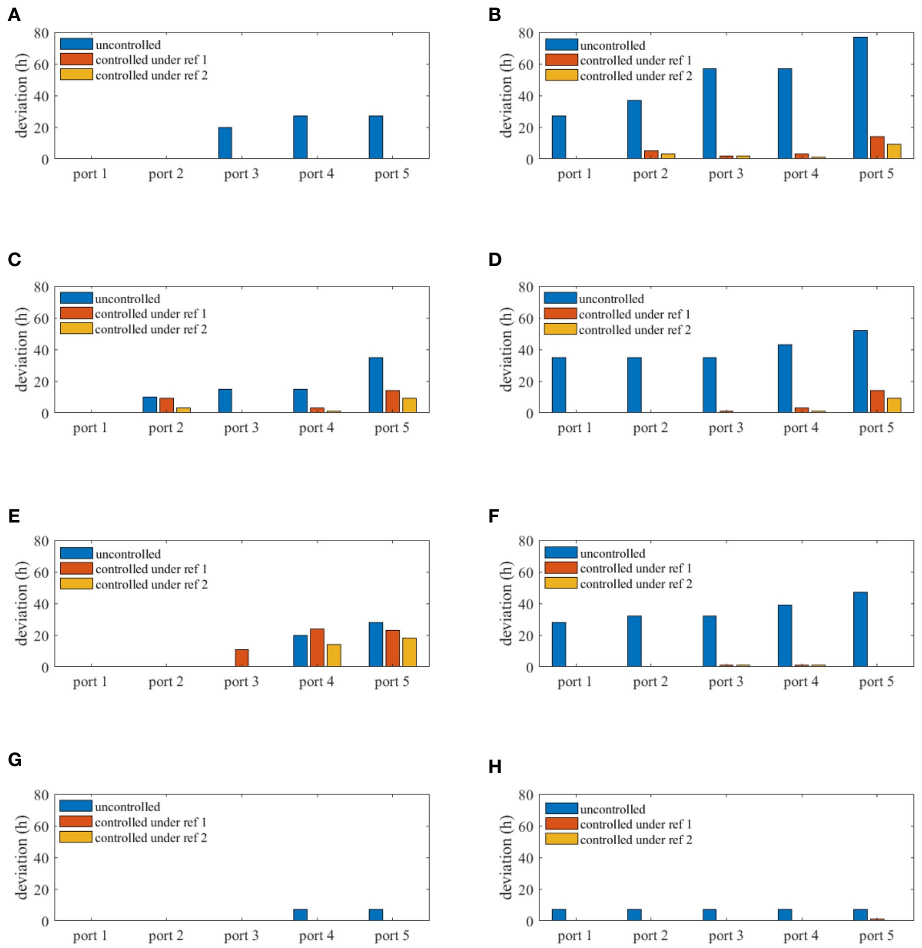

FIGURE 10
Arrival time deviations under different control methods at each port of: **(A)** ship 1 in the first voyage; **(B)** ship 1 in the second voyage; **(C)** ship 2 in the first voyage; **(D)** ship 2 in the second voyage; **(E)** ship 3 in the first voyage; **(F)** ship 3 in the second voyage; **(G)** ship 4 in the first voyage; **(H)** ship 4 in the second voyage.

TABLE 5 Results under different control methods.

Results	Uncontrolled	Controlled with Reference 1	Controlled with Reference 2
Total deviation (h)	879	129	72
Carbon emission (t)	5506.02	7813.94	7032.70
Fuel consumption (t)	1717.41	2437.29	2193.61
Weighted cost	2.41	2.15	1.89

the transferability of port delays. On the first voyage, ship 4 experienced a delay of 7 hours at port 4 due to fluctuations in handling efficiency at port 3. Thereafter, despite the normal efficiency of subsequent port operations, there were still 7-hour delays in each port. Instances of such delays will decrease (or even be eliminated) when control measures are taken, thus proving the effectiveness of our proposed DMPC controller.

Table 5 shows the total delay time, carbon emissions, and fuel consumption for various scenarios after two complete voyages; furthermore, we calculate the weighted comprehensive costs by the following formula:

$$c_w^i = \alpha_1 \frac{d_{ttl}^i}{\max\left\{d_{ttl}^1, d_{ttl}^2, \cdots, d_{ttl}^n\right\}} + \alpha_2 \frac{E_{ttl}^i}{\max\left\{E_{ttl}^1, E_{ttl}^2, \cdots, E_{ttl}^n\right\}} + \alpha_3 \frac{O_{ttl}^i}{\max\left\{O_{ttl}^1, O_{ttl}^2, \cdots, O_{ttl}^n\right\}} \tag{37}$$

where c_w^i is the standardized and weighted comprehensive costs under the i_{th} scenario; d_{ttl}^i is the total schedule deviations under the i_{th} scenario; and E_{ttl}^i and O_{ttl}^i are the total carbon emissions and fuel consumption under the i_{th} scenario, respectively. Our standardization operation divides each indicator by the maximum of all indicators under various scenarios, mapping the values of all indicators to the $[0, 1]$ interval (Zhen et al., 2023). The weights of the indicators are $\alpha_1 = 1$, $\alpha_2 = 1$, and $\alpha_3 = 1$.

Table 5 shows that our proposed controller can effectively reduce port delays. The results also demonstrate the superiority of Reference 2 over 1. When the fleet is controlled with Reference 1, the total deviations is 14.68% of the result without control actions, while with Reference 2 the overall deviations only account for 8.20% of that without control. For fuel consumption and carbon emissions, the fleet consumes less fuel and produces fewer emissions due to the lower average speed. When control actions are involved, ships will speed up to the next port to catch the schedule at the cost of higher fuel consumption rates and more carbon emissions. Moreover, Reference 2 is superior to Reference 1 in terms of energy efficiency management. Carbon emissions and fuel consumption in a Reference-1 scenario are 10% less than with Reference 2. Such a result can be explained by the real-time speed displayed in Figures 8, 9. Compared with Reference 1, speed with Reference 2 is smoother. Speed with Reference 1 fluctuates too frequently and sharply, resulting in increased fuel consumption and carbon emissions. Our proposed controller can effectively reduce comprehensive and combined costs. Comprehensive cost under Reference 1 is 10.79% less than that without control, and the combined cost under Reference 2 is 21.58% less, which is twice as much as the former. However, on balance, Reference 2 achieves the best final result.

3.3 Analysis of different EEXI limitations

We designed further experiments to expand the EEXI standard into four phases and explore the impact of carbon emission policies on liner shipping operations. Each phase adopted stricter regulations than the previous, i.e., the reduction factor increases phase by phase. The reduction factors of the four phases are: 20%, 25, 30%, and 40%. The EEXI margin is 5%. Because we proved the superiority of Reference 2 in Section 3.2, we adopted Reference 2 as the reference trajectory for the DMPC controller. Table 6 shows EPL solutions applied to the sample ship in different phases.

Figure 11 and Table 7 show our sensitive analysis results. Port delay statistics (Figure 11) show that a stricter EEXI standard produces higher schedule deviations. In Phase 4, due to the main engine's excessive power limitations, the upper-speed limit drastically reduced—the maximum speed is only 14 knots, which is only 0.5 knots higher than the projected service speed. The speed-up method's potency in reducing schedule delays is greatly diminished; therefore, the port delays cannot be dealt with effectively. Figure 11 shows that the transferability of port delays happened again in Phase 4, indicating that a speed-up strategy failed in eliminating port delays. Table 7 shows performance indicators with progressive emission limits in each phase. The maximum speed a ship can reach is gradually reduced, with carbon emissions and fuel consumption decreasing due to the overall reduction in sailing speed, eventually leading to higher overall costs due to the

TABLE 6 Limited MCR under different EEXI margins.

Phase	Reduction factor	Limited MCR (kW)	Attained EEXI (g/t nm)	Required EEXI (g/t nm)	Max speed (Kts)
1	20%	10787.90	17.38	18.30	18
2	25%	9818.60	16.3	17.16	17
3	30%	8937.35	15.2	16.01	15.5
4	40%	6967.83	13.04	13.73	14

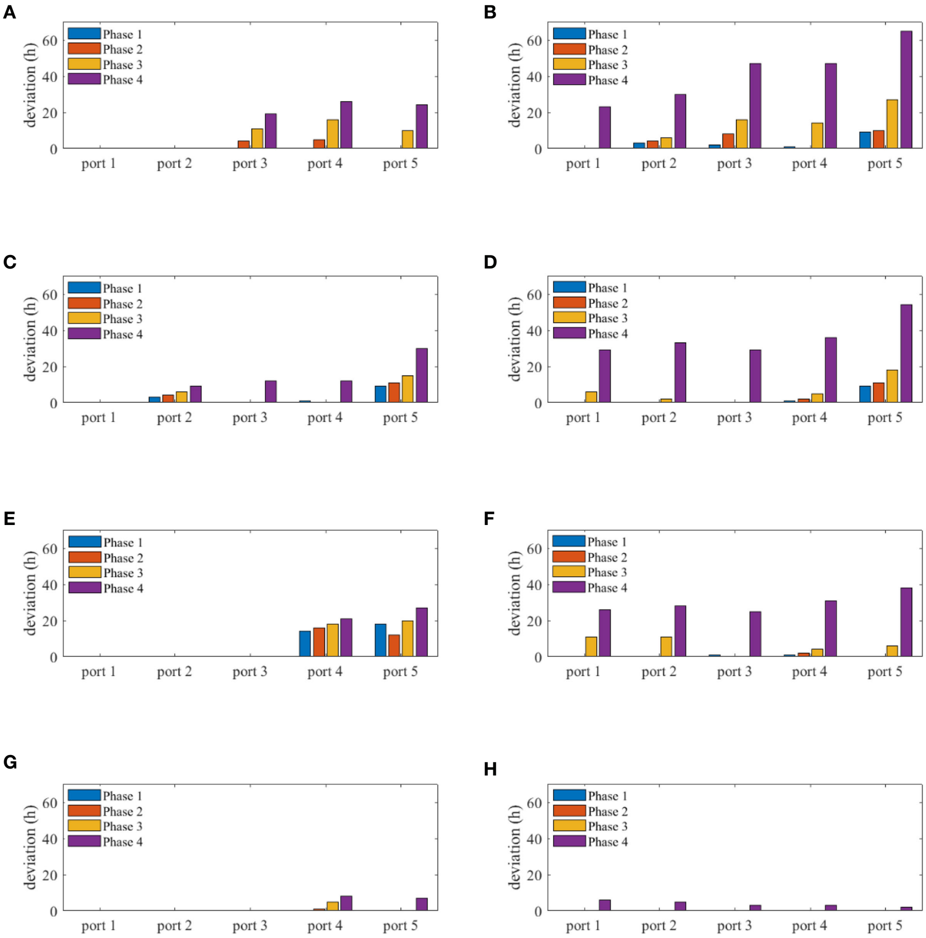

FIGURE 11
Arrival time deviations in different phases at each port of **(A)** ship 1 in the first voyage; **(B)** ship 1 in the second voyage; **(C)** ship 2 in the first voyage; **(D)** ship 2 in the second voyage; **(E)** ship 3 in the first voyage; **(F)** ship 3 in the second voyage; **(G)** ship 4 in the first voyage; **(H)** ship 4 in the second voyage.

expansion of delays. In Phase 2, there is a small increase in port delays; however, overall carbon emissions and fuel consumption are reduced, making the overall cost comparable to Phase 1. Despite this, the comprehensive costs of Phase 3 and 4 are considerably increased due to excessive delays.

4 Discussions and conclusions

In our paper, we investigated how liner shipping lines can maintain schedule reliability while reducing carbon emissions and fuel consumption through real-time speed optimization under the uncertainty of port handling efficiency and the need to meet EEXI standards. Firstly, we established a DHA model to describe the hybrid dynamic characteristics of the liner shipping system. Then, we constructed a prediction model using the DMPC framework by analogy with the previously established DHA model. Next, we designed a DMPC controller based on the receding horizon optimization method. In the DMPC framework, the schedule is converted into tractable position–time coordinates; furthermore, we considered minimizing tracking errors, carbon emissions, and fuel consumption as optimization objectives, and converted the EEXI specification into constraints by using the EPL solution. We adjusted the ships' speeds by an online rolling optimization

TABLE 7 Results in different phases.

Results	Phase 1	Phase 2	Phase 3	Phase 4
Total deviation (h)	72	90	227	755
Carbon emission (t)	7032.70	6968.98	6653.24	5851.27
Fuel consumption (t)	2193.61	2173.73	2075.25	1825.10
Weighted cost	1.89	1.89	1.96	2.37

method to compensate for the impact caused by uncertain port handling efficiency. Our experiments verify the effectiveness of our proposed DHA-DMPC controller. Our sensibility analysis revealed that the rolling optimization method considerably reduces fleet port delays; however, these improvements come at the expense of consuming more fuel and emitting more carbon emissions. Therefore, the liner company must maximize the overall benefits by weighing the relationship between schedule reliability and energy efficiency.

Finally, we present our conclusions from analyzing our experimental results regarding decision making for liner shipping lines:

(a) Liner shipping operations are vulnerable to operational uncertainties in ports, and it is impossible to accurately predict port handling efficiency. As a result, the service speed determined in tactical planning often loses its optimality during operations. When a port delay occurs, if the ship continues to sail at the service speed, the delay will be worsened because of a lack of timely adjustment measures. This will eventually not only reduce the service level of the shipping company but also disrupt the supply chain by affecting the coordination of ships and MCT operators. Therefore, real-time ship speed management is essential. The real-time adjustment of vessel speeds enables robust fleet operation, allowing management to cope with unexpected external conditions and maintain high service levels while effectively controlling overall fleet fuel consumption and carbon emissions;

(b) Table 6 shows the main engine power limitations of the sample ship for various EEXI phases, and we can infer that under strict emission regulations, the fleet's technology performance will be constrained, reducing the maximum speeds that the ships can reach. The ability to improve schedule reliability and energy efficiency by adjusting operation speeds will be considerably constrained if the maximum speed of the ship is further restricted. Liner shipping lines may consider adding more ships to the route or improving the fleet's technical efficiency to maintain a steady schedule;

(c) Table 7 reveals that maintaining high schedule reliability by taking control actions will finally lead to more fuel consumption and carbon emissions. Liner shipping lines should balance the trade-off between ships' fuel consumption, carbon emissions, and schedule reliability by implementing appropriate speed-reduction strategies. Another recommendation is to use sustainable energy so that the ship can significantly reduce its emissions while traveling at the same speed. As a result, the shipping lines can maintain a steady and competitive schedule while traveling faster and emitting less carbon dioxide.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

JZ and QZ contributed to conception and design of the study. JZ organized the database. CM performed the statistical analysis. JZ and CM wrote the first draft of the manuscript. JZ, CM, and QZ wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Algorithm 3

Input: $v_i^{ser}, \hat{h}_j, \hat{H}_{i,j}, l_m$
Initialize $ETA_{i,j}^w$, $ETD_{i,j}^w$ and $x_i(k)$
set $ETA_{i,1}^1 = 0$, $x_i(0) = 0$
while $i \le n_v$ do
  for each w **do**
    for each j **do**
      calculate $ETA_{i,j}^w$ and $ETD_{i,j}^w$ based on $v_i^{ser}, \hat{h}_j, \hat{H}_{i,j}, l_m$
    end for
  end for
  for $k = 1 : T_{stop}$ **if** $k = ETA_{i,j}^w, (w \ge 2)$ **then**
    $x_i(k) = 0$
  else
    for each j
      if $ETA_{i,j}^w \le k \le ETD_{i,j}^w$
        $x_i(k+1) = x_i(k) + \frac{l_m}{ETD_{i,j}^w - ETA_{i,j}^w + 1}$
      end if
    end for
  end if
  end for
end while

ALGORITHM 3
reference trajectory generator ignoring berthing process.

Appendix B. Experiment results

TABLE 8 ETA/ETD in the ideal situation.

Port	Ship 1	Ship 2	Ship 3	Ship 4
ETA/ETD (h) of the first voyage				
Port 1	0/11	93/104	186/197	279/290
Port 2	42/63	135/156	228/249	321/342
Port 3	148/169	241/262	334/355	427/448
Port 4	203/234	296/327	389/420	482/513
Port 5	289/303	382/396	475/489	568/582
ETA/ETD (h) of the second voyage				
Port 1	372/383	465/476	558/569	651/662
Port 2	414/435	507/528	600/621	693/714
Port 3	520/541	613/634	706/727	799/820
Port 4	575/606	668/699	761/792	854/885
Port 5	661/675	754/768	847/861	940/954

TABLE 9 ATA/ATD (Actual time of arrival/departure) in an uncontrolled scenario.

Port	Ship 1	Ship 2	Ship 3	Ship 4
ATA/ATD (h) of the first voyage				
Port 1	0/11	93/114	186/197	279/290
Port 2	42/83	145/171	228/249	321/342
Port 3	168/196	256/277	334/376	427/455
Port 4	230/260	311/262	409/448	489/520
Port 5	316/330	417/431	503/517	575/589
ATA/ATD (h) of the second voyage				
Port 1	399/420	500/511	586/601	658/669
Port 2	451/492	542/563	632/653	670/721
Port 3	577/598	648/676	738/766	806/827
Port 4	632/683	711/762	800/839	861/882
Port 5	738/752	816/830	894/908	947/961

TABLE 10 ATA/ATD in the scenario under reference 1.

Port	Ship 1	Ship 2	Ship 3	Ship 4
ATA/ATD (h) of the first voyage				
Port 1	0/11	93/114	186/197	279/300
Port 2	42/83	144/170	228/249	321/342
Port 3	148/176	241/262	345/387	427/455
Port 4	203/234	299/350	413/452	482/513
Port 5	289/303	396/410	493/507	568/582
ATA/ATD (h) of the second voyage				
Port 1	372/393	465/476	558/573	651/662
Port 2	419/460	507/528	600/621	693/714
Port 3	522/543	614/641	707/735	799/820
Port 4	578/628	671/722	762/801	854/885
Port 5	675/689	768/782	847/861	941/954

TABLE 11 ATA/ATD in the scenario under reference 2.

