Study on the Impact of the Whole Life Cycle Operation Process of Large Ports on Environmental Externalities

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Abstract. As global economic integration continues to advance, ports are playing an increasingly important role in trade demand and are supported by national policies. However, the expansion of port facilities has had adverse effects on the local natural and social environment, posing threats to economic sustainability and residents' quality of life. These issues urgently need to be addressed.

This study employs statistical analysis methods, including ANOVA, multiple regression, and least squares, with the aim of quantitatively analyzing factors related to port sustainability in three cases: Wuhan Port, Shanghai Port, and Tianjin Port. Specifically, we focus on various stages of construction, operation, technological advancement, and technological innovation, while also considering intermodal transportation as a significant factor. Through in-depth analysis, we find a significant positive correlation between increased research investment and the number of rail-water intermodal routes with port sustainability.

This research aims to provide valuable insights for port managers and policymakers to promote port sustainability. Our study emphasizes the critical role of statistical analysis methods in understanding the impact of environmental externalities throughout the entire lifecycle of ports.

Keywords: Ports, Ecological environment,full life cycle, Rail-water intermodal transport, Negative externality impacts, R&D investment

1 INTRODUCTION

In today's globalized economic landscape, large ports play an indispensable role as critical links in international trade, facilitating the movement of goods and contributing to global economic prosperity. However, the rapid expansion and high development of large ports are accompanied by an urgent challenge: how to maintain and protect the health of the surrounding natural environment and social ecosystems during the process of port development.

To address this challenge and answer the question of "how to do it," we first need to understand how large ports impact the environment during their development and lifecycle, as well as which factors are crucial in influencing this impact. Therefore, the central focus of this study is to comprehensively examine the mechanisms behind the external environmental impacts of large ports throughout their entire lifecycle, including key stages such as port construction and investment, operational phases, technological advancements, and future innovations. We aim to

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delve into how these stages interrelate and the magnitude of their effects on environmental externalities.

Existing literature on the environmental externalities of ports is abundant and covers a wide range of case studies involving different large ports. However, these studies often focus on specific stages of port development, lacking a holistic perspective. For example, taking Shanghai Port as an example, Eric Tamatey (2019) concentrated on the construction phase, emphasizing the significant ecological and social impacts of land reclamation[1], while Ilza Machado Kaiser (2013) focused on the planning phase, highlighting the direct role of local government environmental regulations and policies in the environmental externalities of the port[2]. Similarly, research on Wuhan Port conducted by Stephen J. Ramos (2014) focused on the development phase, pointing out that port competition was the most significant influencing factor on its environmental externalities, potentially causing irreversible harm to the fragile local ecosystem[3]. Yang Xiaoying (2019) studied the environmental governance phase of Tianjin Port, emphasizing the critical importance of treating and disposing of dredged sediments for the port's environmental externalities[4]. Weichen Liu (2022) also centered on the expansion phase of Yangluo Port, concluding that the effective utilization of waterfront areas would directly impact the port's environmental externalities[5].

Current research has two key shortcomings. Firstly, large ports in different regions and cultural contexts are influenced by a variety of factors. However, existing literature often does not delve into the common characteristics among these influencing factors, limiting the overall understanding of the impact of large ports throughout their lifecycle. Secondly, existing research often only focuses on the external environmental impacts of specific stages of port development, lacking an analysis of the overall environmental externalities throughout the entire port lifecycle. Therefore, it is not possible to answer two more crucial questions through the study of this literature: which stage has the greatest impact on the environmental externalities of ports throughout their entire lifecycle? What measures can be taken during which stage to better mitigate the negative environmental impact of ports? The answers to these two questions are essential for analyzing the mechanisms of port environmental externalities from a global perspective.

Hence, this study aims to evaluate the relative importance of different stages and factors in the environmental externalities of large ports' development, using Wuhan Port, Tianjin Port, and Shanghai Port as case studies and employing quantitative analytical methods. Ultimately, the goal of this research is to provide a more comprehensive perspective on the sustainable development of large ports and promote the synergistic progress of economic growth and environmental protection.

2 LITERATURE REVIEW

2.1 Adverse Environmental Impacts of Ports:

In today's globalized economic landscape, ports play an indispensable role as key hubs of international trade. According to data from C40 CITIES, over 80% of global trade goods are transported by ships, and 99% of commercial ships use diesel engines as their power source. This situation has made the international shipping industry a major contributor to greenhouse gas emissions, currently accounting for 2% to 3% of global greenhouse gas emissions. More concerningly, without measures in place, this proportion could increase to 17% in the next 20 years, further exacerbating climate change. Meanwhile, the health costs due to emissions from the international shipping industry amount to as much as $16 billion annually, resulting in approximately 60,000 premature deaths each year, with coastal areas being particularly affected.

The adverse environmental impacts of ports throughout their entire lifecycle can be categorized into several aspects. Researcher Schipper (2017) summarized these impacts into three categories: port location, port construction, and port operations, which correspond to the three stages of the port lifecycle—planning, construction, and operation[6]. Specifically, port location involves the presence of structures, landfill sites, and the choice of the port's construction site. Port construction encompasses activities both at sea and on land, including dredging, the handling and transportation of dredged materials, and the generation of related waste. Port operations include factors related to vessels and cargo, such as vessel emissions, cargo handling and storage, and hazardous materials management.

Different researchers have classified the adverse environmental impacts of ports at various stages of their development from different perspectives. For instance, C. Trozzi and R. Vaccaro (2021) categorized them into four aspects: air pollution, water pollution, waste generation, and noise production[7]. On the other hand, Ruiz-Guerra (2019) grouped them into four major categories: impacts on climate change, impacts on air quality, impacts on water quality, and impacts on the health of surrounding community members[8]. These classifications demonstrate the multifaceted negative impacts of ports on the environment, including deterioration of air and water quality, waste generation and disposal issues, and harm to the health of nearby community residents.

Of particular concern is Salvador del Saz-Salazar's (2013) emphasis on the negative impacts of ports on the quality of life of surrounding residents. This includes land reclamation, air and water pollution, noise, odors, and visual pollution, all of which collectively have adverse effects on residents' lives. However, what is worrisome is that those affected residents often do not receive any compensation, leading to resistance to the expansion of local urban ports and a deteriorating public image[9].

