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Transport carbon emission reduction in a seaport: dry port system

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TRANSPORT CARBON EMISSION REDUCTION IN A SEAPORT-DRY PORT SYSTEM

by

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

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Supervisor’s affiliation: ___________________

Abstract

Title of Dissertation: **Transport Carbon Emission Reduction in A Seaport-dry Port System**

Degree: **Master of Science**

This dissertation focuses on the issue of reducing carbon emissions from seaport and dry port systems. The dissertation examines the effect of different modes of transport on reducing carbon emissions in the overall seaport-dry port system, comparing road transport with two intermodal road-rail transport options. The dissertation first examines the centralised classification of maritime carbon emissions and, through a review of relevant data, summarises the methods used to estimate the carbon dioxide emissions generated at the seaport, dry port and cargo transport stages. The dissertation then proposes three common transport options between dry ports and seaports, including one road transport option and two road-rail intermodal transport options, and then compares and ranks the carbon emissions, transport costs, transit times and convenience of transport of the three transport options. The dissertation also uses analytic hierarchy process to evaluate several different transport options in a comprehensive way. With the aim of reducing carbon emissions, evaluation indicators are proposed for the three transport options, and the hierarchical analysis is used to compare the three options in terms of carbon emissions, transport costs, transit time and transport convenience, in order to select the optimal transport option. In the last part of the dissertation, the Zhengzhou port -Tianjin port is chosen as a specific case of carbon reduction, and the carbon emissions of the whole port are estimated by taking into account the throughput, electricity consumption and transport distance of the relevant ports. The dissertation concludes with a general estimate of the contribution of the reduction in carbon emissions from the use of reasonable transport modes to the reduction of the total carbon emissions of the seaport- dry port system. This dissertation concludes that the use of more intermodal transport using internal combustion locomotives and roads instead of traditional road transport can significantly reduce the carbon emissions of the entire seaport-dry port system. The value of the study is to help the seaport-dry port system choose the right carbon reduction options.

KEY WORDS: Seaport-dry port system，Carbon emission reduction，Multimodal transport， AHP

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1. Introduction

1.1. Research Background

With the rapid development of society and technology and the increase in people's production and consumption levels, the energy consumption of the entire transport industry is increasing at an accelerated rate and ports are facing increasing pressure on carbon emissions. According to World Bank statistics, the share of CO2 emissions from liquid fuels in total CO2 emissions has been increasing year on year and exceeded ten percentage points in 2016. Road transport is the least fuel efficient of the common transport modes, at around a quarter of the efficiency of rail transport. For some transoceanic transport corridors, the carbon emissions of the entire inland transport link can even reach 40-50% of the carbon emissions of the entire transport link. Therefore, reducing the transport costs and carbon costs of inland transport links, developing dry ports and related collection and distribution systems, and transforming from road transport to road-rail intermodal transport are crucial for seaports to complete their carbon reduction work.

At present, the scale of maritime container transport is increasing year by year, and the number of seaports available for large container ships to call on is seriously insufficient against the background of large-scale ships and the scale of maritime transport. And in the face of the shipping industry's growing traffic, most countries still rely on road transport to solve the task of door-to-door transport, which will undoubtedly put enormous pressure on seaports to reduce emissions costs. China's current dry ports are mainly inland river ports, and there are still many shortcomings in the development of dry ports and the related collection and distribution systems, specifically the shortage of land resources in the port hinterland, the incomplete development of the railway collection and distribution systems supporting inland ports, and the weak correlation between the layout of dry ports and seaports.

To solve these problems, apart from introducing relevant policies to encourage the development of dry ports & collection and distribution systems that complement seaports, it is also important to consider reasonable transport options in terms of carbon emissions, transport costs and transport times.

1.2. Research Purpose

In view of the problems of China's current seaport， dry ports and related collection & distribution systems, this paper will focus on the following three aspects with the objective of reducing carbon emissions generated during the transportation process of the seaport-dry port system.

1. Estimation of carbon emissions from seaport, dry port and freight transport
2. Comparison of carbon dioxide emissions from different transport options
3. Emission reduction effect of a change in transport mode on a specific seaport-dry port system

The focus of this dissertation is on the evaluation of CO2 emissions from different transport options and the selection of the optimal option. The dissertation will design several mainstream transport options between dry ports and seaports, evaluate them in terms of carbon emissions, transport costs, transit time and transport convenience, and finally select the best transport option and align the reduction effect. Finally, for a specific seaport-dry port system, data and calculations are collected to visually study the effect of choosing a reasonable transport option on reducing the carbon emissions of the system.