Port	Ship 1	Ship 2	Ship 3	Ship 4
ATA/ATD (h) of the first voyage				
Port 1	0/11	93/114	186/197	279/300
Port 2	42/83	138/164	228/249	321/342
Port 3	148/176	241/262	334/376	427/455

(Continued)

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TABLE 11 Continued

Port	Ship 1	Ship 2	Ship 3	Ship 4
Port 4	203/234	297/349	403/442	482/513
Port 5	289/303	391/405	484/498	568/582
ATA/ATD (h) of the second voyage				
Port 1	372/393	465/476	558/573	651/662
Port 2	417/458	507/528	600/621	693/714
Port 3	522/543	613/641	707/735	799/820
Port 4	576/628	669/720	762/801	854/885
Port 5	670/684	763/777	848/862	940/954

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Policy-driven or market-driven? A new perspective on the development of China's cruise industry

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The past 15 years have witnessed the rapid development of China's cruise industry from scratch and the formation of a policy system in the cruise industry, reflecting the shift of the Chinese government's attitude towards the cruise industry from wait-and-see, recognition and encouragement to active support. The paper conducts a statistical analysis of 128 policies related to the cruise industry issued by China's administrative departments at all levels. It is found that the release of policies synchronizes with the development of the cruise industry, with each one providing feedback to the other. The policies do not exhibit a time lag with respect to their effects. The evolution of policy types from macro-level guidance to concrete operation is rapid, with the policy structure gradually improving. In line with current characteristics of the development of China's cruise industry, the themes of the policies concentrate on five areas: cruise tourism services and products, port construction and development, cruise industry chain expansion, cruise industry environment and cruise industry management. However, there is still a lack of adequate policies to support and guide the industrial upgrading of cruise operation and cruise construction and its green and low-carbon development. In addition, the paper points out the main directions of future policy formulation.

KEYWORDS

cruise tourism, industrial upgrading, policy, evolution, cruise industry

1 Introduction

From the 1980s to the outbreak of COVID-19, the cruise industry has grown steadily at an average annual rate of 7.6%, becoming one of the most active parts in the world's tourism industry (Sun et al., 2014). Although the current international cruise tourism market is still predominantly concentrated in North America and Europe, international cruise lines continue to explore new markets and develop new routes and destinations, with more cruise tourism destinations and markets emerging at a rapid pace. Among them, the Asia-Pacific market has become one of the most striking emerging regions, with the development rate surpassing the world average level. The skyrocketing growth of the Chinese cruise market in recent decades has become a miraculous phenomenon in the global cruise economy over the past 40-odd years (Hung et al., 2019).

The year 2006 has generally been regarded as the beginning year in the development of China's cruise industry, when Allegra of Costa Crociere, owed by Carnival Corporation & plc, launched its first homeport route in Shanghai. Within just a dozen years, China ranked second in the global cruise market, with 2.1 million tourists in 2016 and 4.88 million in 2018(Wang et al., 2020). Increasing Chinese tourists begin to accept and love cruise travel, which is a new means of tourism (Li et al., 2021a). During this period, Carnival Corporation & plc, Royal Caribbean International, Star Cruises and Mediterranean Shipping Company S.A. entered the Chinese market one after another and they deployed 15 ships in the Chinese market, with more than 40,000 beds on board in 2020 (Qian et al., 2021). Meanwhile, several domestic cruise companies have also started to boom by purchasing and leasing international cruise ships, including SkySea Holding International Ltd, Nanhai Cruises, China Taishan Cruises and Diamond Cruise. Under the impact of COVID-19, these cruise ships were suspended temporarily. During the Covid-19 epidemic, cruise epidemic prevention and control, the risks in the cruise supply chain and the impacts of cruise ship anchoring have received great attention and discussion (Li et al., 2021b; Zhang et al., 2022; Zhou et al., 2023). This has also contributed to the formation of a new pattern in the cruise industry during the post-epidemic recovery process. With the normalization of the global epidemic, cruise lines in most regions have resumed service on a large scale. Cruise companies will develop more cruise brands and deploy varied routes to provide diversified products and services to cater to the needs of the gradually mature Chinese market.

With the joint efforts of the government, industry organizations, various enterprises and other stakeholders of the cruise industry, China's cruise industry has developed from scratch, overcoming numerous difficulties in the management as well as the system and achieving remarkable results. What is noteworthy is the springing up of modern cruise terminals (Ma et al., 2018). Although most of the tremendous wharf construction costs have not been recovered and the profits of the wharf operation itself are unstable, the supporting services such as ship supplies and trade services driven by the wharf services have brought generous profits to the port cities and related industries.

China aims at developing a more complete cruise industry chain and gaining more economic benefits. In this process, a series of policies to promote the development of the cruise industry at the national and local levels were issued in succession to bridge the gaps in policies and systems, while trying to solve new problems encountered in such areas as tourism services, transportation, labor, trade, market regulation and so on. While China has gradually established institutional measures in line with the international standards of the cruise industry, it has also innovatively explored the "China model" in the industry.

Related studies have also gradually deepened with the development of the industry and its policies. At the early stage of the development of China's cruise industry, Li and Yan (2013) and He (2015) analyzed the gaps and obstacles in the policies and laws related to the development of China's cruise industry, and suggested the implementation of such policies as tax preferences, customs clearance facilitation, cruise finance, foreign investment access, and cruise ship supply. With the further development of the industry, policy studies of industrial elements have also begun to emerge, such as policy research concerning the construction of domestic cruise ships in China (Xie, 2020), and environmental policy response and evolution of pollution problems in cruise shipping (Qin and Wang, 2019). In terms of policy innovation, Sun and Lin (2021) explored the relationship between policy innovation and industrial evolution, arguing that the interaction between cruise industry elements, operational management systems, and macro and auxiliary support systems must be considered holistically in the process of policy formulation.

The paper collects 128 cruise-related policy documents issued by Chinese governments at all levels during the 15 years of the initial development of China's cruise industry, systematically analyzes their themes, contents and characteristics, and seeks to address the following questions: First, does China's cruise policies reflect the change in the government's attitude towards the cruise industry in the past 15 years? Second, how effective are the cruise policies? Third, do policies and the market develop synchronously? Do policies drive markets, or vice versa? Fourth, how do the policies affect the development of China's cruise industrial chain? Are the policies proactive or passive to meet the needs of industrial development and upgrading?

The main contribution of this study lies in two aspects: First, by probing into China's cruise policies and the development process of China's cruise industry, we can reveal the evolutionary relationship between the policy and the industry. Second, based on the above-mentioned study, the problems regarding policies in the development and upgrading process of the cruise industry are identified, and future directions for cruise policies are proposed. Therefore, this study will help to provide reference and support for the development of China's cruise industry from a policy perspective.

2 The cruise industrial chain and its status quo in China

2.1 Modern cruise industrial chain

Cruise industry is a composite industry with the cruise ship as the core and sea sightseeing as the main content, involving many sectors, from transportation, ship design and manufacturing, homeport construction, port services, tourism services, ship material supply and replenishment, cruise operation, food shopping and business development, finance, insurance, to

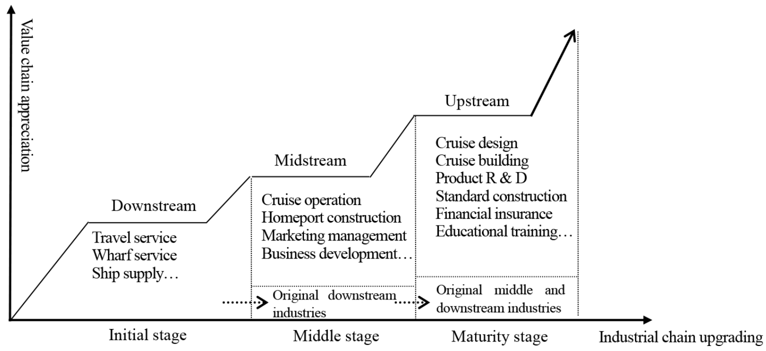

FIGURE 1
The developmental trajectory of cruise industry upgrading.

education and training (Clancy, 2008; Gibson, 2018). The trajectory of the upgrading and development of the cruise industry chain can be summarized as Figure 1 according to industrial value chain.

In terms of supply, international cruise ship industrial chain is basically composed of three parts:

The first is the design and construction of cruise ships, whose main body is the cruise shipyard. Since cruise ship design and manufacturing is a capital and technology intensive industry, it requires a large number of supporting products and technical services, which can drive the common development of related industries with a ratio of 1:44 in business, so it belongs to the upstream industrial chain (Liu et al., 2011). With the advanced design concept and shipbuilding technology, European corporations has dominated the global cruise manufacturing industry, obtaining tens of billions of euros in revenue every year (Kowalczyk, 2018).

The second, the midstream industrial chain, is the operation of the cruise itself, whose main body is the cruise company. At present, cruise companies such as the world's three largest cruise groups, namely Carnival Corporation & PLC, Royal Caribbean International and Star Cruises, account for virtually 80% of the market share in the world cruise industry (Syriopoulos et al., 2020).

The third is the downstream industry chain, composed of the construction of cruise terminals and supporting facilities and related services. The cruise terminal services mainly provide supporting services such as berthing, towing, marine supplies, tourism services and business services for cruise ships.

With the continuous extension of the international cruise industrial chain, cruise tourism will bring a great flow of people, information and traffic to cruise home ports and port cities, thus effectively driving the formation and development of logistics, communications, real estate, culture, tourism, catering, shopping and other related industries in these regions (Pallis, 2015). Being at the high end of the value chain, Cruise tourism connects cruise ships and multiple cruise destinations, drives the flow of products and services in port cities and surrounding areas, stimulates massive consumption and triggers value-added effects.

2.2 Main characteristics of China's cruise industry development

From the perspective of industrial chains, China's cruise industry is still in its infancy. Apart from the exploration of cruise market and port construction, China's current main industry is centered on cruise port cities, and its main business is the construction and development of tourism services and terminal services. The main characteristics are reflected in the following three aspects:

First, the Chinese cruise market has developed by leaps and bounds. Since the 1980s, modern cruise tourism has entered the stage of rapid development with an average annual growth rate of 7.2% (Qian et al., 2021). The United States is now the world's largest cruise consumption market, accounting for approximately half of the global cruise market share. Britain, Germany, Italy and Spain are the main sources of passengers in the European cruise market (Dowling and Weeden, 2017). However, in recent years the market share of other emerging regions has been increasing. After a dozen years of rapid growth, China's cruise market has jumped to the second largest one next only to the United States (Table 1). With a high percentage of about 90%, the travel agency charter model is a unique sales mode in China and a catalyst for the vigorous growth of the Chinese market (Sun et al., 2016; Li et al., 2021a).

Second, there is a new wave of Chinese cruise port construction and a rapid growth of home port voyages. At present, China's coastal port cities are also competing to develop cruise economy. From 2010 to 2019, port facilities with the function of home ports were built in 13 cities, including Tianjin, Shanghai, Xiamen and Sanya and basic supporting services have been provided through development, thus bringing preliminary economic benefits to port cities and regions. The water depth conditions and terminal facilities of cruise ports have laid a solid foundation for cruise companies to open homeport routes. Figure 2 shows the statistics of homeport voyages and visiting port voyages in Mainland China from 2007 to 2019, and Figure 3 shows the number of cruise trips in various ports in China. Cruise companies in the Chinese market

TABLE 1 The distribution of world cruise tourists in 2018.

Ordering	Countries	Global Market Share	Change Rates within 5 Years
1	America	46.60%	9.14%
2	China	8.50%	148.19%
3	Germany	8.00%	2.10%
4	Britain	7.69%	5.25%
5	Australia	5.26%	35.13%
6	Canada	3.23%	10.36%
7	Italy	3.23%	20.67%
8	France	2.43%	0.45%
9	Brazil	2.02%	40.91%
10	Spain	2.02%	10.13%

Source: CLIA 2018 State of the Cruise Industry Report.

launched a variety of cruise tourism products, among which the more mature lines are distributed in Northeast Asia, Southeast Asia and Taiwan, China.

Third, China's cruise products are supplied mainly by foreign cruise companies. In general, cruises operating in China are from corporations with foreign capital. In 2006, Costa Crociere opened its home port in Shanghai for the first time and its huge potential passenger source market is valued by cruise companies. Since then, Costa Crociere of Italy, Royal Caribbean International of the United States and Genting Hong Kong Limited (Star Cruises) have successively opened cruise lines departing from their home ports in China, and the number of beds on international cruises operating in China has increased from 900 in 2006 to 16,000 at present. Figure 4 presents a timeline of cruise ships operating in China. Despite several attempts, local cruise companies haven't really been established.

3 The statistical analysis of cruise policies in China

3.1 The analysis of policy-issuing entities

As a complex industry, the cruise industry includes, among others, cruise manufacturing, cruise operations, port reception and tourism consumption. It depends on the combined support of the related industries, national strategies, rules, regulations and policies. To solve bottleneck problems, it requires government departments to strengthen guidance in the formulation of policies and the reinforcement of management mechanisms, thereby promoting industrial upgrading and alleviating possible negative effects (Johnson, 2002; Small and Oxenford, 2022). Since international cruise ships are imported goods in China, the original ship and ocean transportation management systems are not necessarily

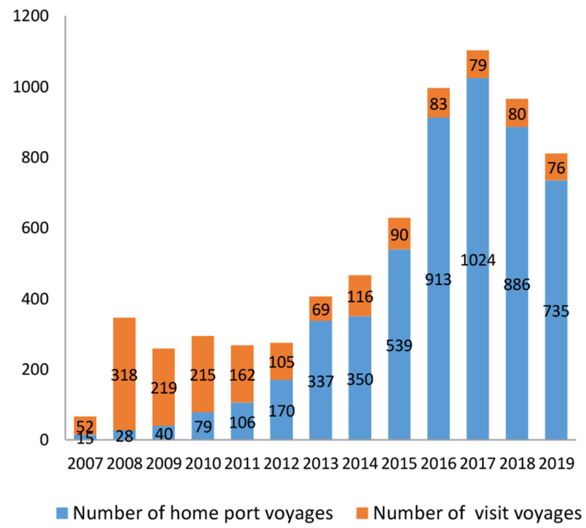

FIGURE 2
Voyage Statistics in Mainland China from 2007 to 2019.

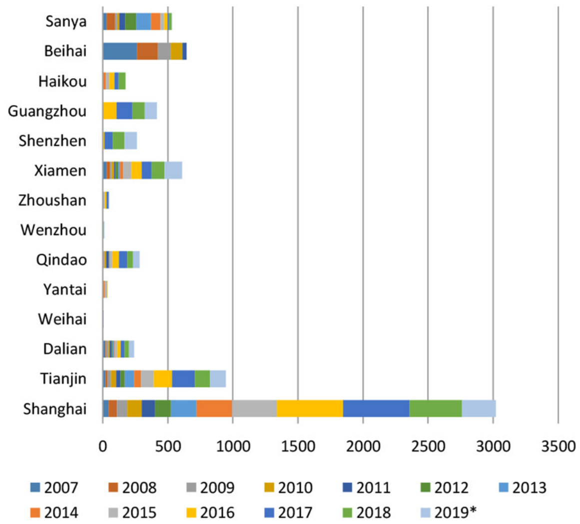

FIGURE 3
Cruise voyages of Chinese ports from 2007 to 2019.

suitable to the Chinese market and therefore after 2006, policies were frequently rolled out in China to promote the growth of the cruise industry.

The policy documents selected by this study are all from public data, including 128 cruise policy documents obtained from official government websites. Overall, the policy-releasing entities exhibit the following three characteristics:

First, there is a large number of policies, at both the national and the local levels, among which 70 documents were from national agencies and 83 from local agencies (the total documents outnumber the policies because some policies are jointly released by multiple departments). Figure 5 shows that at the national level, The State Council, the highest administrative authority in China, is the major policy-issuing body (up to 26) and at the local level, the local authorities are the principal issuing entities (up to 45). This strongly indicates that the national and local government agencies attach great importance to the cruise industry.

Second, the fact that policy-issuing entities include many departments is indicative of the gradual maturity of cruise industry policies in China. According to Figure 5, it can be found that there are more than a dozen policy-issuing departments. Besides the State Council and local governments, the departments involved include the National Development and Reform Commission, the Ministry of Culture and Tourism, the National Customs Administration, the Ministry of Transport, the Supreme People's Court, the State Oceanic Administration, the Ministry of Public Security, the Ministry of Finance, the National Immigration Bureau, the Ministry of Foreign Affairs, the Ministry of Commerce, the Ministry of Information Industry. It can be also noted that the Ministry of Transport and the Ministry of Culture and Tourism

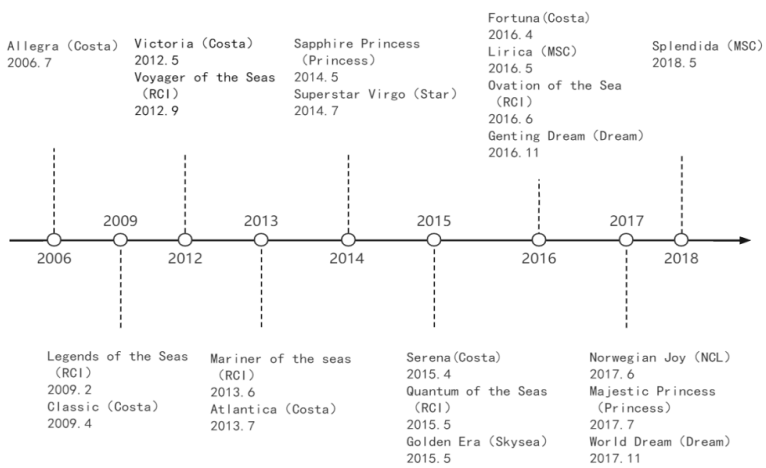

FIGURE 4
The timeline of cruise companies and ships operating in China.

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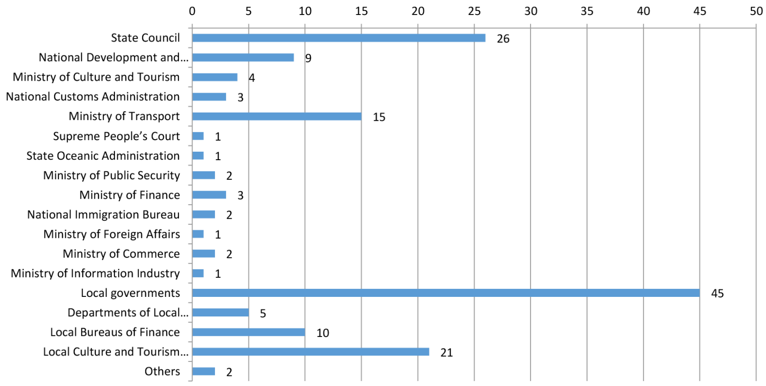

FIGURE 5
Statistics of policies by central and local government agencies.

rank among the top in the number of released policies, showing that China's cruise industry policies mainly support and serve port construction and tourism services. The number of policies released by the National Development and Reform Commission and local finance bureau is also quite large, demonstrating China's substantial support of the cruise industry concerning industrial planning layout and local financial policies.

Third, local policies are mostly issued by cities and regions where cruise ports are located (Figure 6), such as Shanghai, Tianjin and Hainan. There is no doubt that these local policies are beneficial to the development of cruise ports and tourism in these cities. Is it the case that there are more cruise lines where more policies are made? Which is more obvious, local policies or national ones? A correlation analysis will be conducted later to address these issues.