While existing research has summarized the negative environmental impacts of ports and the international shipping industry, there is a common deficiency—insufficient consideration of regional and contextual differences. This has resulted in a limited understanding of regional and contextual factors, making it difficult to formulate precise environmental policies and sustainable development strategies. Additionally, although existing studies generally cover various stages of the port lifecycle, they do not provide in-depth comparisons and assessments of the environmental externalities of ports at different stages. To more effectively address the environmental challenges posed by port expansion, future research can focus on regional and stage-specific studies, exploring differences in environmental impacts based on geographical location, climatic conditions, cultural factors, and community needs, as well as the varying impacts of ports on the environment at different stages. This would provide robust support for more precise policy and strategy development.

2.2 The Necessity of Mitigating the External Environmental Impact of Ports:

Several researchers have emphasized the importance of balancing port development with environmental protection and have provided their conclusions and recommendations. Lawer, Eric Tamatey (2019) stressed the importance of achieving a balance between economic activity and environmental protection in global large-scale infrastructure projects, with stakeholder engagement and Environmental and Social Impact Assessments (ESIA) being crucial[1]. De Boer, W.P (2019) noted that ports must consider the intrinsic value of ecosystems for long-term sustainable development, suggesting that early incorporation of ecosystem protection measures can reduce adverse impacts[10]. Teerawattana, Rattaporn (2019) considered environmental management crucial in port operations, offering advantages for customer satisfaction, corporate image, and environmental protection[11]. Giuffrida, Nadia (2021) underscored the critical role of container terminals and other ports in energy consumption, environmental pollution, and climate change, advocating for environmental impact assessments and mitigation measures[12]. Finally, Herrero, Alvaro (2022) highlighted the proactive efforts of society and leadership in addressing the role of the port industry in climate change and CO2 emissions reduction, emphasizing the need for more improvement measures to enhance sustainability[13]. In summary, port expansion has significant impacts on environmental and social sustainability, necessitating comprehensive consideration of multiple stakeholders and the adoption of measures to reduce adverse impacts.

The above-mentioned literature highlights the necessity of incorporating environmental factors into port development over the long term, covering various stages of the port lifecycle, including planning, construction, and operation. However, in practical implementation, addressing environmental issues during port expansion remains challenging. Firstly, while these studies propose important concepts, the port industry may face various challenges in practice, such as coordinating multiple stakeholders and resource constraints. Secondly, although early ecosystem protection measures are beneficial, implementing and maintaining these measures may require substantial investment and long-term commitment. Additionally, while environmental management is considered crucial for port operations, effective implementation and regulation remain complex issues, potentially necessitating stronger policies and regulatory mechanisms. Finally, improvement measures for reducing CO2 emissions in the port industry require more technological innovation and international collaboration, posing a challenging task. To address these issues, it is essential to first analyze the mechanisms of environmental impact by ports at various stages of their entire lifecycle, determine the influence weights of different stages and factors, and then plan accordingly. This is the research objective of this paper.

2.3 Analysis and Strategies for Mitigating the Environmental Impact of Ports at Various Development Stages:

Amidst the global trends of trade and sustainable development, the sustainable expansion of ports has become an inevitable direction for development. Over the past two decades, various ports have explored the mechanisms by which ports affect the environment, considering local conditions and available technologies as the basis for planning their sustainable development. For example, de Boer, W.P (2019) used Ghana's port as an example, emphasizing that early ecosystem-based planning can reduce adverse impacts and proposed an ecosystem-based hierarchical framework for port design[10]. However, similarly based on Ghana's port, Lawer, Eric Tamatey (2019) studied efforts to mitigate adverse impacts through stakeholder involvement but ultimately concluded that they were unsuccessful[1]. In South Africa, Taljaard, S (2021) introduced a comprehensive port management framework that integrates the natural environment into port expansion considerations, offering a new approach to sustainability[7]. Additionally, Teerawattana, Rattaporn (2019) used Thailand's Laem Chabang port as a case study and proposed assessment criteria for green ports, emphasizing the importance of environmental protection[11]. In 2023, Wang, Peng used Tianjin port as a case study, providing a multidimensional analysis of pollutant emissions to support policy-making and promote sustainable development[14]. However, Kaiser, Ilza Machado (2013) discussed the impact of the local government bureaucracy on sustainable expansion using Brazil's ports as an example, highlighting the complexity of the government's role[2]. In 2020, Borja, Nogué-Algueró used Spain's Santander port as a case study and proposed a carbon reduction method for comprehensive port logistics systems, offering innovative solutions for environmental protection[15]. Finally, in 2021, Franchi, Lorenzo used Barcelona's port as a case study, questioning the compatibility of ports with environmental sustainability and suggesting degrowth as an alternative. In 2022, Deng, Gaodan used Shenzhen port as a case study, examining the relationship between government environmental regulatory strategies and corporate green port construction, emphasizing the importance of policy and practice coordination[16]. These case studies provide valuable historical experience and serve as references and inspiration for the sustainable development of ports. They underscore the need to proactively take measures to reduce environmental and social adverse impacts while facing the growth of global trade.

These studies cover multiple major ports worldwide, encompassing various stages of the port lifecycle, including planning, construction, and operation, among others. However, these articles still lack consideration of regional differences and stage-specific analysis. Each article typically analyzes a single factor from one region and one stage, lacking foresight and a global perspective. In light of this, this paper will conduct an analysis of factors throughout the entire lifecycle of different ports, comparing the degree of influence and positive/negative effects of different factors on the port environment. The goal is to provide conclusions and recommendations that are both widely applicable and able to accommodate various contextual differences.

3 RESEARCH METHODOLOGY

3.1 Research Plan:

To formulate a specific research plan, this paper needs to clarify the research objectives and the problems to be addressed. The core research question of this paper is: "In the entire lifecycle of ports, which stage and which factors play a critical role in the external environmental impacts of ports?" To answer this question, this paper needs to select representative factors from various stages of the port lifecycle for comparison and analysis, ultimately identifying the factors significantly related to the external environmental impacts of ports and providing recommendations based on these factors.

3.2 Case Selection:

When conducting comparative case studies, case selection must be clearly filtered based on research objectives and methods, with clear justifications provided. In the context of this paper, the research aims to answer the question, "In the entire lifecycle of ports, which stage and which factors play a critical role in the external environmental impacts of ports" through comparisons between cases. Therefore, case selection needs to go through multiple layers of restrictions[17].

