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China's Port Carbon Emission Reduction: A Study of Emission-Driven Factors

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Abstract: Ports offer an effective way to facilitate the global economy. However, massive carbon emission during port operating aggravates the atmospheric pollution in port cities. Capturing characteristics of port carbon emission is vital to reduce GHG (greenhouse gas) in the maritime realm as well as to achieve China's carbon neutral objective. In this work, an integrated framework is proposed for exploring the driving factors of China ports' emissions combined with stochastic effects on population, affluence and technology regression (STIRPAT), Global Malmquist-Luenberger (*GML*) and multiple linear regression (MLR). The port efficiency is estimated for each port and the potential driving factors of carbon emission are explored. The results indicate that port carbon emissions have a strong connection with port throughput, productivity, containerization and intermodal transshipment. It is worth noting that the containerization ratio and port physical facility with fossil-free energy improvement have positively correlated with carbon emissions. However, the specific value of waterborne transshipment shows a complex impact on carbon dioxide emission as the ratio increases. The findings reveal that China port authorities need to improve containerization ratio and develop intermodal transportation; meanwhile, it is responsible for port authorities to update energy use and improve energy efficiency in ways to minimize the proportion of non-green energy consumption in accordance with optimizing port operation management including peak shaving and intelligent management systems under a new horizon of clean energy and automatic equipment.

Keywords: emission driving factor; integrated model; carbon emission; China ports

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1. Introduction

Since the reform and opening-up in 1978, China has made significant progress in terms of economic and social developments. However, China's rapid economic development has benefited from the extensive use of energy resources, which increased carbon emissions ultimately. As a result, China has become the top carbon emitter in the world [1,2]. Among global carbon emissions, transportation is the second-largest man-made source, accounting for 24.34% of the total carbon emissions, according to the International Energy Agency (IEA) reporting in 2020. Therefore, the control of transportation energy consumption and carbon emission are important issues for sustainable economic development [3]. Ports are essential nodes of transportation [4], emitting around 940 million tons of CO_2 annually, and their share is expected to increase in the future [5]. In China, several policies have been published to control carbon emissions in the maritime realm. For example, the 14th Five-Year Plan on the transportation industry begins in 2020 and ends in 2025 in China [6]. The rate of integrated energy consumption and carbon emissions should be decreased by 3% and 4%, respectively, with unit operation throughput in the ports; the retention rate of clean energy and new energy trucks should be increased by 50%. The development of the port has led to the economic growth of the port hinterland according to the report by IMO in 2020. For example, Shanghai is port city with a population of 24.3 million. Similarly, Guangzhou, Shenzhen and Xiamen are all defined as port cities as well as endowed with a huge population. However, increasing carbon dioxide emissions from growing port operations are posing a threat to port cities. The atmospheric environmental awareness is now creating new challenges for the development and management of port systems [7]. As the main control objective during port transportation chain, general reliability of the freight data is also an issue of concern. Especially in the multimodal mode, a reliable data support system can effectively simulate the freight transportation under different conditions [8]. Moreover, the acceptance of changing freight modes by shippers is also an important influencing variable [9]. In addition, unexpected events such as the COVID-19 pandemic can also affect port handling data, which also needs to be considered after the event [10].

In recent years, the research on the carbon dioxide emission of the port transportation system has been raised as a hot topic; most scholars have focused on the economic and efficiency factors' exploration in the port's low-carbon analysis with the view of a macro perspective. For example, port selection from the perspective of freight forwarding was studied and found that port efficiency, infrastructure and location are the three most important factors affecting port selection [11]. A calculated analysis of inland container transportation in China was carried out and illustrated the need for using coastal transport to reduce carbon emissions [12]. Meanwhile, other studies regarded coastal shipping services as a low-carbon alternative to road transport for the coastal ports [13]. In summary, most of the research discussions are on port operation and route optimization or how to provide alternative transport solutions to replace traditional transportation modes with higher unit emissions including container trucks. The findings of the present study revealed that there are still insufficient explorations of multi-level driving factors that potentially influence on the carbon emission in the fields of economy and transportation. Moreover, there are also deficiencies in the formulation of targeted strategies about ports' low-carbon emission due to the inaccurate forecast of ports throughout China. Based on the above, this work proposed an innovative integrated framework to forecast the port productivity and explore the potential carbon emission driving factors.