1.3. Research Structure

In line with the research objectives of this dissertation, the research structure of this dissertation can be summarised in the following technical roadmap.

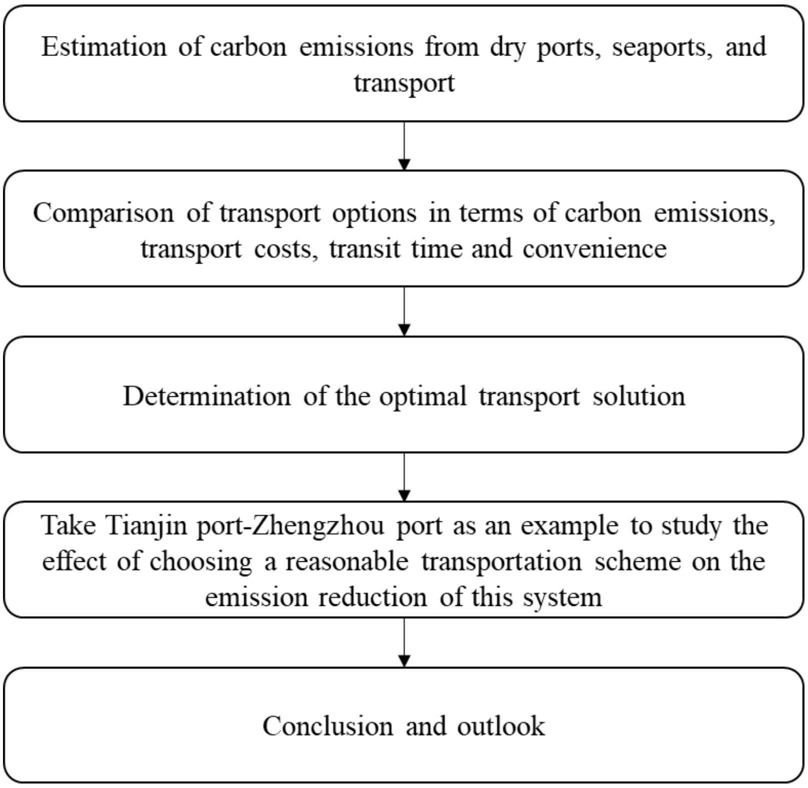

Figure 1 Technology Roadmap

2. Literature review

The relevant literature can be broadly divided into three categories according to the research direction: literature on the carbon reduction effect of dry port systems, literature on the design of dry port-seaport intermodal transport systems and literature on the improvement of seaport-dry port models.

2.1. Literature on the carbon reduction effect of dry port systems

The literature that is most relevant to this paper is the literature on the carbon reduction effects of dry port systems. Congestion and capacity shortages in container seaports have led to an increasing reliance on dry ports for global inland transport systems (Fazi & Roodbergen, 2018). With the rising cost of production along China's coast, the country is making great efforts to develop a dry port system (Zeng et al., 2013). One study found that by comparing road seaport transport with additional dry port transport, it was concluded that one way to reduce carbon emissions originating from transport is to utilize more railways rather than relying solely on road transport (Lättilä et al., 2013). Furthermore, an article by Tsao (Tsao & Linh, 2018) investigates the flow of land transport networks through CA modelling and concludes that the development of the dry port concept and intermodal transport can reduce the carbon costs of road transport. Meanwhile, the article by Qiu (Qiu & Lam, 2018) demonstrates that transporting lighter goods saves more CO2 emissions when the total distance travelled in a direct transport system is longer than the total distance travelled in a shared transport system. The article by Li (Li et al., 2019) demonstrates that seaports that serve the surrounding hinterland more evenly compared to seaports that serve a single hinterland will The results of this study show that seaports serving a more evenly distributed hinterland will achieve greater carbon reduction than those serving a single hinterland. According to Miraj's study (Miraj, P et al., 2020). The finding of this study reveals that scholars are interested in competition, port performance, and dry port planning and development.