Firstly, ports are the initial limiting condition, meaning that the selected cases must be ports that are still in operation. Secondly, case selection needs further restriction, and the chosen ports must have experienced sustained growth in cargo volume and throughput (cargo throughput is a key indicator reflecting the scale of ports) in recent years. Finally, for effective comparison, there must be some degree of variation in background conditions among the selected ports; otherwise, the comparison would lose its meaning.

Based on the above theoretical considerations, this paper selects Shanghai Port, Wuhan Port, and Tianjin Port as the study areas. The choice of these three ports is based on a series of clear reasons, while also taking into account the key differences among these three ports.

Firstly, the selection of these three ports is because they represent ports in different geographical locations and economic regions within China. This selection helps capture diversity and comprehensiveness in the study. Shanghai Port, located in eastern China at the mouth of the Yangtze River, is one of China's largest ports and serves as a gateway for international trade. Wuhan Port, situated in central China in the middle reaches of the Yangtze River, is an inland port serving the inland regions of the Yangtze River Economic Belt. Tianjin Port, located in northern China, is a crucial hub connecting northern China and Central Asian countries. The choice of these three ports adequately reflects the operational conditions of ports in different geographical and economic environments within China.

Secondly, the choice of these three ports also includes their significant differences in terms of port expansion and environmental impacts. Shanghai Port, as a major international trade hub, faces significant challenges in terms of cargo throughput and environmental concerns, thus having unique environmental management needs. Wuhan Port, located in an inland area, may face different types of environmental impacts during expansion, such as inland water resources and ecological protection. Tianjin Port, as a vital port in the north, may encounter specific climatic and hydrological conditions, which also differ from the other two ports.

In summary, this paper selects Shanghai Port, Wuhan Port, and Tianjin Port as the case studies, aiming to delve into which stage and which factors in the entire lifecycle of ports play a critical role in the external environmental impacts of ports. The unique differences among these three ports will provide valuable comparative data to support our interpretive claims regarding the sustainability of ports. Our research will focus on how to reduce adverse environmental impacts during port expansion in different geographical and economic contexts and at different stages of development.

3.3 Research Approach:

The research approach and its visual representation are as follows:

1.Problem Identification and Literature Review:

Define the research theme and questions.

Conduct an extensive literature review to identify research gaps and knowledge voids.

2.Research Design:

Select the comparative case study method.

Develop a detailed research plan.

3.Case Selection:

Set constraints for case selection (e.g., geographical location, time frame, port type).

Choose representative cases.

4.Data Collection:

Conduct systematic data collection, including literature research, field surveys, interviews, questionnaires, and various methods.

Ensure standardization and repeatability of data collection tools and methods.

5.Variable Selection:

Define independent and dependent variables, establish a conceptual model.

6.Data Analysis and Testing:

Perform univariate data feature analysis to understand the basic characteristics and trends of each case.

Validate the relevance and operability of variables through literature review and preliminary data analysis.

Analyze collinearity among independent variables and between independent and dependent variables.

7.Regression Analysis:

Use statistical tools for multivariate analysis, including regression analysis, to explore the influence of independent variables on dependent variables.

8.Recommendations and Summary:

Based on the research findings, identify the stages and factors in the port's entire lifecycle that have the most significant impact on the environment.

Discuss the theoretical and practical significance of the study.

9.Reflection and Prospects:

Reflect on research methods, data analysis, and conclusions.

Propose future research directions and improvement suggestions.

Figure 1 below is a specific illustration of the research process in this paper, showing the steps of advancement and decision-making mechanisms of the research process.