The remainder of this paper is summarized below. The paper begins with a review of both ports' carbon emission factors selection and ports' carbon emission reduction, followed by a brief description of the models and methods used in this paper. Actual data from 12 ports in China have been used to validate the carbon emission model. Next, the potential carbon emission driving factors are discussed and finally, the management suggestions are given.

2. Literature Review

2.1. Port Carbon Emission Estimation

Ports play an important role in shipping logistics networks, where various types of vehicles and cargo handling equipment operate [14]. However, the construction, operation and development of ports and other related activities inevitably have a direct or indirect impact on the ecological environment of ports. In recent years, studies on indicators for measuring port carbon efficiency have mostly focused on a single indicator, such as carbon emissions per unit of value-added transport, carbon emissions per unit of turnover or full-factor indicators of port carbon efficiency Nwanosike et al. [15] used the Malmquist index to find the comparison of reforms in six major ports in Nigeria. Ai et al.

[16] used the stochastic frontier approach (SFA) to analyze the efficiency of container ports. To simplify the complex process of the port system, most existing studies adopted to use a data envelopment analysis (DEA) model based on a self-assessment system to measure port carbon efficiency. To improve the reliability of results, other studies also incorporated the basic Malmquist index with DEA. In this work, the Global Malmquist-Luenberger Index model (*GML*) is taken into account in the port efficiency estimation.

2.2. Port Carbon Emission Reduction

The sustainable development of green ports is the main trend of future port development [17]. Exploring the influential factors which caused the carbon emission to increase is the key to deduct the GHG and obtain the green port goal achieved. In 2009, the Port of Long Beach started calculation of carbon emissions in ports and carried out several carbon reduction strategies. In Los Angeles, the calculations results involved the full range of ship types in service and equipment deployed in the yard; then the “Clean Air” program was put forward to carbon emission reduction [18]. Similarly, the port of Sydney, Australia implanted a “Government Air Action Policy” to make the best use of rail to replace high fuel consumption roads [19].

Port site selection, energy utilization efficiency and resource utilization are the main factors causing port environmental problems [20]. Shipping, cargo, terminals and cities are the four main port pollution-influencing factors [21]. Additionally, the authors also proposed suggestions on the environment and harbor transportation. Oil tankers, container ships, bulk carriers and trucks are considered as the main sources of emissions [22]. However, the environmental protection issues should be introduced into the production function of ports, i.e., the conflicts of objectives between the two E.U. main directorates (Transport and Environment) [23]. Therefore, a method for quantifying the success of innovations in relation to a specific set of objectives was developed [24]. Some researchers suggested the retrofitting of RTG’s cranes and the replacement of terminal tractors powered by fuel for a new liquefied natural gas tractor, which contributed to a large reduction of carbon dioxide emissions [25]. The establishment of “Emission Control Areas (ECAs)” can also effectively reduce emissions from ships in port waters [26]. The use of shore power systems when a ship is calling at port also provide another way which can significantly reduce its carbon footprint [27]. Port infrastructure, such as public lighting, is also a major source of emissions from onshore facilities, and port energy consumption can be effectively reduced by replacing renewable energy sources and improving the energy efficiency of buildings. The port of New York has established a port environmental management system and expanded high-speed rail to build a green, low-carbon port. Finally, the view from shipping safety is another way to reduce emissions in port waters [28].

2.3. Summary of Literature Review

It can be concluded that the study on port carbon emission considering efficiency and influencing factors is of great significance to the sustainable development of the marine economy and the low-carbon development plan. However, relevant researches in China are insufficient. Hence, this research will adopt a systematic approach, combining *GML*, STIRPAT and MLR methods to tackle the carbon emission issues of container ports in China.

3. Methodology

3.1. GML

The Malmquist index method was proposed by Sten Malmquist in 1953 to analyze consumption changes in different periods. The distance function was extended into a directional distance function and proposed the Malmquist-Luenberger (ML) index [29]. The index should define the direction distance function of two adjacent periods. Therefore, the ML index adopts the geometric mean form of the indices in two periods, which have potential infeasible solutions and are not cyclic and additive. A new Global Malmquist-Luenberger (*GML*) index was proposed which takes the total set of production technologies in all research periods as a reference set [30]. It solves the shortcomings of the ML index, such as lack of cyclic transitivity and no solution for linear programming, so it can more objectively and accurately reflect the changes in the total factor productivity of port carbon emissions.