3.2 The analysis of release time and types

There are 128 cruise policy documents collected and this study analyzes their release time and types. We find that the number of released policies fluctuates greatly during the period from 2007 to 2021(Figure 7), which can be roughly divided into three stages:

3.2.1 Phase I: policy exploration period (2007-2011)

In these four years, the number of issued policies was relatively small, totaling only 4. From the perspective of policy types (Figure 7), the policies are all macro-guiding ones at the national level, lacking policies released at the provincial and municipal levels. The themes of the four policies manifest that at this initial stage, the Chinese government recognizes the role of cruise tourism as a new tourism product in enriching the tourism consumption market. However, it has not yet been made explicit how to develop the cruise industry. Therefore, policies at this stage reflects that China takes a positive approach towards the cruise industry but are still on the sideline s.

3.2.2 Phase II: Policy development period (2012-2018)

There were 101 policy documents issued during the seven-year period, with the number of policies rising sharply for each subsequent year. In 2017 alone, there were 34 policies released. The types of released policies are also diversified. The number of provincial and municipal documents increased to a large extent, and especially from 2016 to 2018, the proportion of local policies

FIGURE 6
Local cruise policies issued by cities and provinces.

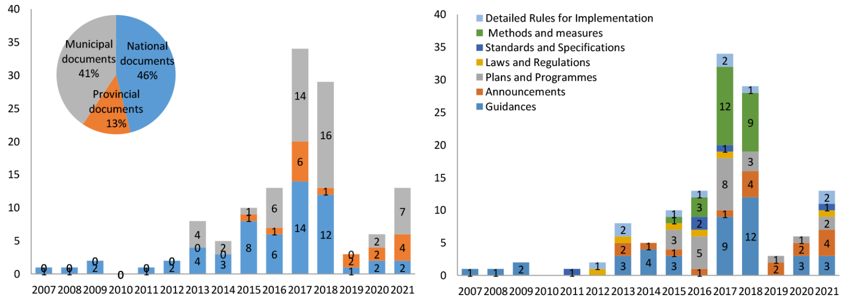

FIGURE 7
Types of released policies. Note: The figure on the left shows statistics of policies issued by administrative bodies at different levels; The figure on the right shows the statistics of the number of different policy types.

exceeded that of national policies. Local cruise policies mainly focus on cruise port cities and regions. With national policies as the basis, they have issued more documents on cruise port construction and development, cruise tourism services and market norms to resolve practical issues in local industries.

At this stage, the proportion of guiding documents gradually decreases, and more specific operational documents are put in place, including announcements, plans and programs, laws and regulations, standards and specifications, methods and measures, detailed rules for implementation. This change shows that China's cruise policies and the development of the industry, to some extent, mutually reinforce each other. Put simply, the policies promote the development of the industry, which in turn calls for new policy requirements. From macro-level guidance documents to micro-level specific operational documents, the cruise policies have been systematically formulated, indicating the gradual process of development in China's cruise industry.

3.2.3 Phase III: Policy improvement period (2019-2021)

After the period of policy development, the speed of issuing policies began to slow down, and a total of 22 policy documents were released in three years, which is related to the impact of the Covid-19 pandemic on the cruise industry. Since the outbreak of the pandemic, China's tourism industry has ground to a halt and the normal operation has not been resumed yet.

However, it is true that cruise policy documents in the past three years were mainly issued by local documents, and policies are executed more efficiently and operationalized in a more standardized manner, indicating that the policies have penetrated into the specific industry level.

Compared with the previous two phases, the policy themes touch more on deep-rooted and new issues of industrial development, including epidemic prevention and control, safety and hygiene, encouragement of new routes and combined transportation, and planning and development of local cruise ports and tourism services.

4 The analysis of the impact and effects of cruise policy

4.1 Assumptions on policy impact and effects

Because the cruise policies issued by the state and local governments will actively promote the development in all aspects of the cruise industry, enhance the market attraction of cruise products, and provide cruise enterprises with more convenience and support conditions, international cruise companies will deploy more cruise ships in China to operate more voyages. Therefore, cruise voyage is a very straightforward indicator, and the change can be a good measure of the size of the market and the development of the cruise industry (Dwyer et al., 2004).

To verify the impact and effect of cruise policies, we conducted a correlation analysis between the number of policies and the number of voyages. The following four hypotheses are formulated in this study.

Hypothesis 1: The effects of national and local cruise policies are immediate. The release of the policy directly affects cruise voyages of the year. In other words, the release of the policy is directly related to cruise voyages of the year.

Hypothesis 2: It is generally believed that it takes a certain period of time for a country's macroeconomic policy to play its role. This is the time-lagging effect of the policy, because it sometimes acts on certain factors and indirectly changes the economy. Therefore, the impact and promotion of policies on the cruise industry may be lagging behind, regardless of national or local policies. This study assumes that the industry is lagging, with a one-year delay.

Hypothesis 3: Cruise policies should promote and influence domestic and international markets in all directions. Therefore, the release of the policy is not only conducive to promoting the development of home port cruise ships, but also to attracting foreign cruise ships touring China.

Hypothesis 4: The China's soaring cruise market is different from that of other countries and regions. Is it possible that national and local governments passively issue policies to meet and adjust to the needs of the cruise industry because of difficulties or barriers encountered in the development of the cruise industry? The study assumes that the policy is lagging, with a one-year delay.

4.2 Hypothesis verification results and the analysis

The statistical data correlation analysis of policies and all kinds of voyages shows that cruise policies include three indicators: the number of cruise policies released, the total number of words in a policy, and the number of policies in a particular place; cruise voyages include four indicators: annual cruise voyages, visiting cruise voyages, home port cruise voyages and total cruise voyages at each port. The results of correlation analysis (Table 2) reveals some interesting phenomena during the verification of the four hypotheses:

Hypothesis 1 is correct. There is a strong positive correlation between the number of policies and total voyages, with correlation coefficient up to 0.8323. An even higher correlation shows up between the number of words in policy documents and total voyages (0.865011). This result can be interpreted as: the policy directly stimulates the number of trips and there is an obvious linear relationship between the two (Figure 8). But is it really that simple? Here arises a question: does the policy affect the voyage or does the voyage affect the release of the policy? This is an issue worth discussing, since as is customary with cruise companies, itineraries and ship deployment plans are usually determined a year, or at least six months, in advance. In this case, if there is a positive correlation between the number of policies and the total voyages of the year, it can be understood that the cruise company's confidence in the market affects its voyage deployment and thus policy release.

Hypothesis 2 is not correct. The number of policies and total voyages (one-year lag) present a weak positive correlation, and the correlation coefficient is 0.735551. Statistically speaking, the correlation is not low. However, compared with hypothesis 1, the correlation coefficient is reduced by 0.1, proving that China's cruise policy does not have a significant lag, meaning that the correlation between policy issuance and the number of voyages in the current year is significantly greater than that of a one-year lag. Is the development and policy of China's cruise industry synchronized?

Hypothesis 3 is partially correct. We analyzed the correlation between the release of cruise policies and homeport voyages and that between the release of cruise policies and visiting cruise voyages. It can be found that the correlation coefficient between cruise policies issued by the central government and local governments and homeport voyages in China is 0.8281, showing a strong positive correlation and an obvious linear relationship (Figure 9). However, the correlation coefficient between policy releases and visiting voyages is -0.5245, demonstrating a weak negative correlation, which is unexpected. Does the release of policy restrict the number of visits? Doesn't the Chinese government welcome cruise ships to its ports? This is highly unlikely. According to the analysis of policy contents, policies about tourism services, port construction, incentives for cruise stops and visa-free transit are ones China has issued in recent years to encourage cruise visits, but to little effect. What is the reason behind the decrease in cruise visits?

The reason needs to be considered from the source market of cruise visitors. Most cruises to ports of visit in China come from long-haul routes in Europe and the United States, or world voyage cruise lines that extend to the Asia-Pacific region. At present, there are few world voyages in the Asia-Pacific region, and it is hard to attract enough customers in the Asia-pacific region due to consumption habits. Since the 2008 financial crisis, the European economy has continued to decline with fewer round-the-world cruise lines from the United States, so there have been fewer cruise ports of call in recent years. The areas covered by cruise lines of ports of visits are mostly distributed in the tourist destinations around the world-class home ports, such as the Caribbean region and Alaska near the source market of the United States, and the Mediterranean region near the European continent. For cruise ports in China's coastal areas, they fail to attract sufficient cruise passengers in neighboring areas such as Japan and South Korea, so there are few short-range routes within the region.

Hypothesis 4 is not correct. In the previous analysis, it is found that China's cruise policy has no time-lagging effect. We might as well make a bold guess. Does the government passively issue policies to meet and adjust to the needs of industrial development? A careful analysis demonstrates that it is not valid, because the correlation coefficient between the number of policies with a one-year lag and the total voyage is 0.731261. Although it presents a weak correlation, this coefficient is lower than the correlation coefficient of the

TABLE 2 The correlation between the number of cruise policies and voyages between 2007 and 2019.

Cruise policy	Different voyage types	Correlation Coefficient	Illustration
Number of policies	Total voyage	0.8323	Strong positive correlation
Number of words in a policy document	Total voyage	0.865	Strong positive correlation
Number of policies	Access to the voyage	-0.5245	Weak negative correlation
Number of policies	Home port voyage	0.8281	Strong positive correlation
Number of local policies	General voyage of local ports	0.4277	Weak positive correlation
Number of policies	Total voyage (one year behind)	0.7355	Weak positive correlation
Number of policies (one year behind)	Total voyage	0.7313	Weak positive correlation

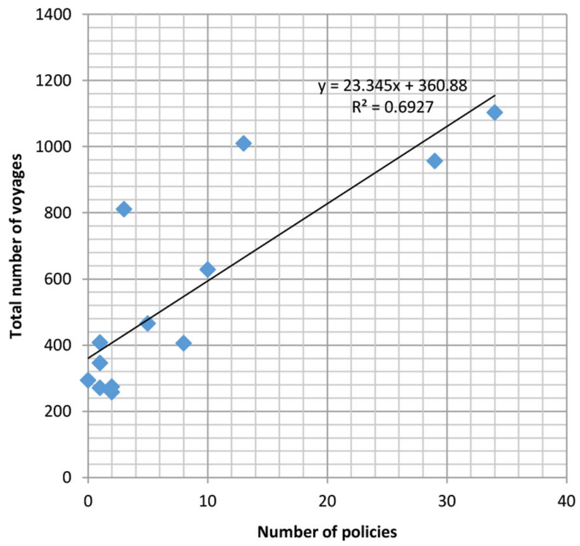

FIGURE 8
Linear relationship between cruise policies and total voyages.

synchronization of the two indicators (0.832277). Therefore, it cannot be concluded that industry promotes the policy release. However, through the analysis and verification of these assumptions, it is confirmed that policies and industrial development are synchronous, and that they provide timely feedback to each other, with a high correlation and no time lag.

5 The analysis of themes and contents of cruise policies

In the previous section, we analyzed the number of released Chinese cruise policies and their impact, and we found that the number of release policies and the number of Chinese cruise voyages exhibit a relatively obvious synchronization. Then, the following questions need to be answered: does the release of the policies synchronize with the development of the cruise industry chain? The cruise industry chain is divided into upstream, middle and downstream. Is China's cruise policy conducive to the upgrading of the industry?

The 128 cruise policies-related policies collected in this paper involve entry-exit, customs, maritime affairs, transportation, tourism, shipping, passenger transport, port, environmental protection, public security, taxation, among others. Following the meticulous reading and analysis of the contents of these policies, they are summarized in the following five themes: cruise tourism

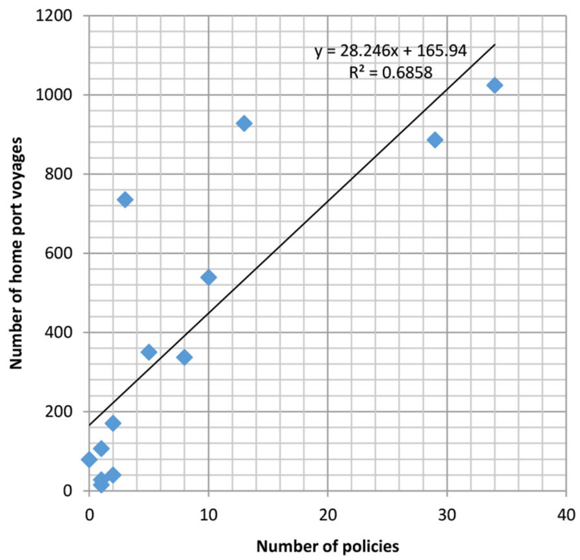

FIGURE 9
Linear relationship between cruise policies and home port voyages.

services and products, port construction and development, cruise industrial chain expansion, cruise industry environment and cruise industry management. Among them, cruise tourism services and products have the highest percentage (29%), followed by the cruise industry environment (23%) and, the other three (coincidentally 16%). In terms of the classification of cruise industry, the cruise policies issued by China actually shows the evolutionary process and stages of China's cruise industry. The percentages of various theme policies in the three stages of cruise policy development are schematized in Figure 10. It can be found that the policy themes are becoming more and more diversified, which reflects the development and maturation of China's cruise industry.

In the initial stage, especially in the first three years, the policies issued were mainly related to the environment of the cruise industry. Industrial environment refers to the development environment created by various supporting policies and measures (Tanaka, 2011), such as policies to promote reform and opening up, as well as the investment in consumption and tourism industry, incentive policies in finance, insurance and law, policies on tax rebates for international tourists, and macro development opportunities brought by China's "One Belt, One Road" initiative (Chen and Yin, 2018). All of these comprise the supporting environment system for the cruise industry. Macro environment involved in national and local policies and the development direction has created a new opportunity for the development of the cruise industry.

Cruise port construction and port reception services are the main themes in cruise policies from 2011 to 2014. National and local government departments encourage and support the layout of cruise infrastructure in areas with good conditions for development, such as the Bohai Rim, Yangtze River Delta, Southeast Coast, Pearl River Delta and southwest coast, thus providing basic conditions for international cruise companies to deploy cruise ships and open up routes. Meanwhile, the trend of large-scale cruise ships in the world has imposed increasingly higher demands on the berth conditions and service level of cruise terminals (Rodrigue and Notteboom, 2013). The issuing of a series of policies related to the planning of Cruise ports and the development of supporting facilities in China has pushed forward the transformation of Chinese port cities and the rapid construction of several modern large-scale cruise terminals.

The policy themes released from 2015 onwards began to exhibit variation. Most notably, there has been a large number of policies released on cruise tourism services alongside the continued increase of policies on the cruise industry environment and cruise port construction.

Cruise tourism service serves as an important part of cruise policy-making and the process of the domestication of cruise tourism industry. Innovative attempts have been made in various aspects, including cruise route layout, market promotion and channel optimization, product design and brand building, tourism commodities and duty-free shopping, cruise culture and consumer market cultivation(Wang et al., 2018). Thus, China's cruise industry has completed its layout in the primary stage in ten years, due to the fast-paced advancement of industrial environment, port construction and the tourism market.

It is also found that some polices for industry chain expansion began to be released in later years. The policies involve operating domestic Chinese-funded cruise ships and encouraging Chinese enterprises to establish Chinese-foreign joint venture or wholly owned local cruise companies by means of new construction, purchase or leasing through policy innovation, financing and financial support. The cruise design and construction is adopted in the nationally-encouraged industry list to support the localization of cruise manufacturing, and the development of the cruise industry is encouraged through the combination of technology introduction and independent innovation

Under the guidance of industrial policies, Chinese enterprises together with foreign cruise companies, the Classification Society, cruise manufacturing enterprises have jointly set up cruise manufacturing companies. The policies also cover the development of cruise ship supply, distribution services and supporting facilities, such as developing bonded warehousing for cruise ships, attracting domestic procuring business and so on. All these initiatives have paved the way for the gradual upgrading of China's cruise industry.

The global cruise industry in 2021 showed a marked improvement over 2020, with more than half of the ships returning to sea and the carrying capacity restored. Although China's cruise market has yet restarted, the government is still planning the layout of the industry in the years after the suspension. In the past three years, 22 policy documents have been issued in the

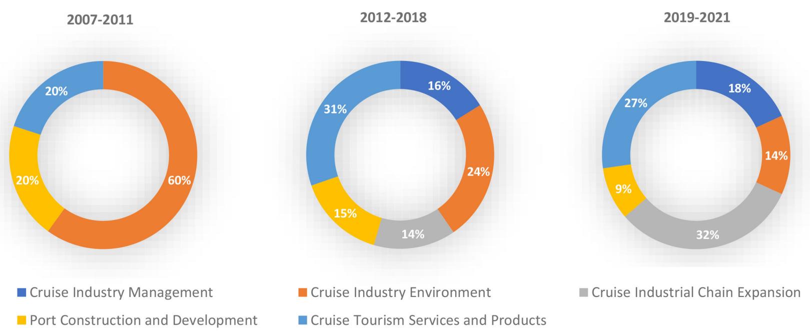

FIGURE 10
The theme distribution of cruise policies from 2007 to 2021.

fields of industrial environment, industrial management and industrial chain expansion to promote the upgrading and acceleration of the cruise industry. A package of policies has been released concerning creating a more open institutional environment, cultivating markets and responding to public security emergencies. For example, local governments have been encouraged to establish comprehensive bonded zones featuring cruise economy to promote the docking and linking of international cruise ports, cruise industrial parks and pilot free trade zones, and explore comprehensive supporting systems suitable for the development of new business forms of cruise economy.

6 Conclusions and prospects

6.1 Conclusions

China has issued 128 cruise policies in 15 years, and is unmatched by any other industries in terms of number and speed, showing the change of the Chinese government's attitude towards the cruise industry from wait-and-see, recognition and encouragement to active support. The analysis of this study has found that:

Firstly, the release of China's cruise policy is almost synchronous with the development of the cruise industry, and there is no time lag in the effect of the policy. The release of relevant policies in China is closely related to the development of the cruise industry and they provide mutual timely feedback. The issuing of China's cruise policies in the past 15 years indicates a new round of internationalization and reform and opening up in the tourism industry, port development and other fields. China has made many valuable attempts in policy innovation, such as the policy of innovative cruise industry pilot zones and free trade zones and special support policies related to finance, capital, talent recruitment and route approval for the development of cruise ships with five-star flags.

Secondly, the subjects and types of policies are evolving rapidly. From national governments and relevant departments to local ones, from the macro-level guiding policies to specific program plans, laws and regulations, industry standards and the detailed rules for the implementation, a policy system has been gradually formed with the growing number of policies and the enrichment of structures, which optimizes the industrial development environment and industrial development systems and promotes the development of the cruise industry.

Thirdly, China's cruise policies focus on five areas: cruise tourism services and products, port construction and development, cruise industry chain expansion, cruise industry environment and cruise industry management, which have accelerated the advancement of the cruise industry. However, the current policies are far from enough to achieve industrial upgrading and a policy system has not been established to meet the development requirements of middle and high-level cruise industries. There is still a long way to go in many fields, especially (Xie, 2022) cruise operation and construction.