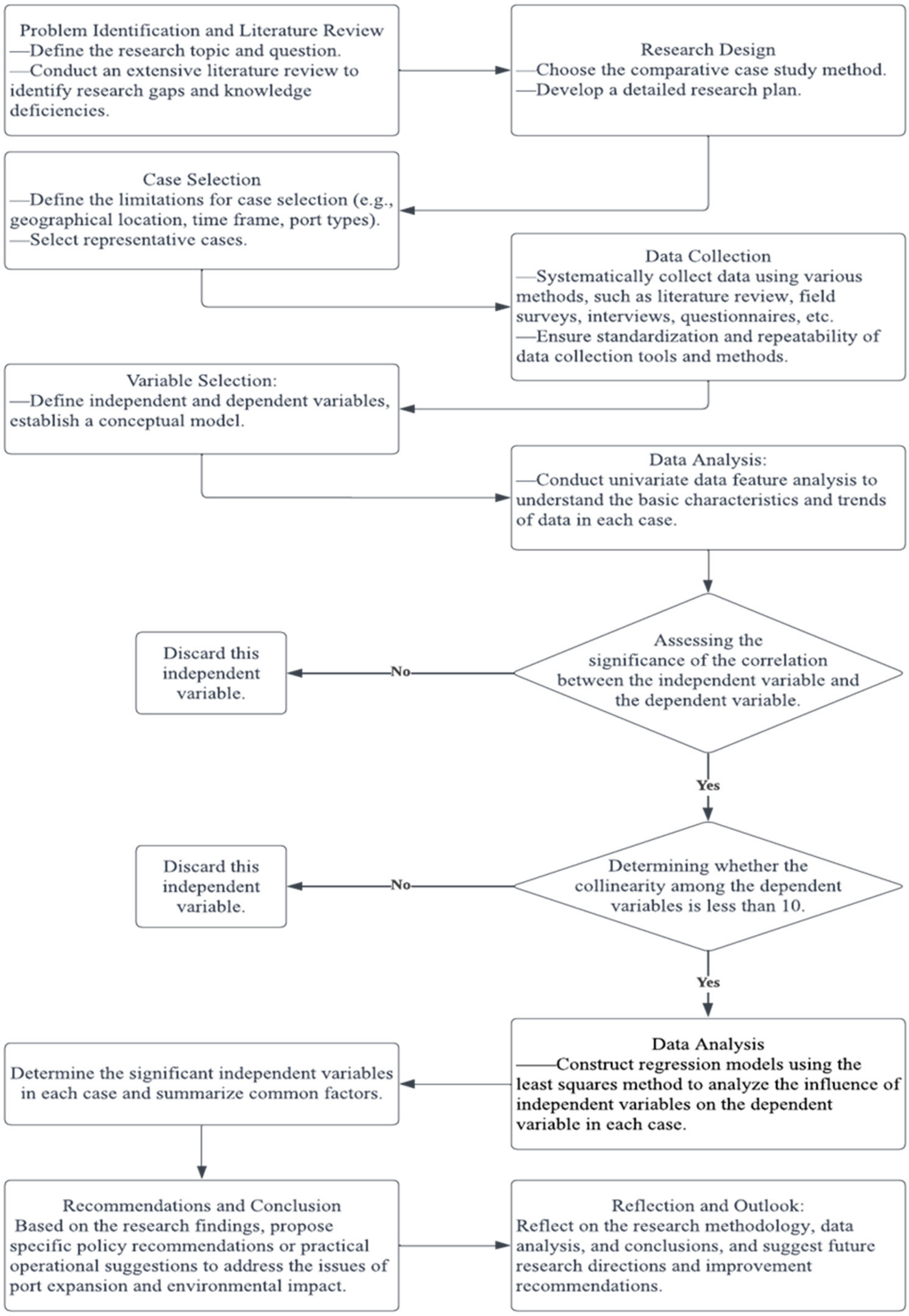

Figure 1 research process

3.4Specific Research Methods:

This paper primarily employs the Analysis of Variance (ANOVA) method to analyze univariate data characteristics and uses the least squares method and multiple regression analysis to examine the interaction between independent and dependent variables. The model constructed in this paper is as follows:

$$Y_1 = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \varepsilon \quad (1)$$

This formula, where x represents the independent variable and y represents the dependent variable, is applicable to the analysis of all ports and is used a total of 10 times in subsequent analyses.

4 EMPIRICAL ANALYSIS RESULTS PRESENTATION

4.1 Variable Selection and Presentation:

This study analyzed data from three ports over an 11-year period from 2012 to 2022. Shanghai Port had fifteen relevant variables, Wuhan Port had ten relevant variables, and Tianjin Port had ten relevant variables. These variables were selected from various stages of the ports' lifecycles, including planning, construction, operation, and environmental impact management, making them representative. After preliminary analysis and testing, some variables were excluded from regression analysis due to severe collinearity or significant impact on regression results. After data screening, seven variables (three independent variables and four dependent variables) were included in the regression analysis for Shanghai Port data, six variables (three independent variables and three dependent variables) for Wuhan Port data, and six variables (three independent variables and three dependent variables) for Tianjin Port data. As there were commonalities among variables for the three ports, they are presented collectively. Additionally, to facilitate regression analysis and mitigate the impact of heteroscedasticity, natural logarithms were applied to some variables with large numerical values. Furthermore, in rare cases where independent variables had missing data for certain years, linear interpolation using Stata was employed to ensure data completeness and reliable regression results. The following chart provides the full names, units of measurement, and specific definitions of the dependent and independent variables.

Table 1 independent variable

Full name of variable	measurement unit	abbreviated name	Explanation
Government expenditure on port construction	Hundred million Yuan	government	Financial expenditures invested by local governments in port construction over the years
Number of national level patents	None	patent	Number of national patents obtained by port operating companies per year
Logarithm of innovation inputs/Innovation investment as a	None/Percentage	innovation	The amount of money invested in science, technology and innovation by the port operating

percentage of turnover			company each year and the percentage of that money in the turnover of that year
Logarithm of port cargo throughput	None	throughput	Annual port cargo throughput
Number of rail-water intermodal routes	None	intermodal	Number of railways using rail-water connections for transport

Table 2 implicit variable

Full name of variable	measurement unit	abbreviated name	Explanation
Logarithm of the value of social contribution	None	Social contribution	Value of social contributions calculated in accordance with United Nations sustainable development-related documents, 2008
Comprehensive energy consumption	ten thousand tonnes	Energy consumption	Annual energy consumption of the company, including all energy sources
carbon emission	ten thousand tonnes	emission	Annual carbon emissions from ports
Carbon Emission Intensity	kg CO2 per TEU	Emission Intensity	Carbon dioxide emissions per standard container throughput
Area of new green space around the port	ten thousand square metres	Green place	Area of new green space around the harbour over the past eleven years
Quantity of water recycled in harbours	ten thousand tonnes	Water recycle	Annual water use for port recycling
Energy use intensity	Gigajoules per TEU	Energy intensity	Energy consumption per TEU throughput
Water consumption intensity	Cubic metres per TEU	Water intensity	Water consumption per standard case of throughput

Tables 1 and Table 2 above are all the data involved in the regression analyses in this study, in which the independent variables in Table 1 have been tested for correlation and covariance, and have proved to be of value for regression analyses. The eight dependent variables included in Table 2 are all indicators that can measure the environmental quality of the port. Next, the paper will start to analyse the data specifically.

4.2 Regression Analysis Results for Each Port

(1) Regression Analysis Results for Shanghai Port

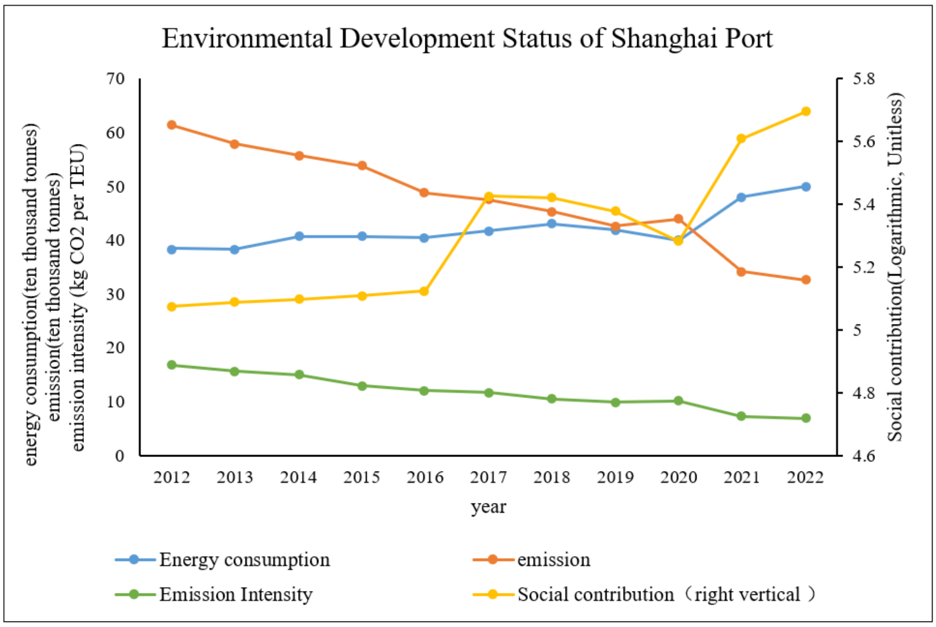

Figure 2 Environmental development status of Shanghai port

Table 3 Summary Statistics(shanghai port)