The decision unit has X inputs, Y expected outputs and B unexpected outputs. The input vector of the i th decision making unit in period t is $x_{it} = (a_{it}, b_{it}, c_{it})$, where a_{it}, b_{it} and c_{it} are, respectively, the length of berth, the number of berth and the number of berth over 10,000 tons of the i th port in period t. Expected output vector $y_{it} = (d_{it}, e_{it})$, where d_{it} and e_{it} are, respectively, the cargo throughput and container throughput of the i th port in period t; unexpected output vector, where f_{it} is the carbon emission of the i th port in period t. The calculation steps are shown in the following formula:

$$\begin{aligned} ML_{t,t+1} &= \left\{ \frac{\left[1+\vec{D}_{0,t}(x_t, y_t, b_t; y_t, b_t)\right]}{\left[1+\vec{D}_{0,t}(x_{t+1}, y_{t+1}, b_{t+1}; y_{t+1}, b_{t+1})\right]} \cdot \frac{\left[1+\vec{D}_{0,t+1}(x_t, y_t, b_t; y_t, b_t)\right]}{\left[1+\vec{D}_{0,t+1}(x_{t+1}, y_{t+1}, b_{t+1}; y_{t+1}, b_{t+1})\right]} \right\}^{\frac{1}{2}} \\ &= \frac{\left[1+\vec{D}_{0,t}(x_t, y_t, b_t; y_t, b_t)\right]}{\left[1+\vec{D}_{0,t+1}(x_{t+1}, y_{t+1}, b_{t+1}; y_{t+1}, b_{t+1})\right]} \\ &\times \left\{ \frac{\left[1+\vec{D}_{0,t+1}(x_t, y_t, b_t; y_t, b_t)\right]\left[1+\vec{D}_{0,t+1}(x_{t+1}, y_{t+1}, b_{t+1}; y_{t+1}, b_{t+1})\right]}{\left[1+\vec{D}_{0,t}(x_t, y_t, b_t; y_t, b_t)\right]\left[1+\vec{D}_{0,t}(x_{t+1}, y_{t+1}, b_{t+1}; y_{t+1}, b_{t+1})\right]} \right\}^{\frac{1}{2}} \\ &= MLEC_{t,t+1} \times MLTC_{t,t+1} \end{aligned} \tag{1}$$

$$\begin{aligned} GML_{t,t+1} &= \frac{1+\vec{D}_{0,G}(x_t, y_t, b_t; y_t, b_t)}{1+\vec{D}_{0,G}(x_{t+1}, y_{t+1}, b_{t+1}; y_{t+1}, b_{t+1})} \\ &= \frac{1+\vec{D}_{0,t}(x_t, y_t, b_t; y_t, b_t)}{1+\vec{D}_{0,t+1}(x_{t+1}, y_{t+1}, b_{t+1}; y_{t+1}, b_{t+1})} \\ &\times \frac{\left[1+\vec{D}_{0,t+1}(x_t, y_t, b_t; y_t, b_t)\right]/\left[1+\vec{D}_{0,t+1}(x_{t+1}, y_{t+1}, b_{t+1}; y_{t+1}, b_{t+1})\right]}{\left[1+\vec{D}_{0,t}(x_t, y_t, b_t; y_t, b_t)\right]/\left[1+\vec{D}_{0,t}(x_{t+1}, y_{t+1}, b_{t+1}; y_{t+1}, b_{t+1})\right]} \\ &= GMLEC_{t,t+1} \times GMLTC_{t,t+1} \end{aligned} \tag{2}$$

In these equations: $ML_{t,t+1}$ is the change of *ML* index; $MLEC_{t,t+1}$ is the technical efficiency change; $MLTC_{t,t+1}$ donates the technological progress change; x_t presents the input; y_t is the expected output; b_t means the undesired output; $\vec{D}_{0,t}(x_t, y_t, b_t; y_t, b_t)$ is the square distance function based on the set of production possibility for the same period. $\vec{D}_{0,G}(x_t, y_t, b_t; y_t, b_t)$ is the direction distance function based on the global production possible set and $GML_{t,t+1}$ is the *GML* exponential change. $GMLEC_{t,t+1}$ is the change of technical efficiency; $GMLTC_{t,t+1}$ is the technical progressive change. If $GMLEC_{t,t+1} > 1$, then $t+1$ period is closer to the current production frontier than t period, that is, the efficiency is higher; if $GMLEC_{t,t+1} < 1$; 1. Then the period of $t+1$ is further away from the current production frontier than the period of t, that is, the efficiency is lower. The same procedure may be easily adapted to $GMLTC_{t,t+1}$, if $GMLTC_{t,t+1} > 1$, it means technological progress. If $GMLTC_{t,t+1} < 1$, it means technological regression. Unlike the traditional geometric mean form of the *ML* index, the *GML* index is cyclic [31].