Fourthly, given that carbon emissions exert constrains on China's economic development, the development of the cruise industry requires more explicit policies to guide and regulate emission behaviors, especially in the context of the clear target of carbon peak and carbon neutrality (Xiao and Cui, 2023). Currently, there is a relative lack of relevant policy documents in China and it is by no means enough to have only a guiding document entitled *Port and Shore Power Layout Scheme*. Policies to promote the green development of the cruise industry need to be perfected at the earliest opportunity and a couple of initiatives shall be introduced, such as the application of various low-carbon and zero-carbon technologies and equipment on cruise ships, and the installation of shore-based power facilities and alternative energy refueling facilities in cruise ports.

6.2 The future policy directions

6.2.1 Incentive programs for the optimization and upgrading of the industrial structure

The cruise industry covers numerous sectors, including cruise ship construction, port infrastructure, terminal, waterway and port services, ship replenishment, ship maintenance and renovation, tourism, hotels, transportation, shopping, etc. Those activities are intertwined with each other, producing direct and indirect economic contributions, with the multiplier effect. Statistics reports the European cruise industry's multiplier effect from 2013 to 2018 was 1:8, but Norway, Finland and France account for almost all the market of cruise design and construction, with actual higher multiplier effect (Braun et al., 2002). Therefore, how policies can better promote the development of China's cruise industry from the current primary stage of port construction and tourism services to a higher stage is an issue that needs to be addressed.

6.2.2 Financial policies for cruise industry development

In general, the cost of building cruise ships is very high. From 2006 to 2021, international cruise lines have deployed 34 cruise ships in China, including 11 new ships specially customized for China, running up to 76.5 billion yuan, with an average cost of 7 billion yuan and 1 billion dollars per ship (Ros Chaos et al., 2021). Because of the lower capital cost, the construction of new ships in Europe and the United States shall not exert great impacts upon the operation of cruise companies (Chang et al., 2017), while the high capital cost of cruise construction in China severely limits the advancement of cruise construction, which requires relevant policy systems to be formulated to lower the costs. To provide continuous financial support for cruise construction, the establishment of cruise industry development or investment fund can be initiated under the guidance of the nation and through the participation of enterprises and private capital.

6.2.3 Policies for cruise ship supplies

It is worth noting that Chinese cruise ships spend around 1.4 billion yuan annually on food and consumables, and 1.8 billion yuan on fuel respectively, but they have not made significant economic contributions to China. The main reason for this phenomenon can boil down to the complicated supervision of customs, which renders it difficult for many products to be replenished at Chinese ports due to complicated formalities. Over the years, through innovative policies in pilot free trade zones and cruise development zones, the proportion of replenishing at Chinese ports is increasing. However, since cruises are novelty in China, the government still needs to introduce flexible new policies to attend to the needs of the market, so as to promote the development of the cruise industry chain.

6.2.4 Policies for cruise talent cultivation and management

The cruise industry has created a wide variety of job opportunities. Statistically, the total number of people employed by cruise companies, cruise ports, waterways and ports and travel agencies in China has exceeded 35,000. The development of China's cruise industry and the gradual expansion of the industrial chain require more professionals to work in related fields. Therefore, more policies are required to support talent cultivation and management.

6.2.5 Supporting policies for port service management and innovation

The operation of cruises ports has brought tiny gains with the annual revenue of about 770 million yuan before Covid-19, although 13 cruise ports were built along China's coast from 2010 to 2019, totaling more than 20 billion yuan (Chen et al., 2019). Therefore, if China's cruise ports intend to gain more economic benefits in the future, soft services shall be further improved on the basis of a complete infrastructure, such as improving the customs clearance efficiency of cruise tourists and upgrading their experience in cruise ports. All these require the government to further simplify customs clearance procedures, and encourage management innovation of cruise ports so as to enrich the functions of ports and deliver unlimited business opportunities.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

HT: Conceptualization, Writing - Review & Editing. SC: Investigation, Methodology, Formal analysis. HL: Supervision, Resources. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Environmental efficiency of ports under the dual carbon goals: Taking China's Bohai-rim ports as an example

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In 2020, China proposed the country's dual carbon goals of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. Under the dual carbon goals, the low-carbon transformation has become an important development direction for Chinese ports. Taking eight ports in China's Bohai-rim port group as an example, this study adopts the Slacks-Based Measure (SBM) model to evaluate the port efficiency considering the environmental factor of carbon dioxide (CO_2) emissions. The results show that the average scale environmental efficiency of the eight ports during 2005-2020 is the highest, followed by local pure technical environmental efficiency and global technical environmental efficiency. The efficiency values of each port under different environmental efficiency categories vary greatly. Overall, each port is in a state of environmental inefficiency. From port technology, input-output optimization, supervision, and management of relevant departments, recommendations for improving the environmental efficiency of ports under the dual carbon goals are put forward.

KEYWORDS

environmental efficiency, carbon emissions, China's Bohai-rim ports, SBM model, dual carbon goals

1 Introduction

Under a series of social challenges, including environmental pollution, the World Commission on Environment and Development proposed the concept of sustainable development in 1987. Since then, sustainable development has become a common goal of the world (Huang, 2022). In order to achieve the goal of sustainable development, China has formulated many strategies and measures to improve the environment. Currently, the most extensive strategy implemented by China is the dual carbon goals of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. China has made great efforts to save energy and reduce carbon emissions in recent years. For example, starting from the "Twelfth Five-Year Plan" period, China has incorporated the reduction of carbon intensity into the national economic and social development planning outline as a binding goal.

World Bank data shows that since 2005, China's cumulative energy savings have accounted for more than 50% of the world's. In 2020, China's carbon intensity dropped by 48.4% compared to 2005, exceeding the goal that China promised to the international community to reduce its carbon intensity by 40% to 45% by 2020.

In economic globalization, trade exchanges between countries have increased rapidly, and China's trade has been in line with world trade. Since 2005, China has ranked among the top three world trading countries. And since 2017, China has been the world's largest trading country, and the total import and export commodities in 2021 have reached about 6.05 trillion US dollars. As a critical node for import and export, the vital role of the port is self-evident. According to the Outline of the Eighth Five-Year Plan for National Economic and Social Development of the People's Republic of China to the Outline of the Fourteenth Five-Year Plan for National Economic and Social Development of the People's Republic of China, China's support policy for the port industry has transformed from "strengthening the construction of coastal ports" to "optimizing and upgrading key port clusters," and then to "accelerating the construction of a transportation power." Moreover, with the advancement of the One Belt and One Road policy, Chinese ports have been extensively developed.

Ports should take responsibility for their interests, implement national requirements, and enjoy national policy dividends. In 2019, the Ministry of Transport of China issued the Guiding Opinions on Building World-Class Ports, emphasizing that by 2025, meaningful progress will be made in constructing world-class ports, and significant breakthroughs will be made in the green, intelligent and safe development of major ports. Compared with developed countries, the construction of China's green ports is lagging, and multiple problems such as waste of resources and high pollution have emerged, especially China's dual carbon goals have set new targets for energy conservation and emission reduction of ports. In order to improve port efficiency, it is necessary to clarify its influencing factors. The evaluation study of the environmental efficiency of the port can quantitatively identify the redundancy and shortage of the port in terms of input and output. However, existing studies on port efficiency do not pay enough attention to direct energy input and carbon emissions, and cannot objectively identify the green development level of ports under the dual carbon goals. Therefore, the primary purpose of this study is to evaluate port efficiency considering energy input and carbon emissions under the double carbon goals.

The possible contribution of this study is reflected in two aspects. First, the existing port efficiency evaluation research generally selects port infrastructure as an input factor, and seldom considers energy consumption. This study takes port energy consumption as one of the input variables, which can better reflect the greenness of port development. Second, this study takes the CO_2 emissions of the port as an undesirable output, which is more in line with the development direction of ports under China's dual carbon goals, and has practical significance for the sustainable development of the port.

The remainder of this study is structured as follows. Section 2 reviews the relevant literature. Section 3 describes the methodology, selected indicators, samples, and data used in our study. Section 4 presents the results and discussion. Section 5 provides the conclusion and policy implications.

2 Literature review

2.1 Port efficiency evaluation method

In terms of efficiency evaluation, data envelopment analysis (DEA) is a well-known method, and transportation is one of the most widely used industries (Liu et al., 2013). The DEA model is a non-parametric production frontier approach. It assumes that inputs and outputs change proportionally to each other, so it is considered to evaluate the relative efficiency of a group of decision-making units. The Charnes-Cooper-Rhodes (CCR) model is one of the most basic DEA models proposed by Charnes et al. (1978), and has been widely used. Tongzon (2001) analyzed a sample of Australian and other international ports using the CCR model and demonstrated that DEA provides a viable means of assessing relative port efficiency. Birgun and Akten (2005) adopted the CCR model to measure the relative efficiency of the ports and illustrate the managers of the ports. The CCR model is built on the assumption of constant returns to the scale of activities. As a representative extension of the CCR model, the Banker-Charnes-Cooper (BCC) model assumes variable returns to scale and has been further applied. For example, Shen (2021) used the BCC model to calculate the green efficiency of four port groups in China. Moreover, some scholars combine multiple types of the DEA model. da Costa et al. (2021) used the traditional two models of DEA to analyze the efficiency of major container terminals in northern Brazil. Barros (2012) applied the Luenberger DEA model and the Malmquist index to analyze the productivity change of African seaports. Baran and Górecka (2015) used CCR and BCC model and applied the Malmquist Productivity Index to evaluate the global technical efficiency, pure technical efficiency, and scale efficiency of container ports and to analyze changes in seaport productivity. In addition, some scholars use the DEA model in combination with other econometric models. For instance, Nikolaou and Dimitriou (2021) used a multi-period DEA-Tobit model to estimate the efficiency of the world's top 50 container port terminals serving the global freight supply chain over five years.

In recent years, the world has paid more and more attention to environmental issues. The marine environment has thus become one of the areas that scholars focus on, such as inland shipping pollution (Xu et al., 2022a), marine sustainable development (Xu et al., 2022b), port pollutant emission (Xiao et al., 2023), and carbon emission reduction technology for shipping companies (Xiao and Cui, 2023). The port is an essential part of the marine environment, and its environmental issues have become the primary concern for ports (Yu et al., 2022). Thus, evaluating port efficiency has gradually introduced undesired environmental outputs, such as pollutant emissions. In this regard, some scholars have further expanded the port efficiency evaluation model, which has undesired output variables, among which the slacks-based measure (SBM) model is widely used. The SBM model is an effective method of efficiency in DEA. On the one hand, the SBM model overcomes the condition that the traditional DEA model assumes that all inputs and outputs change proportionally, and is more in line with the real-world situation. On the other hand, the SBM model can measure the efficiency of decision-making units that consider both desirable and undesirable outputs (Cooper et al., 2007), and the SBM model is proved to be more discriminative among various non-parametric methods for assessing environmental performance method (Zhou et al., 2008). Moreover, the SBM model has good compatibility with other measures of efficiency (Tone, 2001). Lee et al. (2014) used the SBM model to evaluate the environmental efficiency of the port cities. They found that Tianjin is the least environmentally efficient port city compared to other cities such as Singapore, Busan, and New York. Elsayed and Khalil (2017) used two traditional DEA models and the SBM model to evaluate and analyze the factors affecting the efficiency level of Safaga port in Egypt. They found that the more strategically located DP World Sokhna port has higher efficiency than the Safaga port. In addition, Tovar and Wall (2019) used a directional distance function approach (DEA-DDF model) to evaluate environmental and technical efficiency for a cross-section of 28 Spanish Port Authorities. They found that when the output elements are different, the degree of optimal reduction of CO_2 emissions is different when the environmental efficiency of the port is effective.

2.2 The input-output elements of port efficiency

In the selection of input-output elements for port efficiency evaluation, most studies select input elements from port infrastructure or equipment approximating the capital level (Bonilla et al., 2004; Birgun and Akten, 2005; Wiegmans and Witte, 2017; Chang et al., 2021), such as berth length or depth, number or intensity of cranes; output elements mostly select container throughput or cargo throughput (Cullinane and Wang, 2006; Chang et al., 2021), only a tiny number of scholars regard passengers as an output factor (Simões and Marques, 2010; Tovar and Wall, 2019); at the same time, some scholars also examine non-desired output factors, such as carbon dioxide emissions (Na et al., 2017; Dong et al., 2019).

However, the existing research on port efficiency evaluation has not reached a consensus on constructing the input-output index system. For example, Na et al. (2017) used berth length, port area, number of quay cranes, and yard cranes as input variables, container throughput of the port as the output variable, and the CO_2 emission amount of each port as an undesirable output variable. Elsayed and Khalil (2017) adopted water area, storage, terminal, depth of berth passenger station, and labor as input variables, cargo, number of the berth, berth length, land area, fixed cranes, and yard cranes as output variables. Dong et al. (2019) evaluated the environmental performance of container ports along the Maritime Silk Road (MSR) using the number of berths, quay cranes, and berth length as input variables, throughput as desirable output variable, and carbon dioxide emissions as undesirable output variable. Liu et al. (2022) evaluated the efficiency of the primary container terminals in Hong Kong, Guangzhou, and Shenzhen from 2018 to 2019, using gross crane productivity, crane intensity, berth length, and berth depth as input variables, calls and moves as desirable output variables, and finish as undesirable output variable.

3 Methodology

3.1 Sample selection and data

Due to the availability of data and the representativeness of samples, this study selects eight ports in the Bohai-rim port group as the research objects. The eight ports are Dalian Port, Yingkou Port, Qingdao Port, Rizhao Port, Yantai Port, Tianjin Port, Tangshan Port, and Qinhuangdao Port. On the one hand, the data of these eight ports in the Bohai-rim port group are relatively complete, while other Chinese ports lack data on one or more input-output variables. On the other hand, as the center of the three-dimensional transportation network of the Bohai Rim region in the core area of the Northeast Asian economic circle, the ports of the Bohai Rim port group not only play an important role in the economic and social development of China's three northeastern provinces, but also have outstanding representative value for the development of Chinese ports. Specifically, the coastline of the Bohai Sea is 5,800 kilometers, and the Bohai-rim port group is one of the five major port groups in China. The ports in Tianjin, Hebei, Liaoning, and Shandong in the Bohai-rim region are all coastal ports with superior geographical locations (see Figure A.1 for details). In the past ten years, the cargo throughput of coastal ports in the Bohai-rim region has accounted for more than 40% of all coastal ports and about 30% of the national ports. It is worth noting that the cargo throughput of the sample ports selected in this study accounted for more than 80% of all ports in the Bohai-rim region and more than 20% of the national ports (see Table 1 for details). Additionally, in terms of foreign trade throughput, ports in the Bohai-rim region accounted for 42% of the national ports in 2020. The sample ports selected in this study accounted for 92% of the total in the Bohai-rim region.

The data used in this study mainly come from official statistics from 2005 to 2020, including the China Port Yearbook, the Provincial and Municipal Statistical Yearbook, and the official website of the National Bureau of Statistics. In addition, the data of some indicators come from the China Stock Market and Accounting Research (CSMAR) database. CSMAR is a comprehensive research database developed based on the needs of academic research, which simultaneously meets international professional standards and adapts to China's features.

3.2 Variable selection

For the application of the SBM model, the selection of input and output variables is crucial (Cooper et al., 2007). Referring to existing literature and based on data availability, this study selects the number of berths used in port production, the length of the dock for production, and energy consumption as input variables, and selects cargo throughput, container throughput, and passenger throughput as desirable output variables. At the same time, based on the strategic background of China's realization of the dual

TABLE 1 Comparison of port cargo throughput.

Year	Bohai-rim Ports/ Coastal Ports	Bohai-rim Ports/ National Ports	Sample Ports/ Bohai-rim Ports	Sample Ports/ National Ports
2021	43.45%	27.87%	82.92%	23.11%
2020	44.47%	28.98%	82.50%	23.91%
2019	44.92%	29.58%	82.37%	24.37%
2018	46.50%	30.66%	82.65%	25.34%
2017	46.71%	30.20%	80.39%	24.28%
2016	47.57%	30.47%	80.51%	24.53%
2015	47.18%	30.15%	83.03%	25.03%
2014	47.46%	30.62%	83.71%	25.63%
2013	47.02%	30.21%	84.19%	25.44%
2012	46.38%	29.61%	85.22%	25.23%

Data source: China Port Yearbook, Ministry of Transport of the People's Republic of China, and Transport Knowledge Service System.

carbon goals, this study selects CO_2 emissions as an undesirable output variable. The input and output variables are shown in Table 2.

Note that the Ministry of Transport of China began to monitor port energy consumption in 2011, while our research period is from 2005 to 2020, and there is a significant gap in the statistical time of data. To ensure the consistency of data sources and statistical caliber, this study uses the measurement method proposed by Ge and Wang (2021) to calculate energy consumption and carbon dioxide emissions. The formula for calculating the energy consumption of the port is as follows:

$$EC = \frac{HC}{THC} \cdot \frac{WFV}{TFV} \cdot TEC \quad (1)$$

where HC represents the cargo throughput of the port. THC means the cargo throughput of all ports in the province where the port is situated. WFV represents the waterway freight volume of the province where the port is located. TFV represents the total freight volume of the province where the port is located. TEC represents the total energy consumption of transportation, warehousing, and postal industry in the province where the port is located. The data for these indicators come from the Statistical Yearbook of the relevant provinces and the China Port Yearbook. For several missing data, the interpolation method is used to make up.

Furthermore, the formula for calculating the CO_2 emissions of the port is as follows:

$$C = EC \cdot HC \cdot CEF \quad (2)$$

where C is the CO_2 emissions of the port, and CEF is the CO_2 emission coefficient. According to the carbon emission coefficient of 1t standard coal ($0.67tc/tce$) recommended by the Chinese National Development and Reform Commission, the conversion coefficiecnt between carbon emissions and CO_2 emissions is 3.6667, and the CO_2 emission coefficient can be calculated as $2.4567tCO_2/tce$.

Table 3 presents the summary statistics for the input and output variables in this study. Whether it is input variables or output variables, there are significant differences between different DMUs. In particular, the minimum value of CO_2 emissions is 1.98, and the maximum value is 1621.76, so if the undesirable output of CO_2 emissions is ignored, it may lead to bias in the evaluation of the environmental efficiency of the port, especially in the context of dual carbon goals.

3.3 Methods

To explore the environmental efficiency of ports, this study draws on the research methods of the existing literature (Lee et al., 2014; Elsayed and Khalil, 2017), and adopts the SBM model. The

TABLE 2 Input and Output Variables.

	Variable name	Unit
Input variables	Number of production berths	Pcs
	Length of the dock for production	M
	Energy consumption	10,000 tons of standard coal
Desirable output variables	Cargo throughput	100 million tons
	Container throughput	10,000 TEU
	Passenger throughput	10,000 passengers
Undesirable output variables	CO_2 emissions	million tons

TABLE 3 Summary Statistics.