Var Name	Obs	Mean	SD	Min	Median	Max
Social contribution	11	5.30	0.222	5.074423	5.282747	5.69528
Energy consumption	11	42.11	3.702	38.31	40.66	50
emission	11	47.64	9.233	32.6	47.6	61.4
Emission Intensity	11	11.71	3.193	6.9	11.8	16.7
innovation	11	0.00	0.002	0.0008	0.0012	0.0054
Patent	11	21.00	9.808	11	20	39
government	11	3.07	2.598	0	2.9	9.1

Table 4 Correlation Coefficient (Shanghai port)

	Social contribution	Energy consumption	emission	Emission Intensity	innovation	Patent	Gov
Social contribution	1						
Enenrgy consumption	0.914***	1					
Emission	-0.929***	-0.889***	1				
Emission	-0.906***	-0.860***	0.992***	1			

Intensity							
innovation	0.780***	0.808***	0.833***	0.804***	1		
Patent	0.640**	0.573*	-0.617**	-0.622**	0.292	1	
Gov	-0.497	-0.484	0.348	0.338	-0.633**	-0.008	1

(gov is government, and the * symbol represents the level of significance, with * being significant at the ten per cent level, ** being significant at the five per cent level and *** being significant at the one per cent level).

Table 5 Results of covariance test for Shanghai Port data

Variable	covariance test
	VIF
Innovation	1.94
Government	1.77
Patent	1.16

Table 6 Regression results (Shanghai port)

	(1)	(2)	(3)	(4)
	Social contribution	Energy consumption	Emission	Emission Intensity
Innovation	68.438**	1366.310**	-4399.409***	-1435.730***
	(2.37)	(2.65)	(-4.42)	(-3.64)
Patent	0.011**	0.144*	-0.350**	-0.127*
	(2.68)	(2.00)	(-2.51)	(-2.30)
Government	-0.013	-0.095	-0.675	-0.209
	(-0.67)	(-0.28)	(-1.04)	(-0.81)
_cons	4.967***	36.498***	66.340***	18.047***
	(42.01)	(17.32)	(16.28)	(11.18)
N	11	11	11	11
Adj. R^2	0.724	0.686	0.811	0.752

(* Symbols represent levels of significance, with * representing significance at the ten per cent level, ** representing significance at the five per cent level and *** representing significance at the one per cent level.)

In the tables and figures above, figure 2 shows the changes of various environmental data indicators of Shanghai Harbour in the form of line graphs in this decade, and table 3 is the detailed status of each data. Table 4 shows the results of the correlation test of each data of Shanghai Harbour, and table 5 shows the covariance between the independent variables of Shanghai Harbour, and these two tests are to verify that the data being These two tests are to verify that the selected independent variables can draw valid conclusions through the regression analysis. Table 6 shows the final regression results of each data, and the final regression results will be explained in detail in the following section.

From table 6, it can be observed that the regression coefficients of research and development (R&D) investment for the four dependent variables are 68.438, 1366.310, -4399.409, and -1435.730, with t-values of 2.37, 2.65, -4.42, and -3.64, respectively. The significance level shows that the correlations are all significant. It can be concluded that R&D investment significantly affects the four dependent variables. It has a positive effect on social contribution value and comprehensive energy consumption at the 5% significance level and a negative effect on carbon emissions and carbon emission intensity at the 1% significance level.

The regression coefficients of the number of national patents for the four dependent variables are 0.011, 0.144, -0.350, and -0.127, with t-values of 2.68, 2.00, -2.51, and -2.30, respectively. The significance level shows that the correlations are all significant. It can be concluded that the number of national patents significantly affects the four dependent variables. It has a positive effect on social contribution value at the 5% significance level, on comprehensive energy consumption at the 10% significance level, and it has a negative effect on carbon emissions at the 5% significance level and on carbon emission intensity at the 10% significance level.

The regression coefficients of port government construction expenditure for the four dependent variables are -0.013, -0.095, -0.675, and -0.209, with t-values of -0.67, -0.28, -1.04, and -0.81, respectively. The significance level shows that the correlations are not significant. It can be concluded that port government construction expenditure does not significantly affect the four dependent variables.

The goodness of fit for this regression model is 0.724, 0.686, 0.811, and 0.752, respectively. The goodness of fit is at a relatively high level, indicating that the results of this fit are reliable.

Among the four dependent variables, the larger the value of social contribution, the smaller the negative externality of the port on the surrounding environment. Conversely, the smaller the values of carbon emissions, carbon emission intensity, and comprehensive energy consumption, the smaller the negative externality of the port on the surrounding environment. Combining the positive and negative correlations between the independent variables and dependent variables mentioned above, it can be concluded that increasing R&D expenses and improving the level of patent research can reduce the negative externality of the port on the environment during the expansion process.

(2)Regression Analysis Results for Wuhan Port:

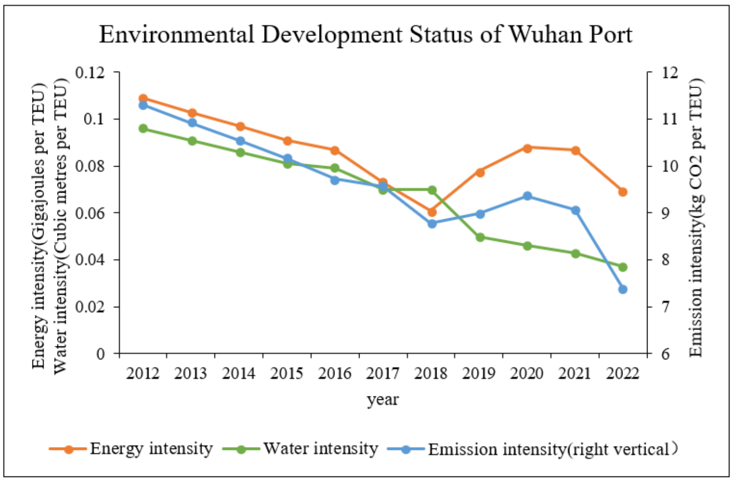

Figure 3 Environmental development status of the port of Wuhan

Table 7 Summary Statistics(wuhan port)