3.2. STIRPAT

An important performance analysis technology (*IPAT*) was constructed to evaluate the pressure of population, affluence and technological factors on the environment [32]. The Kaya equation reformulated *IPAT* identity, which was the basis for calculating GHG emissions [33]. Other similar models include ImPACT, ImPACTS and IPBAT [34,35]. Then the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model was proposed based on the *IPAT* model and believed any factor that has an impact on the environment can be introduced into the model [36]. The model expression is as follows:

$$I = aP^{b}A^{c}T^{d}e \tag{3}$$

where I, P, A and T are environmental pressure, population size, affluence and technology, respectively; a is the coefficient of the model; b, c, d are the driving indexes; e is the random error disturbance of the model. According to STIRPAT model, it is found that there are mainly three driving factors affecting environmental pollution: population (P), economy (A) and technology (T). Therefore, the impact factors of port carbon emissions can also be selected according to these three driving factors. Port throughput corresponds to P, port profit corresponds to A, and carbon emission intensity corresponds to T. Since the annual port profit report involves data privacy, it is very difficult to obtain, and there is a strong correlation between port profit and port throughput, therefore, port profit can be combined into one variable, port throughput. Therefore, port throughput and carbon emission density are selected in the final research. The new formulas are as follows:

$$Q = aP^{b}T^{c}e \tag{4}$$

$$ln(Q) = ln(a) + b(lnP) + c(lnT) + ln(e) \tag{5}$$

In the equation: Q is the CO_2 emission in the transportation sector; a is a constant; P is the port throughput; T is the carbon emission density used to represent the level of economic development and ε is a random disturbance term. b and c are elasticity coefficients.

3.3. MLR

Multiple regression analysis refers to a statistical analysis method that regards one variable as a dependent variable; meanwhile, one or more other variables are independent variables [37]. This method uses sample data to establish and analyze the quantitative relations between multiple variables in linear or non-linear mathematical models. The results reflect phenomenon or the number of things according to a variety of phenomena or the number of things corresponding with the change of the law. In brief, multiple linear regression (MLR) analysis is a statistical method for establishing quantitative relationships between multiple variables in a linear or non-linear mathematical model.

3.4. Proposed Method

An intergraded framework is proposed, which consists of three parts. First, the port productivity is estimated by *GML*. Then, the STIRPAT model is used to explore influencing factors closely connecting with port carbon emission including quantity, economy and technology in three different aspects, i.e., productivity, economic index, container throughput, different transshipment rates and container rate. Finally, the MLR method is embedded to identify the significant level of influencing factors on the port carbon emissions, and the control countermeasures are given based on the analysis results. The flow chart of the proposed framework is shown in Figure 1.