2.2. Literature on the design of dry port-seaport intermodal transport systems

The dry port concept is based on the movement of intermodal terminals from the seaport area to the hinterland (Jarzemskis & Vasiliauskas, 2007). Selection of location of dry port is one of the most important strategic decisions on which depends their competitiveness in the market and the functionality of the logistics network (Tadic, S et al., 2020). Since dry ports can significantly reduce the carbon costs generated by transport, the design of dry port-seaport intermodal systems has turned into an important research direction. For example, Veenstra (Veenstra et al., 2012) have explored the possibility of moving major supply chains from the ports of Rotterdam and Amsterdam to hinterland ports. Ng and Cetin (Ng & Cetin, 2012) have studied on port clusters in northern India and found that dry ports in developing economies tend to be clusters rather than supply chains. Some studies have found that the location of dry ports is generally related to factors such as the function of the terminal, the size of the seaport connected to the dry port, and the transport feeder routes connecting the dry port to the seaport (Nguyen & Notteboom, 2019). In addition, there are also studies on dry ports and intermodal transport in China. Jiang (Jiang et al., 2020) have found that intermodal transport places more emphasis on inland transport costs, inland transshipment and customs clearance time than road transport. This suggests that the dry port-seaport logistics network established under the Belt and Road Initiative can effectively reduce logistics and transport costs and environmental pollution. At the same time, the growth of foreign trade and port substitution effects will also affect container flows in dry ports (Wan et al., 2022).

2.3. Literature on the optimisation of seaport-dry port models.

By reading the literature related to port network improvement, a variety of models for optimising seaport-dry port network systems can be summarised. For example, Liao (Liao et al., 2010) estimate the carbon emissions of the Port of Taipei and its hinterland based on an activity emission model. In Haralambides' research (Haralambides, H & Gujar, G, 2012)， a new eco-DEA model is proposed that simultaneously evaluates both the undesirable and the desirable outputs of port service production which is applied to evaluate dry port efficiency. The paper by Crainic (Crainic et al., 2015) propose an integer programming-based primitive service network design model to solve problems related to the optimisation of dry port container freight distribution. The paper by Wang (Wang et al., 2018) used a discrete location model to determine the optimal dry port location for the port of Tianjin. Sun (Sun & Xie, 2019) attempted a multi-objective optimisation model that considered economic efficiency, carbon emissions and transport costs, using NSGA-II to obtain a Pareto solution to provide decision makers with possible trade-off strategies. Jeevan (Jeevan et al., 2019) used multiple regression to analyse the data and identified 12 factors that are significant to the operation of dry ports in Malaysia. Facchini, F (Facchini, F et al., 2020) attempted a computational algorithm based on non-linear programming to solve problems related to the optimal dry port location of container terminals. In BoPicevic's (BoPicevic, J et al., 2021) study, the AHP method was used to determine the optimal dry port location for Seaport Rijeka. Focusing on the concession cooperation mechanism of seaports and dry ports, and the environmental constraints (carbon emissions and congestion cost),Wei (Wei & Sheng, 2021) developed a bi-objective location-allocation MILP model for the sustainable hinterland-dry ports-seaports logistics network optimization is formulated, aiming at the system logistics costs and carbon emissions to be minimized. In addition, some scholars have classified studies on the location of dry ports. Mtir (Mtir, G et al., 2022) propose an Analytic Hierarchy Process (AHP) ranking for each classification to identify the most relevant approaches on dry port location problem.

2.4. Review of the literature

At present, domestic and international literature has been relatively well researched on the issues of siting dry ports, designing dry port-seaport networks, ways to reduce carbon emissions from seaports, and ways to reduce carbon emissions from shipping and vessels, and the theoretical system is relatively mature. However, there are still shortcomings in the research on the following issues.

(1) Estimation and accounting of carbon dioxide emissions from the seaport-dry port system.

(2) Ways to reduce carbon emissions from seaport-dry port transport.

(3) The effect of the choice of a suitable transport solution and transport structure on the reduction of total carbon emissions for a specific case of a seaport-dry port system.

This dissertation will focus on the above issues to improve the theory of carbon reduction in the whole dry port-seaport system.

3. Overview of carbon reduction effects of a seaport-dry port intermodal transport system

3.1. Carbon emission reduction in a seaport system

3.1.1. Carbon reduction policies in a seaport

Carbon emissions from seaports are mainly generated by carbon emissions from ships in port areas, fuel combustion in ports and transport fuel combustion. In order to prevent serious air pollution problems worldwide, various countries and organisations have introduced policies to curb excessive greenhouse gas emissions from maritime activities.