Var Name	Obs	Mean	SD	Min	Median	Max
Energy intensity	11	0.09	0.015	0.061	0.087	0.109
Emission Intensity	11	9.62	1.100	7.39	9.57	11.3
Water intensity	11	0.07	0.021	0.037	0.07	0.096
innovation	11	16.80	0.278	16.49828	16.7085	17.27659
Patent	11	2.64	5.500	0	0	18
intermodal	11	20.64	10.201	5	21	35

Table 8 Correlation Coefficient (Wuhan port)

	Energy intensity	Emission Intensity	Water intensity	Innovation	Patent	Intermodal
Energy intensity	1					
Emission Intensity	0.856***	1				
Water intensity	0.606**	0.874***	1			
Innovation	-0.502	0.839***	0.979***	1		
Patent	0.022	-0.253	-0.559*	0.620**	1	
Intermodal	0.742***	0.925***	0.969***	0.938***	0.543*	1

(The * symbols here have the same meaning as in the table above.)

Table 9 Wuhan Port Data covariance Test Results

Variable	covariance test
	VIF
Innovation	9.68
Intermodal	8.45
Patent	1.66

Table 10 Regression results (Wuhan Port)

	(1)	(2)	(3)
	Energy intensity	Emission intensity	Water intensity
Innovation	0.064***	-0.407	-0.048***
	(5.39)	(-0.37)	(-4.00)
Patent	0.001***	0.074**	0.000
	(4.34)	(3.25)	(0.81)
Intermodal	-0.003***	-0.111***	-0.001**
	(-9.93)	(-4.01)	(-2.68)
_cons	-0.933***	18.559	0.885***
	(-4.80)	(1.05)	(4.56)

N	11	11	11
Adj. R^2	0.946	0.922	0.974

(The * symbols here have the same meaning as in the table above.)

In the above tables and figures, figure 3 shows the changes of the environmental data indicators of Wuhan port in the form of line graphs in the past ten years, and table 7 shows the detailed status of each data. table 8 shows the correlation test results of each data of Wuhan port, and table 9 shows the covariance between the independent variables of Wuhan port, which are to verify that the selected independent variables can draw valid conclusions through the regression analysis. These two tests are to verify that the selected independent variables can draw valid conclusions through regression analysis.Table 10 shows the final regression results of each data, and the final regression results will be explained in detail in the following section.

From table 10, it can be observed that the regression coefficients of the independent variable "research and development (R&D) investment" with respect to the four dependent variables are 68.438, 1366.310, -4399.409, and -1435.730, with corresponding t-values of 2.37, 2.65, -4.42, and -3.64, indicating that the correlations are all statistically significant. It can be concluded that the independent variable of R&D investment has a significant impact on the four dependent variables. It positively influences "social contribution" and "comprehensive energy consumption" at the 5% significance level, while it negatively influences "carbon emissions" and "carbon emission intensity" at the 1% significance level.

For the independent variable "number of national patents," the regression coefficients with respect to the four dependent variables are 0.011, 0.144, -0.350, and -0.127, with t-values of 2.68, 2.00, -2.51, and -2.30, all indicating statistically significant correlations. It can be concluded that the number of national patents has a significant impact on the four dependent variables. It positively influences "social contribution" at the 5% significance level and "comprehensive energy consumption" at the 10% significance level, while it negatively influences "carbon emissions" at the 5% significance level and "carbon emission intensity" at the 10% significance level.

As for the independent variable "port government construction expenditure," the regression coefficients with respect to the four dependent variables are -0.013, -0.095, -0.675, and -0.209, with t-values of -0.67, -0.28, -1.04, and -0.81, indicating that the correlations are not statistically significant. It can be concluded that port government construction expenditure does not have a significant impact on the four dependent variables.

The goodness of fit for this regression model is 0.724, 0.686, 0.811, and 0.752, respectively, which are relatively high values, indicating that the results of this fitting are reliable.

Among the four dependent variables, a higher value of "social contribution" indicates a smaller negative externality of the port on the surrounding environment. Conversely, smaller values of "carbon emissions," "carbon emission intensity," and "comprehensive energy consumption" indicate a smaller negative externality of the port on the surrounding environment. Combining the positive or negative correlations between the independent variables and dependent variables, it can be concluded that increasing R&D investment and improving the level of patent research can reduce the negative externality of the port on the environment during the expansion process.

(3)Regression Results for Tianjin Port:

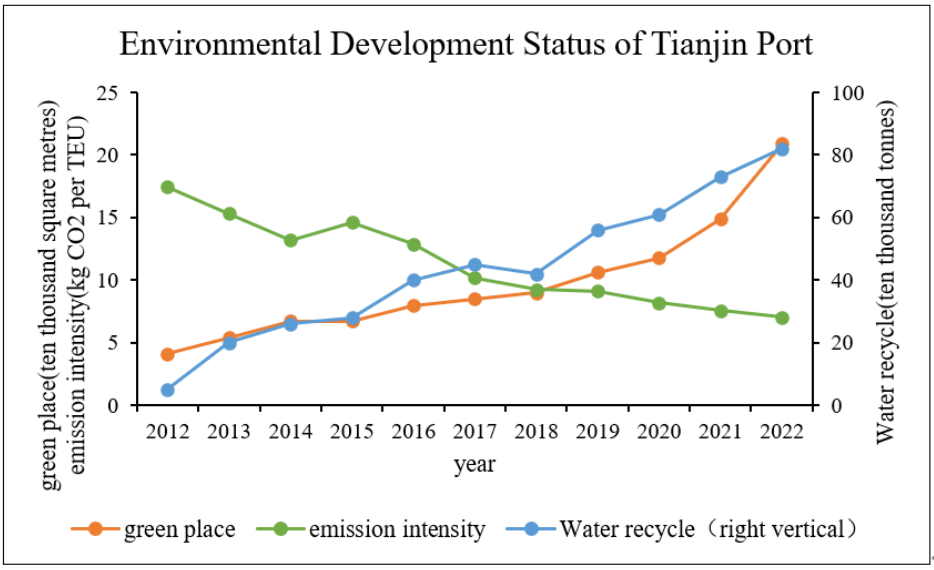

Figure 4 Environmental development status of Tianjin Port

Table 11 Summary Statistics(tianjin port)

Var Name	Obs	Mean	SD	Min	Median	Max
Green place	11	9.68	4.796	4.1	8.5	20.9
Water recycle	11	43.45	23.265	5	42	82
Emission Intensity	11	11.34	3.509	7.03	10.19	17.46
throughput	11	10.85	0.049	10.77262	10.83514	10.91611
intermodal	11	10.27	8.498	0	11	27
innovation	11	18.56	0.315	18.09813	18.57556	18.99635

Table 12 Correlation Coefficient (Tianjin Port)

	Green place	Water recycle	Emission Intensity	throughput	intermodal	Innovation
Green place	1					
Water recycle	0.943***	1				
Emission Intensity	-0.848***	-0.951***	1			
throughput	0.410	0.358	-0.220	1		
intermodal	0.966***	0.964***	-0.930***	0.297	1	
Innovation	0.252	0.486	-0.501	0.130	0.396	1

(The * symbols here have the same meaning as in the table above.)