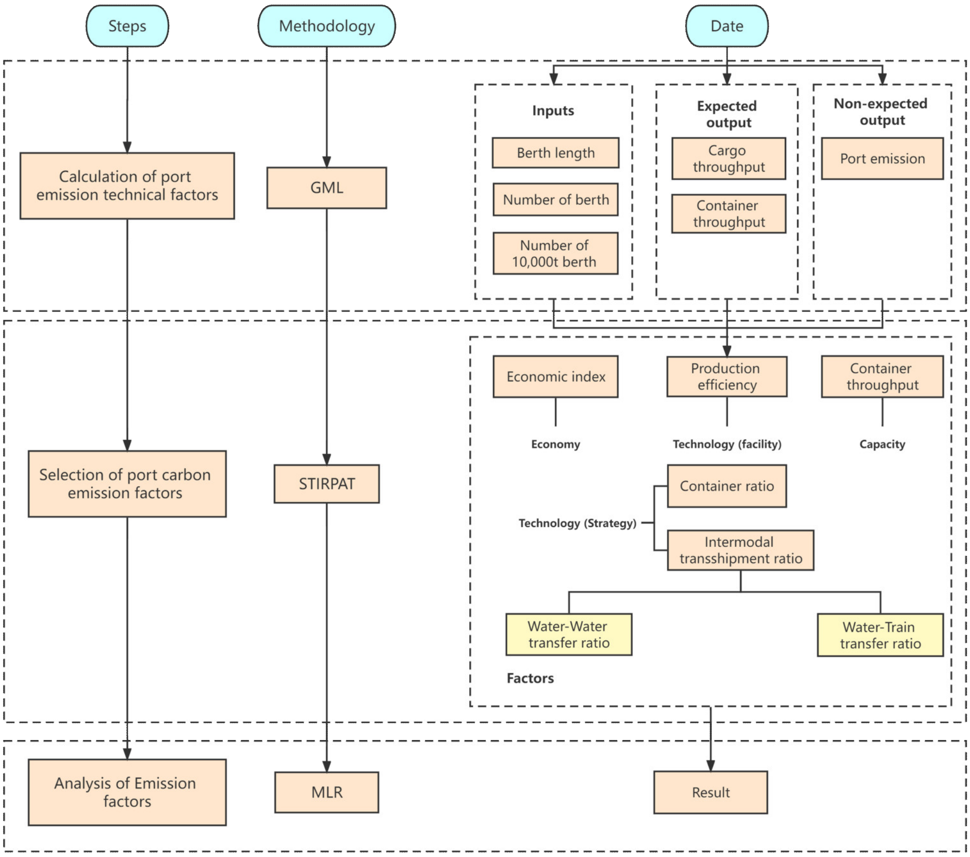

Figure 1. Proposed framework.

4. Empirical Analysis

4.1. Introduction of China Ports

Ports in China have been ranked first on the world ports list in terms of size, with 2444 berths of 10,000 ton class and above. In 2018, China ports handled 14.35 billion tons of cargo and 250 million TEUs of containers. Seven of the world's top ten ports belong to China on the basis of tremendous cargo throughput and container throughput in 2020. Due to the large number of ports in China, five major port clusters have been formed according to their geographical locations, namely the Bohai Rim, Yangtze River Delta, Southeast Coast, Pearl River Delta and Southwest Coast.

The port clusters in the Bohai Sea region consist mainly of the coastal port clusters of Liaoning, Hebei, Tianjin and Shandong provinces. They serve the social and economic development of the coastal and inland areas of northern China. The port cluster in the Yangtze River Delta region relies on the Shanghai International Shipping Centre and is dominated by the ports of Shanghai, Ningbo and Lianyungang, which serve the economic and social development of the Yangtze River Delta and the Yangtze River coastal areas. The port cluster in the southeast coastal region is dominated by the ports of Xiamen and Fuzhou, serving the economic and social development of some inland provinces such as Fujian and Jiangxi. The Pearl River Delta port cluster consists of ports in eastern Guangdong province and the Pearl River Delta region, which includes the ports of Guangzhou, Shenzhen, Zhuhai and Shantou. China's southwestern port group locates at western Guangdong, Guangxi and Hainan provinces, which includes the ports of Qijiang, Fangcheng and Haikou.

According to the annual throughput and the port locations, 17 typical ports were selected for empirical analysis. The selected ports are shown in the following Table 1.

Table 1. Port selection.

Port Group	Name
Bohai Sea Region	Dandong Dalian Yingkou Tianjin Yantai Qingdao Rizhao
Yangtze River Delta Region	Shanghai Lianyungang Ningbo-Zhoushan
Southeast Coastal Region	Fuzhou Quanzhou Xiameng
Pearl River Delta Region	Shantou Shenzhen Guangzhou
Southwest Coastal Region	Haikou

4.2. Selection of GML Variables

The production capacity of port can be measured using the length of berths, the number of berths, the number of berths over 10,000 tons, yard area and other facilities. Indicators used to measure terminal output capacity include cargo throughput, container throughput and tourist throughput. It is necessary to mention that port carbon emission is non-expected output and the tourist numbers are also not considered as output capacity of port. Therefore, three input indicators, two expected output indicators and one non-expected output indicator will be selected and all variables are exhibiting in Table 2. In this study, monthly data from 2010 to 2021 is used.