	Max	Min	Average	SD	N
Number of production berths	231.00	18.00	99.25	56.60	128
Length of the dock for production	43218.00	4444.00	21313.01	10194.20	128
Energy consumption	145.61	2.12	35.97	30.61	128
Cargo throughput	7.03	0.33	3.21	1.45	128
Container throughput	2201.00	3.55	530.21	544.85	128
Passenger throughput	967.00	0.00	122.93	208.17	128
CO_2 emissions	1621.76	1.98	324.16	351.00	128

SBM model is a non-radial and non-angular DEA model proposed by Tone (2001), which overcomes the problem of the overestimate of the efficiency value of the decision-making unit (DMU) by the radial DEA when there is a non-zero slack in inputs or outputs, and the angular DEA must choose between inputs (assuming that outputs are unchanged) or outputs (assuming that inputs are unchanged). The unit of analysis in this study is the port, which is called a DMU in the SBM model. Generally speaking, a basic rule for the successful application of a SBM model is that the number of DMUs exceeds the total number of input and output variables by at least three times (Cooper et al., 2007). According to the sample selection and input and output variables mentioned above, the number of DMUs in this study is 128, while the combined number of input-output items is 7. Given that the number of DMUs is more than 18 times the total amount of input and output variables, the SBM model is desirable for this study.

Given the data, this study measures the environmental efficiency of each port once and hence needs n optimaizations, one for each DMU to be evaluated (Cooper et al., 2007). Suppose that there are n DMUs, each of which contains input variable x, desirable output variable y^g, and undesirable output variable y^b. The numbers of inputs, desirable outputs, and undesirable outputs are represented by m, s_1, and s_2, respectively. The input data matrix M, the desirable output data matrix y^g, and the undesirable output matrix y^b can be arranged as follows:

$$X = [x_1, \cdots, x_n] = (x_{ij}) \in R^{m \times n} \tag{3}$$

$$Y^g = [y_1^g, \cdots, y_n^g] = (y_{kj}^g) \in R^{s_1 \times n} \tag{4}$$

$$Y^b = [y_1^b, \cdots, y_n^b] = (y_{lj}^b) \in R^{s_2 \times n} \tag{5}$$

where $X > 0$, $Y^g > 0$, $Y^b > 0$. The production possibility set P is defined by

$$P = \left\{(x, y^g, y^b) | x \geq X\Lambda, y^g \leq Y^g\Lambda, y^b \leq Y^b\Lambda, \Lambda \geq 0\right\} \tag{6}$$

wherein, the intensity vector is represented by $\Lambda = [\lambda_1, \cdots, \lambda_n]^T \in R^n$.

Further, in order to estimate the environmental efficiency of a DMU (x_0, y_0^g, y_0^b), the following fractional program is formulated:

$$\rho^* = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1+s_2}\left[\sum_{r=1}^{s_1}\frac{s_r^g}{y_{r0}^g} + \sum_{k=1}^{s_2}\frac{s_k^b}{y_{k0}^b}\right]} \tag{7}$$

$$s.t. \begin{cases} x_{i0} = X\Lambda + s_i^-, \forall i \\ y_{r0}^g = Y^g\Lambda - s_r^g, \forall r \\ y_{k0}^b = Y^b\Lambda + s_k^b, \forall k \\ \sum_{j=1}^{n}\lambda_j = 1 \\ s^- \geq 0, s_r^g \geq 0, s_k^b \geq 0, \lambda_j \geq 0 \end{cases}$$

In this model, $s^- \in R^m$ and $s^b \in R^{s_2}$ represent the excesses in inputs and undesirable outputs, respectively. $s^g \in R^{s_1}$ expresses shortages in desirable outputs. The objective function value is the environmental efficiency value of the DMU, which satisfies $0 < \rho^* \leq 1$. If the value of ρ^* is equal to 1, it means that the environmental efficiency of a DMU is efficient, and $s^- = 0$, $s^b = 0$, and $s^g = 0$. Otherwise, the DMU is inefficient and can be improved by removing excess inputs and undesirable outputs, and increasing desirable outputs. Note that convexity constraint $\sum_{j=1}^{n}\lambda_j = 1$ means the assumption of VRS; however, the efficiency under the assumption of CRS needs to remove the convexity constraint.

4 Results and discussion

4.1 Overview of the evaluation results of port environmental efficiency

Based on the SBM model described in Section 3.3, 128 DMUs are used to construct the production possibility set, and the software of DEA-Solver Pro13.1 is used to measure the environmental efficiency of the port. In order to comprehensively evaluate the environmental efficiency of the port, this study estimates the global technical environmental efficiency, local pure technical environmental efficiency, and scale environmental efficiency of the port based on the analysis of returns to scale. A comparative study of these three types of environmental efficiencies helps to understand the sources of inefficiency that a DMU may have, that is, whether the inefficiency is caused by the inefficient operation of the DMU itself or by the unfavorable conditions in which the DMU operates. According to Cooper et al. (2007), the evaluation result under the assumption of CRS is global technical environmental efficiency, the evaluation result under the assumption of VRS is local pure technical environmental efficiency, and the scale environmental efficiency is defined by the ratio of these two efficiencies. That is, the scale environmental efficiency = global technical environmental efficiency/local pure technical environmental efficiency. Further, if a DMU is fully efficient in both the global technical environmental efficiency and local pure technical environmental efficiency, it is operating in the most productive scale size. If a DMU has full local pure technical environmental efficiency but a low global technical environmental efficiency, then it is operating locally efficiently but not globally efficiently due to the scale size of the DMU. It should be noted that the value of scale environmental efficiency is equal to 1 in the most productive scale size and is not greater than 1 (Cooper et al., 2007). The evaluation results of global technical environmental efficiency, local pure technical environmental efficiency, and scale environmental efficiency of the eight ports from 2005 to 2020 are shown in Tables A.1–A.3, respectively.

The results in Tables A.1, A.2 show that during the study period from 2005 to 2020, there are 18 DMUs with a global technical environmental efficiency value equal to 1.0000, accounting for 14.06% of all DMUs, and 26 DMUs with a local pure technical environmental efficiency value equal to 1.0000, accounting for 20.31% of all DMUs. Moreover, the results of scale environmental efficiency in Table A.3 show that there are 18 DMUs with a scale environmental efficiency value of 1.0000, which means that these 18 DMUs are operating at the most productive scale size. And, combining the results of Tables A.1, A.2, the global technical environmental efficiency and local pure technical environmental efficiency of these 18 DMUs are also 1.0000. Therefore, these 18 DMUs are both scale and technically efficient for the assumptions of CRS and VRS. In addition, the remaining 85.94% of all DMUs have a scale environmental efficiency of less than 1.0000, among which 8 DMUs have full local pure technical environmental efficiency but a low global technical environmental efficiency. Thus, the overall inefficiency of these 8 DMUs is caused by their failure to achieve scale inefficiency. At the same time, the local pure technical environmental efficiency and scale environmental efficiency of the 102 DMUs are all inefficient. In other words, the overall inefficiency of these 102 DMUs is not only caused by their technical inefficient operation, but also caused by their disadvantageous scale conditions.

In addition, in order to gain a deeper understanding of the port's environmental efficiency under the dual carbon goals, we also evaluate the port's efficiency without considering carbon emissions. Tables A.5–A.7 in the appendix present the evaluation results of port efficiency without considering carbon emissions. Since carbon emissions are undesirable outputs, the SBM model without undesirable output is used for port efficiency evaluation, and Formula A.1 is shown in the appendix. During the study period from 2005 to 2020, there are 11 DMUs with a global technical efficiency value of 1.0000 for ports that do consider carbon emissions, accounting for 8.59% of all DMUs, which is 5.47 percentage points lower than those considering carbon emissions. Moreover, there are 14 DMUs with a local pure technical efficiency value of 1.0000, accounting for 10.94% of all DMUs, which is 9.37 percentage points lower than those considering carbon emissions, and 11 DMUs with a scale efficiency value of 1.0000, which is 5.47 percentage points lower than those considering carbon emissions. Therefore, under the requirement of realizing the dual carbon goals, it is necessary to include carbon emission elements in the evaluation system of port efficiency; otherwise, it will lead to biased evaluation results, which is not conducive to the green and sustainable development of ports.

4.2 Longitudinal comparative analysis of port environmental efficiency

In order to discuss the environmental efficiency trends, we averaged the three types of environmental efficiency for all ports year by year, and the results are shown in Figure 1. From 2005 to 2020, the global technical environmental efficiency showed a clear trend of fluctuation. Specifically, global technical environmental efficiency showed an upward trend from 2005 to 2007, declined in 2008, began to recover rapidly after 2009, and reached the highest level in 2013. However, it then began to show a downward trend and reached its lowest level in the entire study period in 2017. From 2018 to 2020, the global technical environmental efficiency showed a dynamic of "rise-fall-rise," and the unstable state was more prominent. Furthermore, from 2005 to 2007, the changing trend of local pure technical and global technical environmental efficiency is the opposite. Specifically, pure technical environmental efficiency shows a downward trend, while global technical environmental efficiency shows an upward trend. From 2008 to 2020, the dynamics of local pure technical efficiency and global technical environmental efficiency are similar. Especially from 2008 to 2016, the values of these two types of efficiency are very close. In addition, the average values of local pure technical efficiency are always greater than global technical environmental efficiency, which conforms to the above definition. That is, scale environmental efficiency is equal to 1 in the most productive scale size and is not greater than 1, where scale environmental efficiency is the ratio of local pure technical

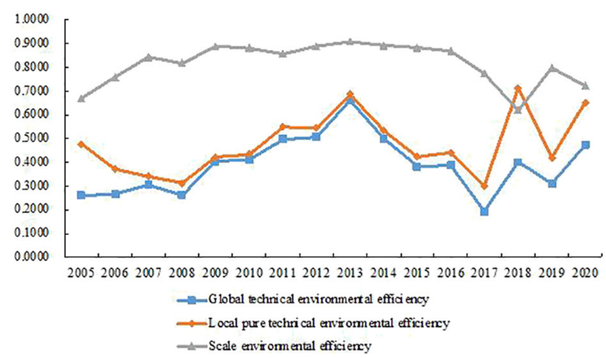

FIGURE 1
The annual average environmental efficiency of the eight ports.

efficiency to global technical environmental efficiency (Cooper et al., 2007).

Further, the changing trend of scale environmental efficiency is closely related to local pure technical efficiency and global technical environmental efficiency, as shown in Figure 1. From 2005 to 2009, the changing trend of scale environmental efficiency and global technical environmental efficiency is consistent, indicating that the change of scale efficiency during this period is the main reason for the change of global technical environmental efficiency. The possible explanation is that before 2007, the Bohai-rim region mainly relied on the extensive economic development mode that invested heavily in production factors, and the ecological environment governance did not receive sufficient attention. In this context, as an essential port group for economic development in the Bohai-rim region, the eight representative sample ports have invested heavily in the number of productive berths, the length of productive docks, and energy, which meet the requirements of increasing revenue and expanding scale. But carbon dioxide emissions are poorly controlled, and the utilization of inputs is low. Therefore, the port development during this period has a noticeable shortage of desirable output and redundant undesirable output. Moreover, the global financial crisis occurred in 2008, which greatly affected international trade and seriously impacted port development, resulting in a further decline in the environmental efficiency of ports. Subsequently, in response to the global financial crisis, China implemented stimulus policies, such as increasing investment, stimulating consumption, and increasing exports, and the port development gradually improved. At the same time, new achievements have been made in technological innovation, energy conservation, and emission reduction. The scale environmental efficiency of ports has been stable from 2009 to 2016, and the efficiency value is at a relatively high level. It is worth noting that in 2013, the global technical environmental efficiency increased significantly, which may be due to the gradual improvement of the ecological level of the Bohai Rim region under the influence of the requirements of China's "Twelfth Five-Year Plan." At the same time, the Ministry of Transport has carried out pilot projects for the regionalization and thematic management of special funds for transportation energy conservation and emission reduction, which not only boosted the confidence of ports in energy conservation and emission reduction, but also provided particular financial support for ports. Through the analysis of ports with high environmental efficiency values, we found that these ports have reached the highest level in terms of local pure technical environmental efficiency and scale environmental efficiency (see Tables A.1–A.3 in the appendix for details), which is closely related to the scientific allocation of resources, development of science and technology, and optimization of port energy utilization structure.

After 2016, the scale environmental efficiency has a clear fluctuation trend, which is related to the extensive fluctuation range of local pure technical efficiency and global technical environmental efficiency. In 2017, the world economy had not yet completely shaken off the profound impact of the financial crisis, and the international trade and investment situation is still idle. However, the ports in the Bohai-rim port group have begun to significantly increase inputs, resulting in a sharp decline in environmental efficiency. Then, in order to quickly improve the air quality, China issued the "Three-Year Action Plan for Atmospheric Cleanliness" in 2018, which proposed to optimize and adjust the cargo transportation structure, requiring bulk cargo to be mainly transported by rail or water in principle. At the same time, it emphasized accelerating the upgrading of vehicle and ship structures, requiring clean energy vehicles to be used for newly added or replaced operating vehicles in ports. As a result, the environmental efficiency of the port has been rapidly improved. However, in 2019, China's foreign trade environment was affected by the Sino-US trade friction and the COVID-19 pandemic. Compared with 2018, the desirable output of ports decreased significantly, resulting in a decline in global technical environmental efficiency and local pure technical of ports. As China proposes to build a new development pattern in 2020 with the domestic cycle as the main body and the domestic and international dual cycles promoting each other, the port has gained new development opportunities. Under the new development pattern, the integration of port resources and the construction of management systems have been promoted. Thus, local pure technical environmental efficiency and global technical environmental efficiency of ports have been improved. The annual average environmental efficiency of the eight ports from 2005 to 2020 is listed in the appendix (Table A.4).

4.3 Horizontal comparative analysis of port environmental efficiency

Table 4 reports the average value and rank of the three environmental efficiencies of the eight ports during the sample period from 2005 to 2020. The differences between the three types of environmental efficiency values in different ports are shown in Figure 2. The results show that under the assumption of CRS, the average value of the eight ports' global technical environmental efficiency is 0.3896, which is at a relatively low level. Among all the sample ports, Tangshan Port has the highest global technical environmental efficiency of 0.7176, followed by Yantai Port, with a global technical environmental efficiency of 0.6251. In contrast, Yingkou Port has the lowest efficiency of only 0.1072. Under the assumption of VRS, the average local pure technical environmental efficiency of the eight ports is 0.4767, which is greater than the global technical environmental efficiency, but still at a low level. Moreover, compared with the global technical environmental efficiency, the average local pure technical environmental efficiency of each port is also more significant. In addition, the rankings of Rizhao Port and Qinhuangdao Port have been reversed, while the rankings of other ports have not changed. Specifically, Tangshan Port ranks first, followed by Yantai Port, while Yingkou Port is still in last place.

Unlike global technical environmental efficiency and local pure technical environmental efficiency, the ranking of scale environmental efficiency varies significantly across ports. During the study period, Yantai Port ranked first in scale environmental efficiency, followed by Qinhuangdao Port, and Tianjin Port ranked last. However, Qinhuangdao Port, which ranks first in both global

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TABLE 4 The average value and rank of the environmental efficiency of the eight ports from 2005 to 2020.

DMU	Global technical environmental efficiency		Local pure technical environmental efficiency		Scale environmental efficiency	
	Value	Rank	Value	Rank	Value	Rank
Dalian Port	0.3658	5	0.4441	5	0.8778	3
Yingkou Port	0.1072	8	0.1706	8	0.8211	5
Qingdao Port	0.4674	3	0.5978	3	0.7830	6
Rizhao Port	0.3306	6	0.4756	4	0.7232	7
Yantai Port	0.6251	2	0.6451	2	0.9691	1
Tianjin Port	0.1295	7	0.2192	7	0.5994	8
Tangshan Port	0.7176	1	0.8392	1	0.8535	4
Qinhuangdao Port	0.3738	4	0.4217	6	0.9044	2
Full Sample Port	0.3896	/	0.4767	/	0.8164	/

technical and local pure technical environmental efficiency, has dropped to fourth in scale environmental efficiency. In addition, it should be noted that whether it is global technical environmental efficiency, local pure technical environmental efficiency, or scale environmental efficiency, there are significant differences in the efficiency values of various ports. Generally, if the local pure technical environmental efficiency is relatively low, port operators can improve efficiency by adjusting inputs. If the scale environmental efficiency is relatively low, it can be improved by adjusting the size of the port. Taking Tianjin Port as an example, its scale environmental efficiency value is the smallest (0.5994), indicating that Tianjin Port needs to control the scale growth rate. Not only that, but the local pure environmental efficiency of Tianjin Port is also at an extremely low level (0.2192) and ranks second to last, indicating apparent input redundancy. Therefore, Tianjin Port urgently needs to optimize resource allocation. As a port with a large scale and high throughput, the environmental efficiency of Tianjin Port is lower than other ports. The reason may be that the port is located in the Beijing-Tianjin-Hebei region, and the excessive competition between different areas has brought enormous pressure to port operations and restricted the development of the port. Moreover, Tianjin Port, as a port that was put into operation earlier, has a particular gap with the requirements of the city's rapid development in terms of infrastructure and operating systems, which further leads to a decline in the environmental efficiency of the port.

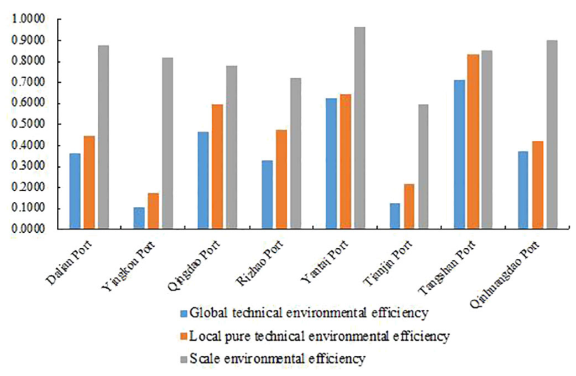

FIGURE 2
The annual average environmental efficiency of the eight ports.

Overall, the main reason for the low environmental efficiency of the eight ports in the Bohai-rim port group is that they have not reached the optimal input-output level. And their scales have not reached the ideal state, especially Qingdao Port, Rizhao Port, and Tianjin Port. Proper sizing is an urgent need for these ports to become more environmentally efficient. In addition, as the only port without a passenger transport function, the global technical and local pure technical environmental efficiency of Tangshan Port are higher than that of other ports. Thus, the passenger transport function is an essential output in the evaluation system of port environmental efficiency. If the output factor of the passenger transport function is ignored, evaluating port environmental efficiency will not be objective and accurate.

5 Conclusion and policy implications

In implementing China's dual carbon goals, ports must establish a green transportation development model to promote the intensive use of resources and contribute to emission reduction and carbon reduction. The traditional evaluation of port efficiency does not fully consider energy consumption and carbon emissions. It cannot provide a practical reference for the current low-carbon transformation of Chinese ports. In this study, taking eight ports in the Bohai-rim port group as examples, the SBM model is employed to evaluate the port efficiency considering the environmental factors of carbon dioxide emissions and energy consumption. First, we estimate the global technical environmental efficiency, local pure technical environmental efficiency, and scale environmental efficiency of eight representative ports in the Bohai-rim port group from 2005 to 2020. Secondly, through longitudinal comparative analysis, the changing trends of the three environmental efficiencies of ports during the study period are discussed. Finally, through horizontal comparative analysis, the differences between the three environmental efficiencies among the eight ports are discussed.