I. IMO Policy

Greenhouse gases are naturally or anthropogenically produced gaseous components of the atmosphere that absorb and release radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted from the Earth's surface, the atmosphere, a property that contributes to the greenhouse effect. According to the Fourth IMO Greenhouse Gas Study 2020, total CO2 emissions from shipping were estimated at 1,056 million tonnes in 2018, accounting for approximately 2.9% of total global CO2 emissions. In order to reduce the greenhouse gases produced globally, IMO has developed a series of guiding policies to help countries reduce the carbon emissions produced in their maritime activities.

The MARPOL Annex VI framework to enhance the energy efficiency of ships

After extensive consideration of the control of greenhouse gas emissions from ships, the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) added in 2011 a series of new measures to reduce carbon emissions from new ship technology and operations, which are set out in Chapter 4 of MARPOL Annex VI and can be summarised in two main measures.

1. Energy Efficiency Design Index (EEDI), which requires new ships to meet a minimum level of energy efficiency performance that increases over time and at different stages;
2. Ship Energy Efficiency Management Plan (SEEMP), which establishes a mechanism for ship owners to improve the energy efficiency of new and existing ships through operational measures such as weather routing, draft optimisation, speed optimisation and timely arrival in port.

The measure came into force with effect from 1 January 2013 and applies to all ships of 400 gross tonnage and above, regardless of their flag and ownership. In 2016, amendments were adopted to MEPC 70. The amendments made it mandatory for ships of 5,000 gross tonnage and above to collect and submit data on fuel oil consumption to their flag state for aggregation and submission to IMO from 1 January 2019.

II. Carbon Emission Trading Mechanism

Since the signing of the Kyoto Protocol, the EU has been playing a leading role in the field of carbon emissions. Among the many EU climate change policies and legislation, the EU Emissions Trading Scheme (EUETS) can be considered a model for EU climate change policy.

EUETS is a market-based mechanism for reducing emissions. This model simply means that a total amount of carbon emissions is set for ships entering and leaving the ports of EU member states, and under the premise of controlling the total amount, ship operators are allowed to transfer their emissions among themselves through free trading in the EU Emissions Trading Market, so as to achieve the goal of reducing emissions and protecting the environment. Emitters can only emit according to the emission allowances they have for a certain period of time, and any excess emissions will be penalised; while surplus allowances can be transferred to other market participants through the emissions trading market. The EU has spared no effort in promoting the establishment of a global carbon emissions trading market mechanism, and although countries still failed to reach a global agreement on climate change at the Copenhagen Conference, many countries have started to build their own carbon emissions trading markets in recent years.

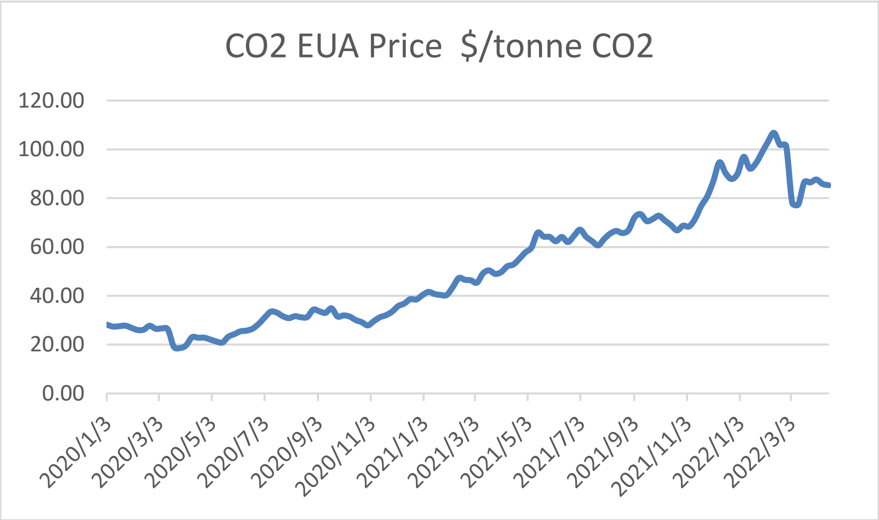

Figure 2 International carbon trading prices continue to rise

Data source: Clarkson Shipping Network

III. Chinese Carbon Emission Policy

On 22 September 2020, Chinese President Xi announced at the 75th session of the United Nations General Assembly that CO2 emissions will peak by 2030 and that efforts will be made to achieve carbon neutrality by 2060.