Table 2. List of *GML* variables.

Classification	Name
Inputs	Berth length Number of berths Number of berths over 10,000 tons
Expected output	Cargo throughput Container throughput
Unexpected output	Port carbon emission

4.3. GML Results

According to *GML* model, each port performance can be described through port efficiency and the values are obtained as shown in Figure 2. It can be seen that the overall trend of port efficiency is increasing every year for all ports. In detail, there was a decline every January or February. The reason is because the specific period between January and February is usually a Chinese long holiday due to the Chinese Lunar Year, which causes fluctuations in ports throughout China. The similar results trend also appeared in other studies [38].

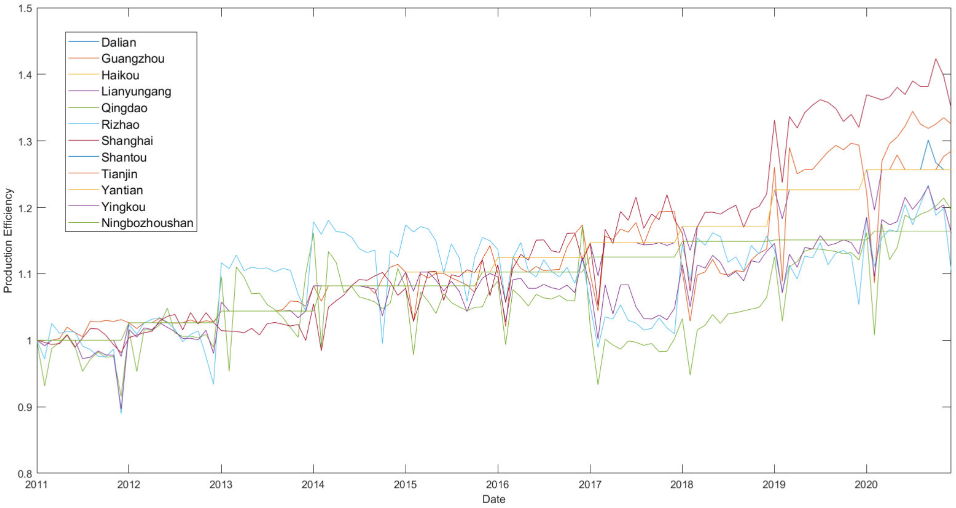

Figure 2. *GML* index results.

4.4. Exploration of Carbon Emission Factors

China ports heavily depend on the traditional fossil energy to support daily operations, which cause high carbon emissions. Carbon emissions are mainly due to a series of operations when ships are mooring at the berth, including cranes and onsite fueling trucks.

In reference to the STIRPAT model, three factors were identified as influencing emissions factors: capacity, economic development and technology [39]. Obviously, port throughput is a directly influential factor which reflects port capacity in container port. Furthermore, port revenue is another indicator that directly exhibits economic benefits in port [40]. However, the revenue data would be instead by China's shipping market sentiment index due to the privacy policy restriction and the need for data integrity. Finally, the technology factor has a significantly positive impact on the reduction of carbon emission in port. Therefore, the technology indicator is viewed as two components: physical facility and management strategy. Facility technology refers to the level of green energy consumption in the port infrastructure, such as the fuel type of crane or on-site container truck engines, etc.

Management strategy technology indirectly impacts on the productivity of the port. Change in strategy usually acts on the performance of port emissions, i.e., container rate and the transshipment rate. Obviously, ship emissions are very noticeable while at maneuvering and hoteling phases. Moreover, the emissions involved in the abovementioned ship activities contributes to 55 to 77% of the total emissions in harbor [41,42]. In order to reduce the carbon emission in the port waters, increasing the ratio of the water-to-water transfer as management strategy to improve the transshipment rate has been raised in many eligible ports. Accordingly, the time for maneuvering and hoteling could significantly reduce. Similarly, increasing the proportion of intermodal and international transshipment has analogous positive effects [43].