The study finds that the environmental efficiency of ports is at a low level from 2005 to 2020. Across all DMUs, only 14.06% of the global technical environmental efficiency is effective, as is the scale environmental efficiency, and only 20.31% of the DMUs have effective local pure technical environmental efficiency. From the perspective of changing trends, the global technical environmental efficiency and local pure technical efficiency of ports fluctuate significantly. After 2007 their changing trends are consistent and relatively close, while the scale environmental efficiency is relatively stable. However, the gap between global technical environmental efficiency and local pure technical efficiency has gradually increased since 2017. The scale environmental efficiency has also shown a clear fluctuation trend since then. From the perspective of the development of each port, the average local pure technical environmental efficiency of each port is greater than the global technical environmental efficiency, and the ranking of ports changes little. In contrast, the ranking of the scale environmental efficiency is entirely different from the ranking of the other two environmental efficiencies. Moreover, the efficiency values of various ports are pretty different in terms of different environmental efficiencies.

Based on the findings, ports should pay more attention to improving local pure technical environmental efficiency. Global technical environmental efficiency consists of local pure technical and scale environmental efficiency. This study finds that the local pure technical environmental efficiency of the port is significantly lower than the scale environmental efficiency. Therefore, when port operators are making management decisions, it is necessary to spend more funds on technological innovation or improvement. Technological innovation and progress can effectively reduce pollutant emissions and maximize the use of equipment, facilities, resources, etc., reducing redundancy and shortage, and promoting the advancement of port environmental efficiency. In addition, the environmental efficiency of ports has fluctuated significantly in recent years, and port operators must adjust the size of ports promptly. For example, increase cooperation with other ports by integrating resources, or take measures to optimize the size of the port itself. From the perspective of environmental governance, since the environmental efficiency of ports has been at a low level, the government should strengthen supervision and encourage ports to actively adopt operational optimization strategies for energy conservation and emission reduction. For instance, the government regulatory department can publish the environmental monitoring data of each port in real-time, and subsidize or support ports accordingly, thereby incentivizing ports to fulfill their environmental protection responsibilities, such as taking environmental factors as an important indicator of port performance, and accelerating the realization of low-carbon transformation of ports.

Although the SBM model is a well-established efficiency evaluation model and is widely used, it does not have the desirable characteristics to distinguish efficient DMUs with the same efficiency score equal to 1, resulting in limited analysis depth of port environmental efficiency. Therefore, it is necessary to further study the environmental efficiency of ports from the perspective of model improvement. Furthermore, the Bohai-rim ports around the Bohai Sea are coastal ports, so the results have limited applicability to other ports, such as river ports. Future research must focus on the environmental efficiency of non-coastal ports when data are available. In addition, optimizing input-output elements can improve the competitiveness of ports (Xu et al., 2022c). Future research may discuss how to improve port competitiveness under the dual carbon goals from the perspective of enhancing port environmental efficiency.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

JL, conceptualization, writing - review and editing. JR, conceptualization, investigation, and writing - original draft. XM, methodology, formal analysis, and investigation. GX, supervision. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1129659/full#supplementary-material

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A study on the influence of reposition threshold on low-carbon empty container repositioning strategy under an uncertain environment

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The optimization of empty container repositioning nets has become an essential problem in low-carbon port cooperation. This paper proposed three optimization models of multi-port low-carbon empty container repositioning considering threshold under input and output of empty containers as random variables. Non repositioning strategy means the highest threshold, and complete-repositioning strategy means the lowest threshold; threshold-repositioning strategy is in the middle. The probability of empty-container inventory in each port and the storage cost, repositioning cost, lease cost, and carbon emission cost of empty containers are calculated. This paper mainly compares each cost of three models. The results have shown that: (1) Compared with the non repositioning strategy, the threshold-repositioning strategy and complete-repositioning strategy can reduce the ports storage costs and lease costs of empty containers and also reduce carbon emissions. The lower the repositioning threshold of empty containers between ports is, the more obvious the advantages of the threshold-repositioning strategy become. (2) When the cost of storage per empty container increases, under three strategies, the total cost, storage cost, lease cost, and carbon emission cost of the port will all increase. The ports proportion of dependence on its own empty-container storage will decrease, and the proportion of dependence on other ports and leasing companies will both increase.

KEYWORDS

reposition threshold, empty container reposition, low carbon, port cooperation, uncertain environment

1 Introduction

The shipping industry plays an important role in the development of international trade, and more than 80% of international freight is completed by sea (UNCTAD, 2018). International shipping is one of the main modes of international cargo transportation (Xu et al., 2023). However, due to the imbalance of regional trade, improper management of container operations, and many other reasons, the number and flow of containers in the actual operation process also have a certain imbalance. For example, as the world's largest exporter and the world's manufacturing center, China mainly exports groceries and dry bulk cargoes, which are large in size but low in value. However, Europe and the USA, as China's main target markets, also send domestic goods to China, but they mainly export high-tech products with small sizes but high value (Chen et al., 2020). Coupled with the imbalance of international trade, ships often leave with full loads from China but return empty. This has resulted in the accumulation of containers on one side and the lack of containers on the other. A shortage of containers will lead to extra costs. The cost of container storage is mainly due to shipping companies' necessity to rent containers to meet customer needs or the cost of losing customers due to a shortage of containers. On the other hand, overstocking containers will lead to storage costs and management costs in the storage yard, which all add unnecessary operating costs to shipping companies (Xu et al., 2021a). In order to meet a balance between the supply and demand of containers in both destinations, the most cost-effective method is empty-container repositioning. The demand for empty containers originates from the consignor's demand for shipment. The inland cargo distribution points near the consignor will transfer empty containers to the consignor's location. If the quantity of empty containers at the port of shipment cannot meet the needs of the consignor, it is necessary to consider repositioning containers from other nearby ports or to rent containers from local container leasing companies. When the consignor's empty-container demand is met, the empty containers are loaded with the goods and transported to the port, which is then transported to the destination port by ship and further delivered to the consignee (Yang et al., 2021). As the core node of the port and shipping logistics supply chain, the ports gather a large number of upstream and downstream node information, most of which is container flow information. Therefore, if the port participates in the empty-container repositioning of the shipping company, it can improve the efficiency of the empty-container repositioning by virtue of the advantage of the port information intersection.

With the rapid development of the shipping industry, serious environmental problems have been brought about by economic advances, according to the report of the International Maritime Organization (2014). Global marine transportation consumes about 300 million tons of fuel oil every year. These fuels will emit a large amount of tail gas during the combustion process, including SO_2, NO_x, CO_2, and particulate matter (Wang et al., 2022a; Xiao and Cui, 2023). In particular, the carbon emissions of the shipping industry and their impact on the global environment have been widely discussed (Xiao et al., 2023). Building a low-carbon port and a low-carbon shipping network has become a hot topic in the shipping industry as well as in academia. Building a low-carbon container port characterized by resource conservation, environmental friendliness, low energy consumption, and low pollution has become one of the primary tasks of the construction of world-class ports, and the study of energy conservation and emission reduction strategies for container ports has become an urgent need for the construction and development of low-carbon container ports (Trozzi and Vaccaro, 2000). The production and operation of the port are long processes with large total emissions and serious total pollution. The operation process includes all links in the operating system, such as the ships' entry and exit operations, the dock front operation, the yard operation, and the gate operation (Peng et al., 2018a), involving energy consumption and emission sources such as the ships, the quay bridge, the yard bridge, the container truck, etc. Therefore, the accumulation of too many empty containers in the port will also cause carbon emissions, thus calling for studies on the optimization strategy of empty-container repositioning so as to reasonably arrange all the links of empty-container repositioning and smooth the process of container circulation. Such research will have important implications for global container transportation operators, brokers, consigners, and port owners, and at the same time will be conducive to the construction of a low-carbon and highly efficient port network (Ercan, 2022).

2 Literature review

The statistical results have shown that the shortage of containers will cause obvious losses to trade, and even the USA suffers a weakening in the competitiveness of enterprises in foreign markets due to port congestion and container shortages (Department of Agricultural and Resource Economics, 2022; Xu et al., 2021b). Empty-container repositioning can be completed by both road transportation and sea transportation, mainly with the participation of ports, shipping companies, and leasing companies to reasonably allocate and dispatch empty containers (Shintani et al., 2007; Imai et al., 2009). The traditional studies on empty-container repositioning have mostly focused on the intercontinental empty-container repositioning between the origin port and destination port caused by trade imbalance, which belongs to the interregional empty-container repositioning between the supply and the demand sides, and the repositioning mode is solely sea transportation. Therefore, relevant studies are mainly focused on empty-container inventory and empty-container repositioning optimization. Luo (Luo and Chang, 2019) studied the problem of container inventory management when customer demands change under a multimodal transportation system and discusses the impact of empty-container repositioning on the optimal inventory level. Poo (Poo and Yip, 2019) carried out a dynamic control of the empty-container inventory cost and empty-container dispatching cost in regional transportation and formulated dynamic strategy of empty-container inventory control for shipping companies. Chen et al. (2022) proposed a port empty-container allocation model to optimize the number of self-owned empty containers and leased containers at each inland freight station, and a differential evolution algorithm was developed to solve their simplified model. In the aspect of optimizing empty-container repositioning, Chen (1998) also built a two-stage dynamic stochastic network model for empty-container repositioning by sea, aiming to address the deficiencies of previous research results on the optimization of empty-container repositioning on land. This model divided the empty-container dispatching decision into two steps to operate, which is closer to the actual decision-making situation than the previous deterministic models. In the first stage, the supply and demand of empty containers and the remaining empty-container capacity on board are regarded as deterministic variables. In the second stage, these parameters are changed into random and dynamic variables. Cheang and Lim (2004) dynamically considered the problem of empty-container repositioning in combination with the third-party leasing strategy. They provided a decision support system to solve the problem of empty-container repositioning by using the basic method of network flow. Wang (2017) integrated the inventory cost of containers into the existing liner route network design and studied the inventory cost and empty-container repositioning network. Xie et al. (2017) studied the empty-container repositioning strategy with mutual cooperation between a port and a railway and pointed out that empty-container sharing and cooperation can bring benefits to both sides. Yu (Yu et al., 2018) studied the problem of empty-container repositioning between the port and the hinterland, which is composed of a maritime container terminal and an inland container terminal. The study shows that the supply of empty containers at the port through inland empty-container resource sharing can alleviate the situation of an empty-container shortage at the port. Dong et al. (2020) endeavored to determine the route of each voyage and control the inventory of empty containers at the port of call within a reasonable range. Zhou (Zhou et al., 2020) constructed a two-stage stochastic programming model for empty-container repositioning, and a separable piecewise linear learning algorithm is designed to effectively solve large-scale empty-container repositioning problems. Misra (Misra et al., 2020) proposed a hybrid time discretization method combined with the rolling time domain strategy to solve the complex multi-period marine inventory routing problem. Song (Song et al., 2022) established a two-stage particle swarm optimization algorithm to compare parameters such as the total cost of the empty container, storage costs, lease costs, and optimal storage of empty containers in ports under a repositioning strategy and a nonrepositioning strategy. Zhang et al. (2022) introduced the structural hole theory, using the port of Las Palmas as an example, proving that the port occupying the position of the structural hole can become a regional hub by acting as a connecting bridge, which provides a basis for the repositioning decision-making of shipping companies and ports from a new perspective. Yoonjea and Gwang (2023) proposed a new integer linear programming model for the location problem of reliable facilities for folding containers in order to reduce the repositioning of empty containers and achieve cost savings and low-carbon transportation and operation profits for ports. The inventory of empty containers at the port is an important factor influencing the selection of an empty-container repositioning strategy at ports. However, these papers do not consider the impact of changes in the storage volume of empty containers at ports on the repositioning strategy.

The construction of low-carbon ports is the key to energy conservation and emission reduction in the shipping industry (Rajasekar et al., 2014; Wang et al., 2022b). At present, many scholars have studied port management from different angles and obtained some meaningful results. Port operation is a typical research direction in the shipping industry, and its decision-making includes berth allocation (Xu et al., 2022), quayside bridge dispatching and distribution (Correcher et al., 2018), field bridge dispatching and distribution (Galle et al., 2018; Peng et al., 2018b), and internal card dispatching (Tang et al., 2014). For example, based on the top-down model and taking into account factors such as engine power, load factor, and fuel emission factor, it is found that the carbon dioxide emissions from ship berthing activities account for the majority of the total emissions of container port ships (Muhammad et al., 2022). On the basis of considering fuel consumption and emissions, relevant studies on low-carbon port operations still follow the same academic ideas as traditional port operations and focus on the abovementioned decision-making issues. On the other hand, the optimized dispatching of container trucks is an important way to achieve energy conservation and emission reduction in ports. The optimized dispatching of container trucks is an important way to achieve energy conservation and emission reduction in ports. Taking a container port as an example, Esmer et al. (2010) used the method of system simulation to study the optimal configuration of container trucks in the yard to achieve the low-carbon and energy-saving requirements of the port. Li et al. (2018) also wielded the method of system simulation to study the optimal scheduling and management of the trucks to reduce the waiting time of the truck queue and then reduce the carbon emissions of trucks. Chen (Chen et al., 2013), taking the arrival quantity and waiting time of container trucks as the optimization objective, studied the influence of the arrival pattern of container trucks on pollution emissions by using queuing theory and mathematical programming methods. Schulte et al. (2017) deployed a mathematical programming method to optimize the booking arrival model of container trucks to reduce the CO_2 emissions of empty-container trucks. By using the simulation method, Peng et al. (2018b) calculated the optimal configuration of trucks and concluded that CO_2 can be reduced when the ratio of quayside bridge to truck reaches the optimum. Based on GA and PSO, a hybrid optimization algorithm is designed to solve the joint scheduling problem of the quayside bridge, internal truck, and field bridge. The goal is to avoid ship delays and minimize energy consumption in the operation process (He et al., 2015). Zhao et al. (2018), taking the cost of carbon emissions into account, studied the impact of random demand and supply changes on empty-container repositioning in the context of sea-rail intermodal transport. Liu et al. (2019) established a system dynamics model for modular operation. Taking the line from Caofeidian Port to Tangshan City as an example, through a series of process interventions, the long-term impact of the collection and distribution system under different environmental policies was evaluated, and effective suggestions for reducing environmental pollution were put forward. Tao and Wu (2021) introduced "yard-door-port" into a generalized analytical framework to analyze the carbon emissions from the movement of loaded containers and the repositioning of empty containers. Guo et al. (2022) constructed a carbon emission estimation model of a container multimodal transport network based on the hinterland and carried out a case study of Shanghai Port and the hinterland of the Yangtze River Delta. Olgay (2023) estimated the total carbon emissions generated by container handling equipment used in container port operations and planned carbon emission reduction strategies related to climate change adaptation policies. Container repositioning and storage are important sources of carbon emissions at ports. In the process of implementing a low-carbon development strategy for ports, empty-container transportation and storage should be considered. Currently, there are few documents that study this convenience.

Generally speaking, after combing so much literature, we can conclude that most of the studies on ports' low-carbon empty-container repositioning mainly focused on multimodal transport, coordination between seaports and dry ports, truck allocation, etc., rarely paying attention to the relationship between port empty-container input and output or to the impact of empty-container inventory changes and empty-container repositioning on port operating efficiency and carbon emissions. Moreover, strengthening the cooperation in empty-container repositioning, the port group should also consider the restrictions on other ports to carry out empty-container repositioning in order to meet their own empty-container demand. Having summed up the existent studies, in our work, we consider the input and output of containers as random variables under the goal of low-carbon port construction. The port determines the optimal upper limit of empty-container storage and sets up a repositioning threshold for empty containers, with the goal of the lowest total cost. The total cost includes the storage cost, repositioning cost, lease cost, and carbon emission cost of empty containers. Therefore, our work is helpful to optimize the port container repositioning network and to promote the low-carbon development of the port. At present, we have not found any paper that considers the optimization of an empty-container repositioning network at a threshold or involves the probability of a change in empty-container storage capacity at the port. Therefore, this work attempts to bridge a gap on this issue.

3 Model formulation

3.1 Model of port empty containers under threshold-repositioning strategy

3.1.1 Problem description

The goal of ports is to minimize the total cost of empty containers, which includes storage costs, repositioning costs, leasing costs, and carbon emission costs. When there is a shortage of containers in the port, the nearest port will be preferred as the source of empty containers. When all the cooperating ports are unable to transfer empty containers, this port can only rent empty containers from the leasing company. For example, if the port p_i encounters a lack of containers, set p_{iX} as the xth source port of port p_i, then p_i will first turn to port p_{i1} to send an empty-container repositioning request. If the empty-container storage capacity in port p_{i1} is higher than H_1, then empty-container repositioning to p_i can be carried out. If it is lower than H_1, port p_i will turn to p_{i2} to send an empty-container repositioning request, etc. When all ports are unable to help port p_i, it can only seek help from the empty-container leasing company. The abovementioned specific steps are shown in Figure 1.

Before starting the calculation, we define our variables and parameters first as follows:

Variables	
e_i	The number of empty containers transferred from port i to other ports.
S_i	The maximal of empty-container storage in port i.
θ_i	To meet the demand for empty containers, port i should depend on its own storage in θ_i proportion.
β_i	To meet the demand for empty containers, port i should depend on repositioning from other ports in β_i proportion.
γ_i	To meet the demand for empty containers, port i should depend on the leasing company in γ_i proportion.
$\pi_i(m)$	The probability of the empty-container storage capacity of port i being m, with $\sum_{m=1}^{S_i}\pi_i(m) = 1$.
Parameters	
N	The total number of ports.
λ_i	The number of empty containers that obey the positive etheric distribution input of port i.
λ	The total sum of empty-container input of all ports
μ_i	The number of empty containers that obey the positive etheric distribution output of port i.
h_i	Storage cost per empty container for port i.
ϵ_i	Lease cost per empty container for port i.
$V_i^{\max}$	Upper limit of empty-container storage space of port i.
p_{ix}	The xth priority origin port transferring empty containers to port i.
w_{iq}	The probability of port q as the origin of empty containers to port i.
H_i	The empty-container repositioning threshold from port i to other ports, $0 < H_i < S_i$.
t_{il}	The cost of a unit empty container from port i to port j.
c_h	Carbon emission cost per container for storage in unit time.
c_z	Carbon emission cost per container per nautical mile.
TC	Sum of empty-container costs at all ports.
TC_H	Sum of empty-container storage costs at all ports.
TC_z	Sum of empty-container repositioning costs at all ports.
TC_w	Sum of empty-container leasing costs at all ports.
TC_c	Sum of empty-container carbon emission costs at all ports.