The term "carbon peak" refers to a year when carbon dioxide emissions reach their maximum and then enter a phase of decline; "carbon neutral" refers to a period of time when the carbon dioxide produced by a specific organisation or society as a whole is absorbed and offset through natural and man-made means such as afforestation, ocean absorption and engineering sequestration. The "carbon neutral" refers to a period of time in which the carbon dioxide produced by a specific organisation or society as a whole is absorbed and offset through natural and man-made means, such as afforestation, ocean absorption and engineering sequestration, to achieve relatively "zero" carbon dioxide emissions from human activities. China has achieved remarkable results in reducing emissions in recent years, with carbon emissions intensity falling by 48.4% in 2019 compared to 2005. In recent years, China has been actively developing its renewable energy industry. Relevant data shows that during the 13th Five-Year Plan period, China's installed capacity of hydropower, wind power, photovoltaic and nuclear power under construction has remained the world's largest in many indicators; by the end of 2020, China's installed capacity of clean energy power generation will increase to 1.083 billion kilowatts, accounting for nearly 50% of the total installed capacity. In the 14th Five-Year Plan, China has also made it clear that it will build a green cycle development model of "high efficiency, low energy consumption, low pollution and low carbon emissions" to meet the international community's need to reduce carbon emissions.

3.1.2. Seaport carbon reduction targets and methods

According to the GHG protocol, in general, the carbon emissions of ports can be broadly classified into three categories, as shown in the following table.

Table 1 Types of carbon emissions from ports

Type of emission	Description
Direct emissions	The port produces direct emissions from fuel combustion, chemical or production processes.
Indirect emissions	Indirect emissions from electricity and heat consumed by the port, where the actual emissions occur outside the port area.
Other emissions	Other indirect emissions arising from the provision of transport services by the port, where the actual emissions occur within the port area.

Data source: GHG protocol

In the case of seaports, the direct emissions of the seaport are generated within the port area and the source of emissions belongs to the port enterprises, so the source of carbon emissions of the seaport is mainly direct emissions. The actual carbon emissions data for a particular seaport, due to the lack of detailed data on carbon emissions for individual ports, is usually estimated by the following port carbon accounting formula.

$$E_s = E_1 = \mathrm{X} \cdot \mathrm{Y} \cdot \mathrm{Z} \qquad (3.1)$$

Where E_s is the carbon emissions from the port, E_1 is the direct carbon dioxide emissions from the port, X is the port throughput, Y is the unit consumption per tonne (standard coal) of the port enterprise and Z is the carbon emission factor for standard coal based on the data provided in the IPCC Guidelines for National Greenhouse Gas Inventories (2006), which is taken as 2.493 tco2/tce. The main way to reduce carbon emissions from the seaport is through port energy optimisation, reducing the port's unit consumption per tonne and thus reducing the port's carbon emissions.

Measures to reduce carbon emissions in seaports

I. Use of new types of ship fuels

The progressive introduction of new fuels is an important means of reducing carbon emissions in seaport areas. New fuels have important advantages in reducing greenhouse gas emissions. For example, LNG fuel can reduce nitrogen oxide emissions by more than 80% and carbon dioxide emissions by more than 20% compared to fuel oil; LPG fuel can reduce carbon dioxide emissions by 10%; and hydrogen energy has an energy density 40% higher than conventional energy. At the same time, however, the new fuels suffer from high equipment and fuel costs and the difficulty of preserving the fuel.

II. Use of oil-to-electric spreader equipment

Among the carbon dioxide directly generated by the daily operation of seaport enterprises, the fuel consumption of port handling machinery accounts for the largest proportion, and among these handling machinery, the diesel consumption of gantry cranes accounts for the largest proportion, accounting for more than 80% of the total diesel consumption of the enterprise, which is one of the most important sources of carbon emissions in seaports. The conversion of gantry cranes from oil to electricity can reduce the consumption of fossil fuels in ports, thus reducing carbon emissions in ports.

III. Use of clean energy

In addition to electricity and diesel, ports should also actively use clean renewable energy, including solar energy, wind energy, tidal energy and geothermal energy, to improve the energy structure of port enterprises. The port area has sufficient area and geographical conditions to use solar power generation equipment; coastal seaports also have abundant wind resources for port enterprises to use, and ports with space conditions are suitable for installing wind turbines; for seaports located in straits, inlets and other favourable geographical locations are also suitable for building tidal power stations, using tidal energy for power generation.