5. Results and Discussion

The different emission factors of extraction and analysis results for 12 ports are shown in Table 3. The *GML* index and containerization ratio stand for port production efficiency. If the emission influencing factors have not satisfied the significance test, this means the factor has no direct impact on carbon emissions in the according port and the column is represented by '/', i.e., economic index in Tianjin port and Yantian port. Containerization ratio has significant impact on carbon emissions. However, the relationship shows inversely between containerization ratio and carbon emission. Furthermore, *GML* index exhibits inversely proportional to carbon emissions in most ports as well. It indicates that port physical facility improvement would substantially reduce the carbon dioxide emission, i.e., Shanghai port, Ningbo-Zhoushan port and Yantian port. Obviously, port throughput factor is closely related to the port's carbon emission. Moreover, the port throughput always reflects the economics profit of port operations. Finally, the impact of the economic index is complex in different ports. For most ports, the higher the economic index, the lower the carbon emissions. However, it is hard to keep balance between the profit and the emission. Keeping the port environment friendly is a responsibility for port authorities, therefore, the economic index results showing proportional to emission imply that the port investment in environmental protection has not kept pace with economic growth.

Table 3. Relationship between different factors and emissions.

Port Name	Container Throughput	Containerization Ratio	Economic Index	*GML* Index
Dalian	1.209	−0.870	−0.470	−0.711
Yingkou	0.594	−0.781	−0.236	−0.122
Tianjin	0.881	−0.788	/	−0.869
Yantai	2.130	−1.155	/	−1.402
Qingdao	−0.828	−0.503	0.629	0.779
Rizhao	1.213	−1.136	0.364	0.346
Shanghai	1.209	−0.889	−0.548	−0.503
Lianyungang	0.973	−1.733	0.212	−1.955
Shantou	0.653	−0.817	−0.112	−0.434
Guangzhou	1.339	−0.530	0.606	−1.187
Haikou	0.960	−0.747	−0.198	−0.164
Ningbo-Zhoushan	1.823	−0.688	0.198	−1.001

Considering the importance of transshipment in port waters provides a green and effective transport mode, the ratio of transshipment is discussed in each port. In Table 4, transshipment is proved to be an effective way to reduce the port's carbon emission. In actuality, some of the ports in the selecting list have encouraged transshipment strategy. The waterborne transshipment rate is approximately up to 20% in Xiamen port; however, the port Tianjin and Lianyungang only accounted for 2%, 1% of the whole, respectively. The reasons why there are five ports do not satisfy the significance test since they all have high water-to-water transfer ratio over 25% as shown in the third column. It is worth noting that the effect of blindly improving the water-to-water transfer ratio in reducing carbon emissions is continuing to decline. It implies there exists reasonable waterborne transfer ratio depending on the actual situation of the target port. The truth that transshipment can reduce carbon emission is due to the carbon shift from berth to the waters, which decreases with the crane and on-site container trucks moving and operation. At the same time, the transfer efficiency on the water is also much higher than that of the wharf, especially in transportation capacity. However, water-to-water transfer is difficult to meet the door-to-door transportation needs and is limited by natural waterways.

Table 4. Intermodal ratio correlated to the emission.

Port Name	Water-Water	Water-Train
Yingkou	0.048	−0.115
Tianjin	−0.174	−0.002
Rizhao	−0.357	/
Shanghai	0.015	−0.003
Lianyungang	−0.577	−0.040
Ningbo-Zhoushan	0.434	−0.468
Xiameng	0.598	0.022
Shenzhen	−0.067	−0.133
Guangzhou	0.088	0.148

6. Strategies for Reducing Carbon Emissions in Ports of China

According to the results of carbon emissions' influencing factors, the following strategies are given to reduce carbon emissions in ports of China.

6.1. Improve Containerization Ratio and Develop Intermodal Transportation in Seaport

Compared with traditional bulk transportation, containerization transportation provides more efficiency mode and is beneficial to the port environment. Containers can be moved with common handling equipment enabling high-speed intermodal transfers in economically large units between ships, railcars, truck chassis and barges using a minimum of labor. Furthermore, containerization conveys a variety of benefits to the mobility of cargos in port, namely lower transportation costs and lower inventory costs, and a higher service level could be achieved, including improving the reliability of transportation as well as the decline of carbon emissions (shown in Table 3).

In Table 4, the water-to-water transfer is one of the main intermodal transportation modes. Shanghai port, Guangzhou port, Ningbo-Zhoushan port and Xiamen port exhibit high intermodal proportion in waterborne transfer. However, the continuing increment in transshipment is not effective in reducing emissions. It can be understood that under a certain throughput, there exists a balanced solution between the transit ratio and carbon emissions, referring to the actual situation of each port. However, for the others, accelerating the development of intermodal transport would be of great benefit to reducing emissions, i.e., Tianjin port, Rizhao port and Lianyungang port.