Table 13 Tianjin Port Data covariance Test Results

Variable	covariance test
	VIF
Intermodal	1.28
Innovation	1.19
Throughput	1.10

Table 14 Regression results (Tianjin port)

	(1)	(2)	(3)
	Green Place	Water Recycle	Emission Intensity
Throughput	13.358*	36.428	4.593
	(1.99)	(0.85)	(0.49)
Intermodal	0.557***	2.443***	-0.366***
	(13.34)	(9.11)	(-6.23)
Innovation	-2.377*	9.115	-1.768
	(-2.19)	(1.31)	(-1.16)
_cons	-96.908	-546.148	-1.939
	(-1.29)	(-1.13)	(-0.02)
N	11	11	11
Adj. R^2	0.957	0.925	0.842

(The * symbols here have the same meaning as in the table above.)

In the above tables and figures, figure 4 shows the changes of various environmental data indicators of Tianjin Port in the form of line graphs in the past ten years, and table 11 is the detailed status of various data.Table 12 shows the correlation test results of various data of Tianjin Port, and table 13 shows the covariance between independent variables of Tianjin Port, these two tests are to Table 14 shows the final regression results of each data, and the final regression results will be explained in detail below.

From table 14, we can see that the regression coefficients of the independent variable "throughput volume" with respect to the three dependent variables are 13.358, 36.428, and 4.593, with t-values of 1.99, 0.85, and 0.49, respectively. The significance level shows that throughput volume only has a significant positive effect on the change in newly added green area at the 10% level. It can be concluded that throughput volume significantly promotes the growth of green area at a 10% significance level but does not significantly affect changes in water recycling and carbon emission intensity.

For the independent variable "number of rail-water intermodal transportation routes," the regression coefficients with respect to the three dependent variables are 0.557, 2.443, and -0.366, with t-values of 13.34, 9.11, and -6.23, respectively. The significance level indicates that the number of rail-water intermodal transportation routes has a significant effect on all three dependent variables at the 1% level. It can be concluded that the number of rail-water intermodal transportation routes has a significant positive effect on the growth of green area and water recycling and a significant negative effect on carbon emission intensity.

As for the independent variable "research and development (R&D) investment," the regression coefficients with respect to the three dependent variables are -2.377, 9.115, and -1.768, with t-values of -2.19, 1.31, and -1.16, respectively. The significance level shows that R&D investment only has a significant effect on the growth of green area at the 10% level. It can be concluded that R&D investment significantly negatively affects the growth of green area at a 10% significance level but does not significantly affect water recycling and carbon emission intensity.

The goodness of fit for this regression is 0.957, 0.925, and 0.842, respectively, which are very close to 1, demonstrating that the results of this regression are reliable.

Among the dependent variables, a larger increase in newly added green area, a greater amount of water recycling, and lower values of carbon emission intensity represent a smaller negative externality of the port on the environment during the expansion process. Taking all these factors into account, it can be concluded that an increase in the number of rail-water intermodal transportation routes can reduce the negative externality of the port on the environment during the expansion process.

5 SUMMARY AND RECOMMENDATIONS

5.1 Summary of data analysis results:

The above data regression analyses and tests as well as the final comparisons allow us to conclude that increasing R&D expenses as well as the number of rail-water intermodal routes have a significant positive effect on the impact of environmental externalities in the port. Both of these factors belong to the technological R&D phase of the operation phase. From this, we can tentatively conclude that increasing R&D expenses and developing rail-water intermodal transport in the technological R&D phase of the operational phase are more effective in reducing the negative environmental impacts of large ports compared to measures taken in other development phases.

5.2 Reason Analysis:

Firstly, increasing R&D investment can effectively promote the sustainable development of ports and reduce their negative environmental impacts, and I will analyse this idea from four perspectives:

(1) Cleaner energy and technology

Through R&D investment, port operators can develop cleaner energy sources and technologies, such as electric ships. These ships use batteries or fuel cells, eliminating direct tailpipe emissions and reducing pollutants in the environment. Data from the International Maritime Organisation suggests that electric ships are expected to be an important solution for reducing carbon emissions in ports in the coming decades. The adoption of this technology could significantly improve air quality in ports and reduce negative impacts on the communities surrounding them[18].

(2) Smart Logistics

R&D investments also support the development of smart logistics systems that optimise the cargo transport process through data analytics, artificial intelligence and IoT technologies. By reducing transport distances, avoiding congestion and improving transport efficiency, smart logistics systems can significantly reduce carbon emissions. According to the U.S. Federal Highway Administration, logistics optimisation can reduce the idling rate in cargo transport, lower transport costs and further reduce carbon emissions[19].

(3) Innovation in Port Infrastructure

R&D investment has also encouraged the port industry to drive innovation in port infrastructure. For example, the development of shore power systems allows ships to use shore power while at berth rather than running generators, significantly reducing tailpipe emissions from ships in harbours. Data from the U.S. Environmental Protection Agency shows that the use of shore power systems can effectively reduce air pollution in port areas, further improving the environmental quality of ports.

(4) Carbon Emissions Monitoring and Reporting

Finally, R&D investment has also contributed to the development of more accurate carbon emissions monitoring and reporting systems, improving port managers' understanding of carbon emissions. Transparent reporting of carbon emissions data has incentivised more ports to adopt environmentally friendly measures. Some ports have begun to proactively report their carbon emissions data and take targeted measures to reduce their carbon footprint, which further strengthens the sustainability of their ports.