3.2. Carbon emission reduction in a dry port system

3.2.1. Dry port inventory carbon reduction

Dry ports are positioned as inland cargo hubs and logistics centers, and the geographical location and natural conditions of dry ports differ greatly from those of seaports, making it difficult to use clean energy as an alternative to traditional fuels. Therefore, the main approach to reducing carbon emissions in dry ports is to reduce indirect and other emissions in dry ports, focusing specifically on energy optimisation of dry port inventory equipment and optimisation of dry port transport structures.

Due to the nature of dry ports being different from seaports, there is no clear concept of a port area. At the same time, as an inland distribution centre, the storage of goods generates a large amount of energy consumption. Moreover, for dry ports, carbon emissions from electricity consumption will account for a larger proportion of the emissions, and indirect emissions from dry ports should be taken into account in the seaport-dry port emissions system. Therefore, the actual carbon emissions of dry ports should be estimated by taking into account the carbon emissions from the actual electricity consumption of the dry port inventory and the carbon emissions from the marshalling system. For dry ports, the actual carbon emissions are estimated as follows.

$$E_d = E_1 + E_2 \qquad (3.2)$$

$$E_2 = K \cdot 0.0004Z \qquad (3.3)$$

Where, E_1 is calculated in the same way as the seaport, E_2 is the carbon dioxide emissions from electricity used in port stocks, where K is the net purchase of electricity by port enterprises, and since the standard coal consumption for 1 kWh of electricity supply is 400g, the carbon emission factor for 1 kWh of electricity can be converted to a carbon emission factor of 0.0004 standard coal.

3.2.2. Carbon emission reduction from port intermodal transport

In the dry port-seaport system, the carbon emissions generated by its transport processes are classified as the third category of carbon emissions, namely other emissions. Although not strictly classified as either seaport or dry port carbon emissions, these transport emissions are an important part of the total carbon emissions of the dry port-seaport system. The total amount of such emissions is also higher than the first two types of carbon emissions. For this type of transport carbon emissions are estimated as

$$E_t = M \cdot L \cdot P \cdot E_f \qquad (3.4)$$

Where M represents the weight of the cargo, L represents the distance travelled, P represents the fuel consumption per unit weight of the distance travelled and E_f represents the carbon emission coefficients for that fuel.

According to IPCC 2006 data, the carbon emission factors for common fuels in inland marshalling systems are as follows.

Table 2 Carbon emission coefficients for fuels

Type of energy	Carbon emission coefficient	
	kgCO2/L	kgCO2/kg
Petrol	2.3	3.15
Diesel	2.63	3.06
Standard coal	——	2.493

Data source: IPCC 2006

Dry ports and seaports between the container transport methods are mainly divided into road transport and railway transport, and road transport for the main mode of transport. Road transport mainly uses the means of transport for the diesel container truck, according to the information, the diesel container truck energy consumption for 0.0606L/ton kilometer. Railway transport means are mainly divided into internal combustion locomotives and electric locomotives, internal combustion locomotives for the energy consumption of 0.00259 kg/ton kilometer, the energy consumption of electric locomotives for 0.01108 kWh/ton kilometer. Assuming that a TEU has a weight limit of 22 tonnes, the carbon emissions per unit for road and rail transport can be calculated based on their respective carbon emission factors as shown in the table below.

Table 3 Unit carbon emissions by mode of transport

Type of transport	Type of energy	Unit energy consumption	Carbon emission coefficient	Unit carbon emissions
Container trucks	Diesel	0.0606L/TKM	2.63kgCO2/L	3.51kg/TEU KM
Internal combustion locomotives	Diesel	0.00259kg/TKM	3.06kgCO2/kg	0.17kg/TEU KM
Electric locomotives	Electricity	0.1108kWh/TKM	0.996kgCO2/kWh	2.43kg/TEU KM

It can be seen that transporting one kilometer of cargo per unit weight, the carbon emissions of internal combustion locomotives are less than those of electric locomotives less than those of container trucks, which is why the use of intermodal transport in the dry port transport process can effectively reduce carbon emissions in the whole system.