6.2. Adopt Clean Energy by Using Physical Equipment and Improving Energy Efficiency

In order to achieve the goal of carbon neutrality in port cities of China, port authorities need to take responsibility for reducing greenhouse gas emissions, which includes paying more attention to the optimization of physical equipment with traditional fuel energy and improving the efficiency of energy use. There is a need to shift from fossil-fueled land bridge, rubber-tired container gantry crane or container trucks to running them on fossil-free fuels, such as hydrogen or biofuels, or electricity produced by renewable sources such as solar, wind and hydropower. Some solid experience shows that electrification is now a prominent trend in the port industry, however, the changing needs to be accelerated. Increased electrification of the port equipment as well as vessels will strongly contribute to more sustainable port cities [44–46]. Driving the increased demand is the expanded use of shore power, electric cranes, yard trucks and other cargo handling equipment as well as full automation of the whole process.

Managing energy efficiency is a smart way to reduce carbon emissions, such as the Energy Management Action Plan (E-MAP) which was conducted in the port of Los Angeles since 2017. Today, the ports in China not only need to keep up with ever-growing power needs, but also need to improve the overall power profile to provide the best service to the world. Improving energy efficiency and resiliency will reduce the carbon emissions and vulnerability in case of energy shortage or environmental degradation.

6.3. Optimizing Port Operation Management

As electrification becomes popular in industry, the number of new port equipment with the use of electricity as their main energy source has been increasing in the past five years. However, the carbon emissions still increase as does the throughput according to the results in Table 3. Therefore, there is a useful suggestion for port authorities in China to control the peak energy consumption to balance the cost and emissions. Peak shaving is one of the effectiveness operations in daily port management [47]. It refers to operational strategies that include using any stored energy in the case of peak energy demand periods or shifting the energy demand in the peak period to non-peak periods.

Furthermore, automated operation management systems such as the carbon emission mitigation method can be impactful, i.e., a fully automated intelligent production management control system and equipment control system in Shanghai's (Yangshan) automation terminal. The autonomous and intelligent physical equipment propose new challenges in how to model their maneuvering and energy consuming management in current operation systems. It is necessary to optimize the whole process which refers to different port running needs under a full new framework with clean energy and automatic port equipment. Moreover, the assessment of port emission, economical and operational analyses are also considered in an integrated port management framework regarding the international environmental policies.

7. Conclusions

The number of studies in the field of carbon emission reduction increases. The topic has strong environmental relevance because many of China's ports and terminals aim to explore the carbon emission-driven factors and become more sustainable. This study proposes an innovative framework which integrates STIRPAT, *GML* and MLR models to explore the driving factors related to carbon emissions in reference to the 12 selected ports of China. Port capacity, economical development and technology are considered as three categories. Then, the secondary indicators include container throughput, containerization ratio, economical indicators and *GML* indicators. The abovementioned factors are input into the proposed framework to analyze the correlation between each factor and carbon emissions in ports of China.

The results indicate that (1) Containerization ratio has a significant impact on carbon emissions reduction. The containerization can provide more efficient transportation, improve the efficiency of loading or unloading and is beneficial to the environment. (2) Port's physical facility improvement will reduce the carbon emission, especially from the fossil-fueled energy to fossil-free fuels. (3) Port throughput has positive correlation with the carbon emission; however, the intermodal transportation such as water-to-water or water-to-train has a positive impact on carbon emission reduction under a certain intermodal ratio which depends on the throughput in each port. (4) For most ports, the economic index represented by China's shipping sentiment index shows complex correlation with the emission, which implies port investment in environmental protection has not kept pace with economic growth.

According to the above results, management strategies for port authorities are given including (1) Improve containerization ratio and develop intermodal transportation in seaport; (2) Adopt clean energy by using physical equipment and improving energy efficiency and (3) Optimize port operation management by peak shaving and optimizing management systems.

Due to the COVID-19 pandemic, the port industry has been hit hard since 2020 in China. The accuracy of the collected data has also been affected. In further research, the driven factors related to carbon emission will be further subdivided and, accordingly, data after the pandemic will be collected in order to improve the accuracy of the results.

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