This study brings up three basic assumptions:

(1) The storage costs are the same inside and outside the yard of ports.

(2) Every port has one single empty-container leasing company.

(3) The repositioning per empty container between ports is proportional to the distance.

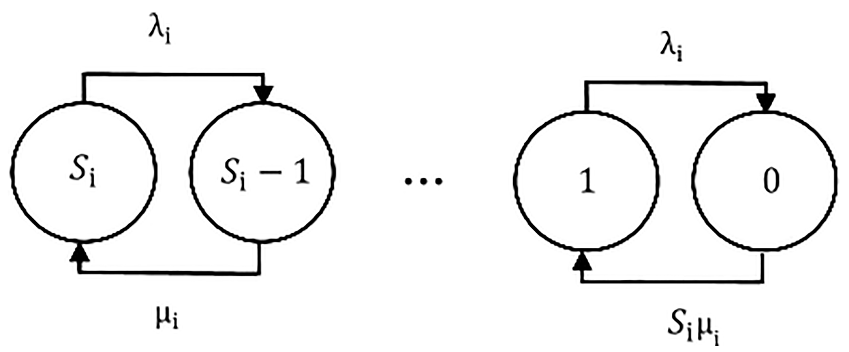

FIGURE 1
Empty-container repositioning order of port *i*.

(4) The empty container is TEU, which is 20 HP.

Next, we calculate θ_i, β_i, and γ_i and every cost of each port. For port *i*, its empty containers are continuously in input and output. So when the empty-container storage status of port *i* is *D*, it is influenced by both *D*+1 and *D*–1. When the empty-container storage of port *i* is higher than H_i, repositioning of empty containers can be carried out, and when it is lower than H_i, to meet the future need of itself, port *i* will stop the repositioning to other ports. Under the threshold-repositioning strategy, the change of empty-container storage in port *i* is shown in Figure 2:

For the convenience of calculation, setting λ as the total sum of empty-container input of all ports, then $\lambda = \sum_{i=1}^{N}\lambda_i$. The empty-container input of port *i* takes a ratio of $f_i = \lambda_i/\lambda$ in all ports, and $f_i\lambda = \theta_i(\lambda_i + e_i) + (1-\theta_i)\cdot 0 = \theta_i\lambda_i + \sum_{q=1,\ q\neq i}^{N}(w_{iq}\beta_i\lambda_i)$. So we have:

$$e_i = \frac{\sum_{q=1,\ q\neq i}^{N}(w_{iq}\beta_i\lambda_i)}{\theta_i} \tag{1}$$

At the same time, $w_{iq_{im}} = \theta_{q_{im}}\prod_{k=1}^{m-1}(1-\theta_{q_{ik}})$. As shown in Figure 2, we can calculate that:

$$\pi_i(S_i)(\lambda_i + e_i) = \pi_i(S_i - 1)\mu_i \tag{2}$$

$$\pi_i(S_i - 1)(\mu_i + \lambda_i + e_i) = \pi_i(S_i)(\lambda_i + e_i) + \pi_i(S_i - 2)\mu_i \tag{3}$$

$$\pi_i(H_i + 1)[(S_i - H_i - 1)\mu_i + \lambda_i] = \pi_i(H_i + 2)(\lambda_i + e_i) + \pi_i(H_i)(S_i - H_i)\mu_i \tag{4}$$

$$\pi_i(1)(S_i - 1)\mu_i = \pi_i(0)S_i\mu_i + \pi_i(2)\lambda_i \tag{5}$$

$$\pi_i(0)S_i\mu_i = \pi_i(1)\lambda_i \tag{6}$$

Using formulas (2)–(6), it is then easy to get:

$$\pi_i(m) = \pi_i(H_i + 1)\frac{(S_i - H_i - 1)!\,(\mu_i)^{m-H_i-1}}{(S_i - m)!\,(\mu_i + e_i)^{m-H_i-1}},$$

$$H_i + 1 \le m \le S_i \tag{7}$$

$$\pi_i(m) = \pi_i(H_i + 1)\frac{1}{\prod_{l=m}^{H_i}(S_i - l)}\left(\frac{\lambda_i}{\mu_i}\right)^{H_i+1-m}$$

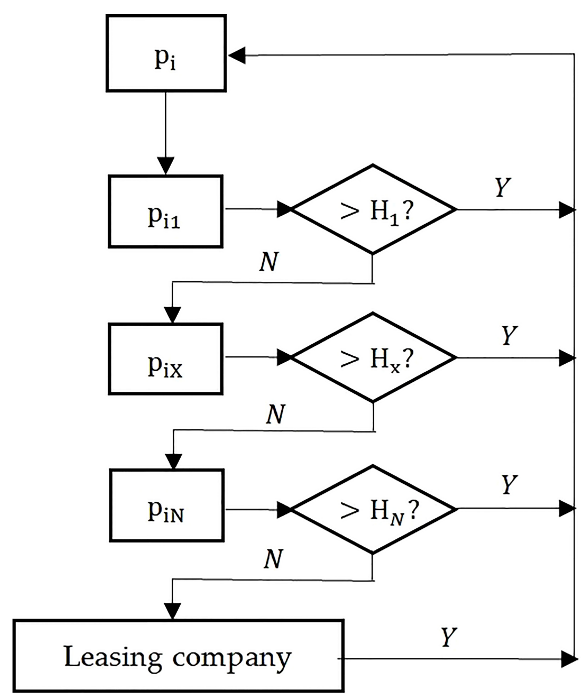

FIGURE 2
Change of empty-container storage in port *i* under the threshold-repositioning strategy.

$$,0 \le m \le H_i \tag{8}$$

Since $\sum_{m=1}^{S_i} \pi_i(m) = 1$, it can be acquired that:

$$\pi_i(H_i+1) = \left\{ \sum_{m=H_i+1}^{S_i} \left[\frac{(S_i - H_i - 1)!(\mu_i)^{m-H_i-1}}{(S_i - m)!(\mu_i + e_i)^{m-H_i-1}} \right] + \sum_{m=0}^{H_i} \left[\frac{1}{\prod_{l=m}^{H_i}(S_i - l)} (\frac{\lambda_i}{\mu_i})^{H_i+1-m} \right] \right\}^{-1} \tag{9}$$

When the empty-container storage in port i is higher than 0, it can meet the demand for empty containers by itself, so we have:

$$\theta_i = 1 - \pi_i(0) \tag{10}$$

Because all the ports will take threshold-repositioning strategy in priority, obviously only when all the ports have a 0 storage of empty containers will they decide to rent them from a leasing company. We get $\gamma_1 = \gamma_2 = \ldots = \gamma_N$. Set λ to be the sum of empty-container input from all the ports, μ to be the sum of empty-container output from all the ports, and S to be the sum of empty-container storage of all the ports, then:

$$\gamma_1 = \gamma_2 = \ldots = \gamma_N = [\sum_{m=0}^{S_i} \frac{S!}{(S-m)!} (\frac{\mu}{\lambda})^m]^{-1} \tag{11}$$

Because $\theta_i + \beta_i + \gamma_i = 1$, $\beta_i = 1 - \theta_i - \gamma_i$.

As for the total costs of empty containers in a port, they include storage cost, repositioning cost, lease cost, and carbon emission cost, which we will calculate in the following.

The empty-container storage cost of port i is correlated to the storage volume as well as its probability, which in detail is $\sum_{m=1}^{S_i} m\, \pi_i(m) h_i$. So the sum of empty-container storage at all ports is calculated as:

$$\mathrm{TC}_H = \sum_{i=1}^{N} \sum_{m=1}^{S_i} m \pi_i(m) h_i \tag{12}$$

The repositioning cost of port i is determined by repositioning volume $\lambda_i \beta_i$ and transferring the cost from port i to l is t_{il}, so the repositioning cost of port i is $\sum_{l=1, l \ne i}^{S_i} \lambda_i \beta_i t_{il}$. Thus, the repositioning cost of all ports is:

$$\mathrm{TC}_z = \sum_{i=1}^{N} \sum_{\substack{l=1 \\ l \ne i}}^{S_i} \lambda_i \beta_i t_{il} \tag{13}$$

The empty-container lease volume of port i is $\lambda_i \gamma_i$, so the lease cost of port i is $\lambda_i \gamma_i \epsilon_i$, from which we can get the total empty-container lease cost of all ports:

$$\mathrm{TC}_w = \sum_{i=1}^{N} \lambda_i \gamma_i \epsilon_i \tag{14}$$

The empty-container carbon emission cost of port i is $\sum_{m=1}^{S_i} \pi_i(m) m c_h$, and the carbon emission cost from empty-container repositioning between ports is $\sum_{l=1, l \ne i}^{S_i} \lambda_i \beta_i t_{il} c_z$, so the empty-container carbon emission cost at all ports is:

$$\mathrm{TC}_c = \sum_{i=1}^{N} \sum_{m=1}^{S_i} \pi_i(m) m c_h + \sum_{i=1}^{N} \sum_{\substack{l=1 \\ l \ne i}}^{S_i} \lambda_i \beta_i t_{il} c_z \tag{15}$$

Therefore, the total cost model of all ports' empty-container repositioning under the threshold-reposition strategy is as follows:

$$Min\ TC = TC_H + TC_z + TC_w + TC_c \tag{16}$$

s.t.

$$TC_H = \sum_{i=1}^{N} \sum_{m=1}^{S_i} m \pi_i(m) h_i \tag{17}$$

$$TC_z = \sum_{i=1}^{N} \sum_{\substack{l=1 \\ l \ne i}}^{S_i} \lambda_i \beta_i \rho t_{il} \tag{18}$$

$$TC_w = \sum_{i=1}^{N} \lambda_i \gamma_i \epsilon_i \tag{19}$$

$$TC_c = \sum_{i=1}^{N} \sum_{m=1}^{S_i} \pi_i(m) m c_h + \sum_{i=1}^{N} \sum_{\substack{l=1 \\ l \ne i}}^{S_i} \lambda_i \beta_i t_{il} c_z \tag{20}$$

$$\pi_i(m) = \pi_i(H_i+1) \frac{(S_i - H_i - 1)!(\mu_i)^{m-H_i-1}}{(S_i - m)!(\mu_i + e_i)^{m-H_i-1}}, H_i + 1 \le m \le S_i \tag{21}$$

$$\pi_i(m) = \pi_i(H_i+1) \frac{1}{\prod_{l=m}^{H_i}(S_i - l)} (\frac{\lambda_i}{\mu_i})^{H_i+1-m}, \ 0 \le m \le H_i \tag{22}$$

$$\pi_i(H_i+1) = \left\{ \sum_{m=H_i+1}^{S_i} \left[\frac{(S_i - H_i - 1)!(\mu_i)^{m-H_i-1}}{(S_i - m)!(\mu_i + e_i)^{m-H_i-1}} \right] + \sum_{m=0}^{H_i} \left[\frac{1}{\prod_{l=m}^{H_i}(S_i - l)} (\frac{\lambda_i}{\mu_i})^{H_i+1-m} \right] \right\}^{-1} \tag{23}$$

$$\theta_i = 1 - \pi_i(0) \tag{24}$$

$$\gamma_i = \left[\sum_{m=0}^{S_i} \frac{(\sum_{i=1}^{N} S_i)!}{(\sum_{i=1}^{N} S_i - m)!} \left(\frac{\sum_{i=1}^{N} \mu_i}{\sum_{i=1}^{N} \lambda_i} \right)^m \right]^{-1} \tag{25}$$

$$\beta_i = 1 - \theta_i - \gamma_i \tag{26}$$

$$\begin{gathered} 0 < S_i < V_i^{\max} \\ i = 1, 2, \ldots, N \end{gathered} \tag{27}$$

3.2 Model of port empty containers under nonrepositioning strategy

If the ports do not adopt the cooperation mode of empty-container mutual repositioning, they can only meet the empty-container demand through their own empty-container inventory or through an empty-container leasing company. Compared with the threshold-repositioning strategy, the change of empty-container storage in the port is also relatively simple. See Figure 3 for the specific change:

Similar to the situation under the threshold-repositioning strategy:

$$\pi_i(0)S_i\mu_i = \pi_i(1)\lambda_i \tag{28}$$

$$\pi_i(m)[(S_i - m)\mu_i + \lambda_i] = \pi_i(m+1)\lambda_i + \pi_i(m-1)(S_i - m + 1)\mu_i,$$

$$m = 1, 2, \ldots, \ S_i - 1 \tag{29}$$

$$\pi_i(S_i - 1)\mu_i = \pi_i(S_i)\lambda_i \tag{30}$$

According to formulas (28), (29), and (30), since $\sum_{m=1}^{S_i}\pi_i(m) = 1$, it can be acquired:

$$\pi_i(0) = [\sum_{k=0}^{S_i}\frac{S_i!\,\mu_i^k}{(S_i-k)!\,\lambda_i^k}]^{-1} \tag{31}$$

$$\pi_i(m) = \pi_i(0)\frac{S_i!\,\mu_i^m}{(S_i-m)!\,\lambda_i^m},$$

$$m = 1, 2, \ldots, \ S_i \tag{32}$$

Also similar to that under the threshold-repositioning strategy, when the empty-container storage of port i is higher than 0, the need for an empty container can be met through the port's own storage, so $\theta_i = 1 - \pi_i(0)$. When the empty-container storage of port i is 0, it can rent empty containers through a leasing company, so $\gamma_i = 1 - \theta_i$ and $\beta_i = 0$. The total cost model of ports' empty containers under the nonrepositioning strategy is as follows:

Min

$$TC = TC_H + TC_w + TC_c \tag{33}$$

s.t.

$$TC_H = \sum_{i=1}^{N}\sum_{m=1}^{S_i} m\pi_i(m)h_i \tag{34}$$

$$TC_w = \sum_{i=1}^{l}\lambda_i\gamma_i\epsilon_i \tag{35}$$

$$TC_c = \sum_{i=1}^{N}\sum_{m=1}^{S_i}\pi_i(m)mc_h \tag{36}$$

$$\pi_i(m) = \frac{S_i!\,\mu_i^m}{\sum_{k=0}^{S_i}\frac{S_i!\,\mu_i^k}{(S_i-k)!\,\lambda_i^k}(S_i-m)!\,\lambda_i^m} \tag{37}$$

$$\theta_i = 1 - \left[\sum_{k=0}^{S_i}\frac{S_i!\,\mu_i^k}{(S_i-k)!\,\lambda_i^k}\right]^{-1} \tag{38}$$

$$\gamma_i = \left[\sum_{k=0}^{S_i}\frac{S_i!\,\mu_i^k}{(S_i-k)!\,\lambda_i^k}\right]^{-1} \tag{39}$$

$$0 < S_i < V_i^{\max}, \quad i = 1, 2, \ldots, N \tag{40}$$

3.3 Model of port empty containers under complete-repositioning strategy

In this section, we propose a third strategy: the complete-repositioning strategy. Compared to the threshold-repositioning strategy, ports under the complete-repositioning strategy do not have a threshold for repositioning, which means that even if there is only one empty container in storage in a port when another port sends a request, the port will transfer this single empty container out anyway. Under this strategy, the change in empty-container storage of the port can be seen in Figure 4.

$$\pi_i(0)S_i\mu_i = \pi_i(1)(\lambda_i + e_i) \tag{41}$$

$$\pi_i(m)[(S_i - m)\mu_i + \lambda_i + e_i] = \pi_i(m+1)(\lambda_i + e_i) + \pi_i(m-1)(S_i - m + 1)\mu_i,$$

$$m = 1, 2, \ldots, \ S_i - 1 \tag{42}$$

$$\pi_i(S_i - 1)\mu_i = \pi_i(S_i)(\lambda_i + e_i) \tag{43}$$

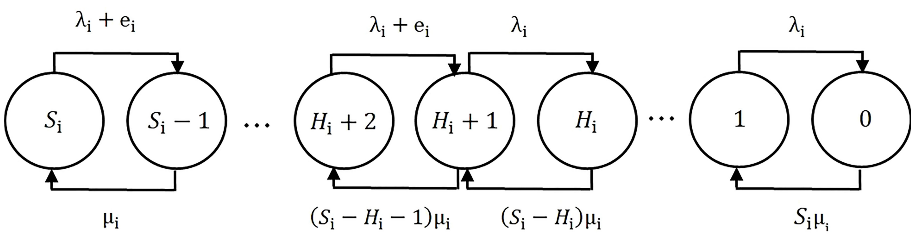

FIGURE 3
The change of port i empty-container storage under the nonrepositioning strategy.

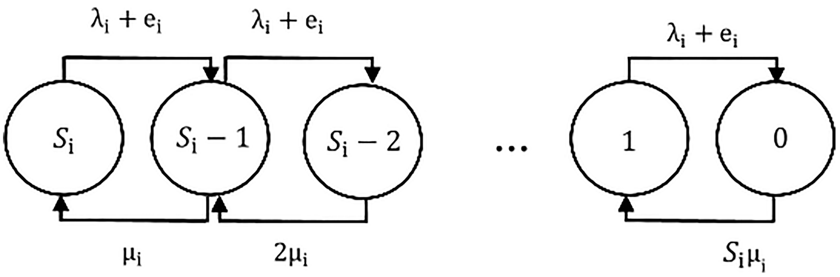

FIGURE 4
Change of empty-container storage in port *i* under the complete-repositioning strategy.

According to formulas (2), (3), and (4), it is known that:

$$\pi_i(0) = \left[\sum_{k=0}^{S_i} \frac{S_i\,!\,\mu_i^k}{(S_i-k)\,!\,(\lambda_i+e_i)^k}\right]^{-1} \tag{44}$$

$$\pi_i(m) = \pi_i(0)\frac{S_i!\mu_i^m}{(S_i-m)\,!\,(\lambda_i+e_i)^m}, m = 1,2,\ldots,\ S_i \tag{45}$$

$$\theta_i = 1 - \pi_i(0) \tag{46}$$

$$\gamma_i = \left[\sum_{m=0}^{S_i} \frac{(\sum_{i=1}^N S_i)\,!}{(\sum_{i=1}^N S_i - m)\,!}\left(\frac{\sum_{i=1}^N \mu_i}{\sum_{i=1}^N \lambda_i}\right)^m\right] \tag{47}$$

The total cost model of ports' empty containers under the complete-repositioning strategy is as follows:

Min

$$Min\ TC = TC_H + TC_z + TC_w + TC_c \tag{48}$$

s.t.

$$TC_H = \sum_{i=1}^{N}\sum_{m=1}^{S_i} m\pi_i(m)h_i \tag{49}$$

$$TC_z = \sum_{i=1}^{N}\sum_{\substack{l=1\\ l\neq i}}^{S_i} \lambda_i\beta_i t_{il} \tag{50}$$

$$TC_w = \sum_{i=1}^{N}\lambda_i\gamma_i\epsilon_i \tag{51}$$

$$TC_c = \sum_{i=1}^{N}\sum_{m=1}^{S_i}\pi_i(m)mc_h + \sum_{i=1}^{N}\sum_{\substack{l=1\\ l\neq i}}^{S_i}\lambda_i\beta_i t_{il}c_z \tag{52}$$

$$\pi_i(0) = \left[\sum\nolimits_{k=0}^{S_i} \frac{S_i\,!\,\mu_i^k}{(S_i-k)\,!\,(\lambda_i+e_i)^k}\right]^{-1} \tag{53}$$

$$\pi_i(m) = \pi_i(0)\frac{S_i!\mu_i^m}{(S_i-m)\,!\,(\lambda_i+e_i)^m}, m = 1,2,\ldots,\ S_i \tag{54}$$

$$\theta_i = 1 - \pi_i(0) \tag{55}$$

$$\gamma_i = \left[\sum_{m=0}^{S_i} \frac{(\sum_{i=1}^N S_i)\,!}{(\sum_{i=1}^N S_i - m)\,!}\left(\frac{\sum_{i=1}^N \mu_i}{\sum_{i=1}^N \lambda_i}\right)^m\right] \tag{56}$$

$$\beta_i = 1 - \theta_i - \gamma_i \tag{57}$$

$$0 < S_i < V_i^{\max} \tag{58}$$

$i = 1,2,\ldots,N$

Theorem 1: Port *i* depends more on its own storage to meet the demand for empty containers under the nonrepositioning strategy, followed by the threshold-repositioning strategy, and finally the complete-repositioning strategy.