4. Evaluation of transport options for a dry port-seaport system using analytic hierarchy process with the aim of reducing carbon emissions

4.1. Problem hypothesis and design of the options

Reducing the part of other carbon emissions in the dry port-seaport system through the selection of suitable intermodal solutions is considered by many countries to be an important means of reducing total carbon emissions in the overall port system; it is also the most direct, economical and relatively least technically demanding means of reducing carbon emissions in the port system. In the next part of the paper, three transport options are proposed. An evaluation system for the three transport options will also be proposed with the aim of reducing carbon emissions, and the three options will be compared using hierarchical analysis as a basis for selecting the optimal transport option.

Problem hypothesis: At present, there is a batch of containers totaling X TEU (individual TEU cargo weighing approximately 22 tons, generally speaking, the value of X is taken to be between 10 and 20) to be transported from seaport A to dry port B. The road transport distance from seaport A to dry port B is L_1 km, the rail transport distance from seaport A to the collection station C near dry port B is L_2 km, and the road transport distance from collection station C to dry port B is L_3 km. For the purpose of comparing options, it is assumed that $L_1 = L_2 + L_3$ .There are now a total of three transport sub-options for the port to choose from.

Option 1: Container truck transport

Option 2: Multimodal transport of container trucks with internal combustion locomotives

Option 3: Multimodal transport of container trucks with electric locomotives

Purpose of the evaluation: In order to meet the premise of reducing carbon emissions, it is necessary to compare and evaluate the economy, efficiency and convenience of the above options to decide on the best transport option. So in addition to carbon emissions, this dissertation selects a few important indicators that shippers may be concerned about. Therefore the following four evaluation indicators have been chosen for this dissertation, carbon emissions, transport costs, transit time and convenience of transport.

4.2. Identification and estimation of evaluation indicators

1) Evaluation of transport candidates based on carbon emission

Using the CO2 emissions per unit distance for each mode of transport as calculated in Table 3 in Part 3 of this paper, it can be roughly estimated that the category 3 carbon emissions generated by each transport option.

Option 1: $E_1 = 3.51XL_1$ kgCO2 (4.1)
Option 2: $E_2 = 3.51XL_3 + 0.17XL_2$ kgCO2 (4.2)
Option 3: $E_3 = 3.51XL_3 + 2.43XL_2$ kgCO2 (4.3)

Comparing the carbon emissions generated by the three modes of transport separately, it is clear that the carbon emissions generated by the three transport options are shown below.

$$E_2 < E_3 < E_1 \qquad (4.4)$$

2) Evaluation of transport candidates based on transport costs

In order to calculate the transport costs incurred by each of the three modes of transport, it is necessary to collect the various parameters included in the transport costs, including the rates for road transport, rail transport, etc. The freight rates for road transport consist of basic tariff+ box time fee+ other freight fee, and the freight rates for rail transport consist of operating base price+ delivery base price, where the freight rates for electric locomotives are subject to additional electrification fee. The following table of rates has been compiled by reviewing relevant information.

Table 4 Freight rates by vehicles

	Road freight		Rail freight
Basic Tariff	2.2￥/TEU KM	Delivery base price	149.5￥/TEU
Box time fee	55￥/TEU	Operating base price	0.66￥/TEU KM
Other fees	10￥/TEU	Electrification fee	0.2￥/TEU KM

Data source: Summary of web information

The transport costs incurred by each of the three options of transport are calculated from the table as follows.

Option 1: $F_1 = 2.2XL_1 + 65X$ ￥ (4.5)

Option 2: $F_2 = 2.2XL_3 + 65X + 0.66XL_2 + 149.5X$ (4.6)

Option 3: $F_3 = 2.2XL_3 + 65X + 0.86XL_2 + 149.5X$ (4.7)

By comparing the transport costs incurred by the three modes of transport and by comparing and simplifying the formulae, the transport costs incurred by the three transport options are related to the distance of L_2 and can be classified according to the distance of L_2 as follows.