Iron-water intermodal transport, as part of intermodal transport, can also help ports to effectively reduce negative environmental impacts throughout their life cycle and contribute to their sustainable development, and I will address this point from a number of perspectives

(1) Reducing Environmental Pollution

Rail and water transport are generally more environmentally friendly than trucks and cars. They produce less noise and emit fewer air pollutants. Data from the U.S. Environmental Protection Agency (EPA) shows that both rail and waterborne transport exhibit lower levels of noise and tailpipe emissions. This reduces the negative impacts on the surrounding communities and environment and helps to improve the quality of life in the areas surrounding the ports, reducing the potential health impacts of noise pollution and air pollution. In addition, rail-water intermodal transport helps to reduce environmental pollution in the areas surrounding the port and contributes to combating climate change by reducing the contribution of port operations to carbon emissions. This environmental benefit is critical to the sustainability of ports, helping to ensure that they continue to provide critical services to society and the economy while reducing adverse impacts on the environment and human health[20].

(2) Improving logistics efficiency

Rail-water intermodal transport helps to improve the efficiency of port logistics. Data from the U.S. Department of Transportation (U.S. DOT) show that rail transport is typically more efficient than truck transport, with lower transport costs per tonne per mile. Cargo mobility and logistics efficiencies are also improved, which can help reduce the amount of time cargo is held in ports and lower supply chain costs.

(3) Reduced cargo loss and damage

Rail and waterway transport is relatively smooth, reducing the rate of loss and damage of goods during transport. Statistics from the U.S. Department of Transportation (U.S. DOT) show that rail transport is typically more stable than truck transport, with lower rates of loss and damage to cargo. Data from the International Maritime Organisation (IMO) also suggests that waterborne transport is relatively stable and helps to maintain the integrity of cargo. This helps to reduce the risk of dangerous goods spills and reduces the negative externalities of ports on the environment[21].

(4) Reducing resource consumption and carbon emissions

Reduced fuel consumption is a significant advantage of rail and waterway transport over traditional road transport. Rail and waterway transport are generally more fuel efficient than road transport because they have lower drag and higher energy efficiency. For rail transport, according to the U.S. Energy Information Administration, U.S. rail transport used just 0.17 kWh of energy per tonne mile in 2019, compared to a whopping 0.41 kWh for truck transport of equivalent goods. This data reveals the remarkable energy-saving nature of rail transport. In addition, data from the Federal Railroad Administration shows that in 2019, the rail freight transport system in the U.S. emitted only 0.46 pounds of carbon per tonne per mile, compared to a whopping 2.31 pounds of carbon per mile for trucking, further proving rail transport's clear advantage in terms of carbon emissions. For waterborne transport, according to the United States Energy Information Administration, inland waterway shipping in the United States is about four times more fuel efficient than road transport and has significantly lower carbon emissions per tonne mile. In addition, according to the U.S. Bureau of Ocean Management, large ocean freighters have relatively low carbon emissions per tonne per mile, about 1/3 to 1/4 that of road transport, again highlighting the environmental advantages of waterborne transport. In contrast, road transport is susceptible to traffic congestion, which not only leads to cargo delays but also increases fuel consumption. The U.S. Transportation Research Board estimates that traffic congestion costs the U.S. economy more than $120 billion annually, and according to the U.S. Department of Transportation, trucking contributes more than 80 per cent of the total energy consumption of the road transport sector in the United States. These figures highlight the clear advantages of rail and water transport in terms of fuel consumption and carbon emissions, helping to reduce environmental burdens and improve the economic sustainability of ports and freight transport[22].

(5) Safety and road maintenance costs

Rail and waterway transport show significant advantages over road freight transport in terms of safety and road maintenance costs. Road cargo transport usually involves a large number of trucks and cars and therefore faces a higher risk of traffic accidents, especially when travelling on congested roads. This not only puts people's lives at risk, but also leads to traffic jams and road damage, placing a huge burden on cities and port areas. In contrast, rail and water transport are relatively safer as they do not usually share corridors with other modes of transport, reducing the chances of accidents, lowering casualty rates and contributing to sustainable security in port areas. In addition, rail-water transport can reduce road maintenance costs. According to the Transportation Research Board, traffic congestion costs the U.S. economy tens of billions of dollars annually. Because there is less demand for road freight transport, wear and tear and damage to roads is mitigated, which in turn reduces spending on road maintenance and rehabilitation. This frees up funds that can be used for other infrastructure projects such as public transport improvements and urban greening projects, increasing the sustainability of cities and port areas. By reducing the risk of traffic accidents and reducing road maintenance costs, rail-water intermodal transport plays a positive role in promoting the sustainability of ports by providing safer and more economically viable options for cities and ports to transport goods[23].

(6) Higher resource efficiency

Railway and waterway transport show obvious advantages in terms of resource efficiency. They have higher throughput and transport efficiency and are able to use energy and resources more efficiently. According to the U.S. Energy Information Administration, rail freight and inland waterway shipping typically have higher throughputs than trucking, and rail transport typically consumes significantly less energy than trucking. These features help to reduce resource wastage and energy consumption, which not only improves the economics of transport, but also positively impacts the sustainability and environmental friendliness of port areas, providing strong support for sustainable development.

Overall, rail-water intermodal transport can improve the efficiency, environmental friendliness and economic sustainability of ports, helping to meet the growing demand for global trade and making port areas more competitive. This is essential for the long-term sustainability of ports[24].

6 CONCLUSION

The continuous development of large ports is an inevitable direction under the development of world trade, but the development of ports also inevitably has a negative impact on the surrounding environment. However, those who profit from port development and those whose interests are harmed by environmental impacts are often not a single group, which leads to the accumulation of conflicts. In order to avoid the development of conflicts and promote the sustainable development of ports, it is imperative to analyse the mechanism of the impact of large ports on the surrounding environment in the whole life cycle, and to determine the important phases and influencing factors.

Through comparative case studies, this paper analyses the factors that influence the negative environmental externalities of ports in different ports, in order to identify the stages of the life cycle of large ports and which factors have an important influence on the environmental externalities of ports. Based on the conclusions drawn from the analyses, this paper concludes that increasing R&D investment and promoting the development of rail-water intermodal transport in the operations and R&D phases has an important positive effect on the environmental externalities of ports.

However, the research in this paper is limited by time and resources, and the access to data is not very sufficient, so the conclusions drawn from the analysis are not perfect, which is a shortcoming of the research in this paper.

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