Prove: If ct represents the complete-repositioning strategy, tr represents the repositioning strategy, and nt represents the nonreposition strategy, we can deduce from formulas (31) and (32) that:

$$\pi_i^{tr}(0) = \frac{\frac{1}{\prod_{l=m}^{H_i}(S_i-l)}\left(\frac{\lambda_i}{\mu_i}\right)^{H_i+1-m}}{\sum_{m=H_i+1}^{S_i}\left[\frac{(S_i-H_i-1)\,!\,(\mu_i)^{m-H_i-1}}{(S_i-m)\,!\,(\mu_i+e_i)^{m-H_i-1}}\right] + \sum_{m=0}^{H_i}\left[\frac{1}{\prod_{l=m}^{H_i}(S_i-l)}\left(\frac{\lambda_i}{\mu_i}\right)^{H_i+1-m}\right]} \tag{59}$$

Therefore, when $H_i = S_i - 1$, $\pi_i^{\mathrm{tr}}(0) = \pi_i^{\mathrm{nt}}(0)$. When $H_i = 0$, $\pi_i^{\mathrm{tr}}(0) = \pi_i^{\mathrm{ct}}(0)$, and we know that

$$\pi_i^{\mathrm{ct}}(0) = \left[\sum\nolimits_{k=0}^{S_i}\frac{S_i\,!\,\mu_i^k}{(S_i-k)\,!\,(\lambda_i+e_i)^k}\right]^{-1} > \left[\sum\nolimits_{k=0}^{S_i}\frac{S_i\,!\,\mu_i^k}{(S_i-k)\,!\,\lambda_i^k}\right]^{-1} = \pi_i^{\mathrm{nt}}(0) \tag{60}$$

Because $0 < H_i < S_i - 1$, we have $\pi_i^{\mathrm{ct}}(0) > \pi_i^{\mathrm{tr}}(0) > \pi_i^{\mathrm{nt}}(0)$, and $\theta_i = 1 - \pi_i(0)$, so $\pi_i^{\mathrm{ct}}(0) < \theta_i^{\mathrm{tr}} < \theta_i^{\mathrm{nt}}$.

According to theorem 1, we know that the higher the repositioning threshold, the higher the dependence of the port on its own empty-container inventory. The lower the repositioning threshold is, the more help other ports can provide, which requires a higher degree of cooperation between port groups.

4 Model solving

For threshold-repositioning strategy and complete-repositioning strategy, the calculations of θ_i, β_i, γ_i, and e_i are quite complicated. Taking threshold-repositioning strategy for an example, according to formula (1), it can be known that the calculation of e_i requires the definition of θ_i and β_i. However, to get θ_i and β_i, we should first clarify $\pi_i(m)$. However, the expression of $\pi_i(m)$ includes e_i. Therefore, this study decided to use the cycle computation method to acquire θ_i, β_i, γ_i, e_i, and $\pi_i(m)$. Also, the same method is used in the calculations of the complete-repositioning strategy's parameters. The specific steps are as follows:

Step 1: Initialize $\theta_i = 0.8,\ \beta_i = 0.1,\ \gamma_i = 0.1$.

Step 2: Set a big enough positive integer, Maximum, and a minimal integer, Minimum, and start cycle computation.

For (l = 1; l<= Maximum; l++) {

$$w^l_{iq_{im}} = \theta^{l-1}_{q_{im}} \prod_{k=1}^{m-1} (1 - \theta^{l-1}_{q_{ik}}) \tag{61}$$

$$e^l_{ij} = \frac{\sum_{q=1,\ q \neq i}^{I} (w^j_{iq} \beta^l_{ij-1} \lambda_i)}{\theta^l_i} \tag{62}$$

$$\pi_i(m) = \pi_i(H_i + 1) \frac{(S_i - H_i - 1)!\,(\mu_i)^{m-H_i-1}}{(S_i - m)!\,(\mu_i + e^l_i)^{m-H_i-1}},$$

$$H_i + 1 \le m \le S_i \tag{63}$$

$$\pi_i(m) = \pi_i(H_i + 1) \frac{1}{\prod_{l=m}^{H_i} (S_i - l)} \left(\frac{\lambda_i}{\mu_i}\right)^{H_i+1-m},\ 0 \le m \le H_i \tag{64}$$

$$\theta^l_i = 1 - \left[\sum_{m=0}^{S_i} \frac{S_i!\,\mu^k_i}{(S_i - k)!\,(\lambda_i + e^l_i)^k}\right]^{-1} \tag{65}$$

$$\gamma^l_i = \left[\sum_{m=0}^{S_i} \frac{S!}{(S - m)!} \left(\frac{\mu^l}{\lambda^l}\right)^m\right]^{-1} \tag{66}$$

$$\beta^l_i = 1 - \theta^l_i - \gamma^l_i \tag{66}$$

if ($|\theta^l_i - \theta^{l-1}_i| \le$ Minimum) {break}; }

5 Computational experiment

5.1 Data setting

We take China's Yingkou Port, Dalian Port, and Yantai Port as the actual research cases. These three ports are all located in Bohai Bay, and there is a cooperative relationship between the three ports for empty-container repositioning. In 2022, the container throughput of the three ports will be 5.00 million, 4.46 million, and 412 million TEU, respectively, and the average monthly throughput will be 416.7, 371.7, and 353.3 K TEU. The upper limit of empty-container storage can be set to 1/2 of the monthly throughput. Ships are used for empty-container repositioning between ports, and the freight rate is \$0.5/n mile. See Table 1 for the distances among the three ports and the repositioning costs.

The empty-container storage charge in each port is \$0.1/h, and generally, the storage period is 10 days, so the storage charge is \$24. According to the statistics of Container xChange in December 2022, the rental fee for empty containers is \$804, and the general round-trip time of the route is 40 days, so the rental fee within 10 days is \$201. The upper limit of the total scale of the port's front yard and the rear yard is one-twelfth of the annual throughput. Set $H_i = S_i \mathring{A} n \sigma$, in which $\sigma \in (0, 1)$, c_h =1\$/TEU, c_z =0.5\$/TEU.

The other data of the three ports are shown in Table 2:

Because of the complexity of this model, we chose the genetic algorithm as our method. Using MATLAB 2018, the results are shown in Table 3:

According to Table 3, it can be seen that under the complete-repositioning strategy, the total cost, carbon emission cost, and empty-container storage are all at the lowest level, while they are higher under the threshold-repositioning strategy and the highest under the nonrepositioning strategy. This is because, under both repositioning strategies, the port can reduce its own storage by sharing empty containers, thus realizing the target of reducing storage costs and sharing the risk of lacking containers. Since under the threshold-repositioning strategy and complete-repositioning strategy, the empty-container storage is lower than that under the nonrepositioning strategy, the ports need to meet the demand for empty containers more through leasing and repositioning means, so the lease cost and repositioning cost will both surpass those under nonrepositioning strategy. Simultaneously, the proportion of meeting demand through the ports' own storage under the nonrepositioning strategy is the highest among the three strategies, which proves Theorem 1.

TABLE 1 Distances and repositioning costs among three ports (n mile (\$)).

	Yingkou Port (port 1)	Dalian Port (port 2)	Yantai Port (port 3)
Yingkou Port	0, 0	156, 78	216, 108
Dalian Port	156, 78	0, 0	89, 44.5
Yantai Port	216, 108	89, 44.5	0, 0

TABLE 2 Other data of the three ports.

	Port 1	Port 2	Port 3
h_i ($)	24	24	24
ϵ_i ($)	201	201	201
σ	0.2	0.2	0.2
c_h ($/TEU)	1	1	1
c_z ($/TEU)	0.5	0.5	0.5
V_i^{max} (K · TEU)	208.3	185.8	171.7
λ_i (K · TEU/h)	$N(40, 1)$	$N(30, 1)$	$N(30, 1)$
μ_i (K · TEU/h)	$N(35, 1)$	$N(25, 1)$	$N(25, 1)$

5.2 Data analysis

The key variables that influence the port's choice of repositioning strategy are h_i and H_i, so in this section, we try to analyze them. The influence of the change of H_i on three strategies are shown in Table 4:

The increase of h_i means the increase in the storage cost of unit empty containers in ports. In terms of Table 4, with the increase of h_i, the total cost, storage cost, lease cost, and carbon emission cost of ports will all increase under the three strategies. For the proportion of empty-container sources, that depending on the port's own storage will decrease, yet those depending on other ports as well as on leasing companies will both increase because when the storage cost of a unit empty-container increases, the port has to reduce its own storage, thus enhancing its dependence on other ports and on the leasing company.

The influence of σ 's change on three strategies is shown in Table 5:

The higher σ is, the higher H_i becomes, which means a higher barrier between ports for empty-container repositioning. According to Table 5, with the increase of σ, the total cost, storage cost, lease cost, and carbon emission cost of ports will all increase under the threshold-repositioning strategy. As to the proportion of empty-container sources, those depending on their own storage and ports will increase, while those depending on leasing companies will decrease. This is due to the fact that the higher the repositioning barrier, the advantage of the threshold-repositioning strategy becomes less obvious compared to the nonrepositioning strategy.

6 Conclusion

The unbalanced distribution of empty containers among ports has become one of the most important adverse factors affecting the normal operation of ports. Strengthening the cooperation of empty-container repositioning between ports is of great significance for improving port efficiency and is also conducive to the construction of low carbon ports. We have built three optimization models for empty-container repositioning between multiple ports, taking into account that the input and output of empty containers are random variables and that there is a threshold for the port to transfer empty containers. We calculated the probability of the empty-container inventory of each port, calculated the probability that the port depends on its own empty-container inventory, on other ports, and on leasing companies, respectively, to meet the empty-container demand, and calculated the costs of port empty-container storage, repositioning, leasing, and carbon emission. The port costs under the threshold-repositioning strategy, nonreposition strategy, and complete-repositioning strategy were also compared. The main conclusions of this paper are as follows:

TABLE 3 Results from two strategies.

	Threshold-repositioning strategy	Nonrepositioning strategy	Complete-repositioning strategy
TC	1,881.9	2,269.3	1,745.6
TC_H	1,424.2	1,983.7	1,253.2
TC_Z	190.3	–	211.2
TC_W	206.2	142.8	224.4
TC_c	61.2	82.7	56.8
θ_i	0.93, 0.92, 0.91	0.95, 0.0.93, 0.94	0.89, 0.86, 0.87
β_i	0.04, 0.03, 0.03	–, –, –	0.11, 0.11, 0.10
γ_i	0.03, 0.05, 0.06	0.05, 0.07, 0.06	0.02, 0.03, 0.03
S_i	74, 38, 42	84, 46, 66	63, 35, 40

TABLE 4 Analysis of the influence of the change of h_i's on three strategies.

	h_i	Threshold-reposition strategy	Non-reposition strategy	Complete-reposition strategy
TC	20	1697.9	1963.6	1567.3
	24	1881.9	2269.3	1745.6
	28	2264.8	2661.8	2036.9
TC_H	20	1296.0	1689.2	1181.8
	24	1424.2	1983.7	1253.2
	28	1703.6	2262.4	1484.6
TC_Z	20	161.9	—	131.7
	24	190.3	—	211.2
	28	221.4	—	230.3
TC_W	20	184.4	137.2	201.4
	24	206.2	142.8	224.4
	28	266.6	199.7	255.7
TC_C	20	55.6	70.4	52.4
	24	61.2	82.7	56.8
	28	73.2	94.3	66.3
θ_i	20	0.94,0.92,0.94	0.95,0.94,0.96	0.90,0.91,0.91
	24	0.93, 0.92, 0.91	0.95,0.0.93,0.94	0.89,0.86, 0.87
	28	0.90,0.90,0.89	0.93,0.90,0.92	0.86,0.83,0.84
β_i	20	0.04,0.03,0.02	—,—,—	0.08,0.07,0.07
	24	0.04, 0.03, 0.03	—,—,—	0.11,0.11,.0.10
	28	0.05,004,0.05	—,—,—	0.11,0.13,0.11
γ_i	20	0.02,0.05,0.04	0.05,0.96,0.94	0.02,0.02,0.02
	24	0.03, 0.05, 0.06	0.05,0.07,0.06	0.02, 0.03, 0.03
	28	0.05,0.06,0.06	0.07,0.10,0.08	0.03,0.04,0.05

(1) For the costs of ports, the empty-container storage of the port is the lowest under the nonrepositioning strategy, followed by the threshold-repositioning strategy. So the port can only lease more empty containers or meet the demand through repositioning from other ports, causing higher leasing costs; repositioning costs under the complete-repositioning strategy are the highest among the three strategies. However, the total cost of the port is the lowest under the complete-repositioning strategy. The increase in unit empty-container storage cost of the port will lead to an increase in total cost, storage cost, lease cost, and carbon emission cost under three strategies. Also, the higher the barrier blocking empty-container repositioning between ports is, the higher the total cost, storage cost, repositioning cost, and carbon emission cost there will be.

(2) For the probability that the port will choose each kind of empty-container source, under the nonrepositioning strategy, it will depend more on its own storage and leasing company than under the threshold-repositioning strategy and complete-repositioning strategy. When the unit empty-container storage cost increases, the ports will depend less on their own storage and more on other ports as well as the leasing company. Also, the higher the barrier for repositioning is, the less the port will depend on its own storage and on other ports, while depending more on the leasing company.

From the above, we can conclude that the repositioning strategy can efficiently reduce the total cost of empty containers for the port and reduce carbon emissions. The lower the repositioning barrier between ports is, the more obvious the advantages of the repositioning strategy become.

The study in this paper still has some limitations. For example, in the calculation of empty-container storage cost, we take the storage charge as a constant, yet it is actually not so in reality. As a matter of fact, the ports will often give some days without charging and then take charges after a certain period of time, which is not indicated in this study. We have not considered the time limit for

TABLE 5 Analysis of the influence of σ 's change on three strategies.

	σ	Threshold-reposition strategy	Non-reposition strategy	Complete-reposition strategy
TC	0.1	1937.3	2126.5	1745.6
	0.2	2026.9	2126.5	1745.6
	0.3	2088.3	2126.5	1745.6
TC_H	0.1	1328.1	1983.7	1253.2
	0.2	1424.2	1983.7	1253.2
	0.3	1443.6	1983.7	1253.2
TC_Z	0.1	212.6	—	211.2
	0.2	190.3	—	211.2
	0.3	171.3	—	211.2
TC_W	0.1	198.3	142.8	224.4
	0.2	206.2	142.8	224.4
	0.3	236.7	142.8	224.4
TC_C	0.1	57.5	82.7	56.8
	0.2	61.2	82.7	56.8
	0.3	61.9	82.7	56.8
θ_i	0.1	0.90, 0.90, 0.89	0.95,0.0.93,0.94	0.89,0.86, 0.87
	0.2	0.93, 0.92, 0.91	0.95,0.0.93,0.94	0.89,0.86, 0.87
	0.3	0.94, 0.92, 0.94	0.95,0.0.93,0.94	0.89,0.86, 0.87
β_i	0.1	0.08, 005, 0.07	—,—,—	0.11,0.11,.0.10
	0.2	0.04, 0.03, 0.03	—,—,—	0.11,0.11,.0.10
	0.3	0.04,0.03,0.02	—,—,—	0.11,0.11,.0.10
γ_i	0.1	0.02, 0.05, 0.04	0.05,0.07,0.06	0.02, 0.03, 0.03
	0.2	0.03, 0.05, 0.06	0.05,0.07,0.06	0.02, 0.03, 0.03
	0.3	0.02, 0.05, 0.04	0.05,0.07,0.06	0.02, 0.03, 0.03

empty-container repositioning between ports. In practice, due to strict shipment date constraints, empty-container repositioning at the port should have a time window. In future research, we hope to carry out further exploration in the following aspects: First, consider the time of the empty container stored in the port, because the storage charge is relevant to the time. Second, to include the shipping company in our optimization model of empty-container repositioning, adding a repositioning responding time limit to the situation of the sailing date. Third, it should be reflected in the model that, according to carbon-reducing policies, only when the carbon emissions exceed a certain level will the government levy a carbon tax on ports.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

XT designed the study and performed the research. CX performed the data analysis. CW performed the validation. JS wrote the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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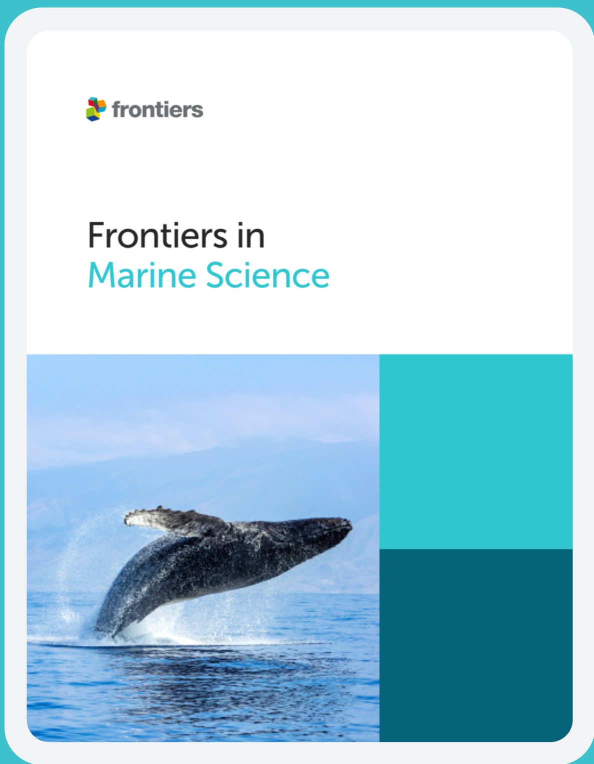

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