When $2.2L_2 \leq 0.66L_2 + 149.5$, namely $L_2 \leq 97.08$ KM, the transport cost incurred is

$$F_1 \leq F_2 < F_3 \qquad (4.8)$$

When $0.66L_2 + 149.5 < 2.2L_2 \leq 0.86L_2 + 149.5$, namely $97.08 \text{ KM} < L_2 \leq 111.57$ KM, the transport cost incurred is

$$F_2 < F_1 \leq F_3 \qquad (4.9)$$

When $2.2L_2 > 0.86L_2 + 149.5$, namely $L_2 > 111.57$ KM, the transport cost incurred is

$$F_2 < F_3 < F_1 \qquad (4.10)$$

Through the above calculation, we can get the following calculation conclusion: when carrying out short-distance transportation, the transportation cost of road transportation is less than the transportation cost generated by railway transportation; when carrying out long-distance transportation, the transportation cost of road transportation is greater than the transportation cost of railway transportation; the transportation cost generated by electric locomotive is always greater than the transportation cost generated by internal combustion locomotive. By consulting the relevant literature, generally speaking, the reasonable transport distance for container cargoes over 10 TEU is about 300 km, and the distance between large international inland dry ports compared to their seaports (home ports) is usually greater than 150 km, so according to the actual situation, the transport costs arising from the three transport options should be estimated as follows.

$$F_2 < F_3 < F_1 \qquad (4.11)$$

3) Evaluation of transport candidates based on transit time

In order to compare the transport time generated by the three transport options in a relatively intuitive way, it is necessary to understand the composition of the total transport time of each transport mode. Generally speaking, the transport time of land transport consists of four parts: customs clearance time, loading time, transport time and unloading time. The length of loading time and unloading time is longer than that of road transport due to the need for temporary loading and unloading in the middle of the road transport. For a more intuitive comparison of the transport time required by the three modes of transport, it is assumed that the total transport distance from seaport A to dry port B is 300 km (the average estimated distance between the mainstream international inland ports and the home port), and that the average operating speed of road transport is 60 KM/h. The technical speed of railway transport is very high, especially for electric locomotives, which can reach 200 KM/h in theory. However, the actual operating speed is much lower than the technical speed due to the need for single line yielding, double line crossing and other technical operations during the operation of the train. Generally speaking, the average operating speed of an internal combustion locomotive is 80 KM/h; the average operating speed of an electric locomotive is 120 KM/h. Based on the above premise, a table of the corresponding transport times for each option can be produced as follows.

Table 5 Estimated transit time

Options	Customs clearance time	Loading time	Transit time	Unloading time	Total
Option 1	1-2 days	1-2 days	5-6 days	0-1 days	7-11 days
Option 2	1-2 days	2-3 days	4-5 days	1-2 days	8-12 days
Option 3	1-2 days	2-3 days	2-3 days	1-2 days	6-10 days

Based on the relevant assumptions and the data obtained from the above table, the length of transport time required for the three options of transport is

$$F_3 < F_1 < F_2 \qquad (4.12)$$

4) Evaluation of transport candidates based on convenience of transport

Convenience of transport is a qualitative attribute based on the subjective perception of the shipper that is closely related and requires a quantitative scale in order to be visually comparable. The qualitative evaluation of attributes is usually divided into nine levels, which correspond to the quantitative values as shown in the table below.

Table 6 Quantitative Dimensions of Convenience

1	2	3	4	5	6	7	8	9

The worst	Very bad	Bad	Less well	General	Well	Good	Very good	The best

As the procedures and steps required for each of the three modes of transport are different, they can have a different impact on the subjective judgement of shippers regarding the ease of transport. Generally speaking, shippers prefer the less complicated and more direct mode of transport, while road transport has the advantage over combined transport in that it is generally direct point-to-point and does not require secondary loading and unloading, making it more convenient for shippers. For shippers, the convenience of the three modes of transport is ranked from best to worst as Option 1, Option 2 and Option 3, while the quantitative ratings of the convenience of the three transport options are 8, 6 and 5 respectively according to the ratings provided by the relevant sources.

4.3. Evaluation of candidate transport options based on analytic hierarchy process

In order to effectively reduce the total carbon emission of the entire dry port-seaport system. At the same time, the choice of transport options is based on the shipper's point of view, taking into account the various factors affecting the transport options and selecting an economical, efficient and convenient transport option. In this paper, several transport options are evaluated using hierarchical analysis. In summary, carbon emissions, transport costs, transit time and convenience are the most important evaluation criteria when evaluating the three dry port to seaport transport options, and they are used as factors in the selection of transport options in this paper. Of these, the carbon emissions indicator has the highest priority and must be guaranteed as a matter of priority. This is followed by transport costs, which must be ensured on the basis of carbon emissions, and finally transit time and convenience, making a hierarchy chart as follows.

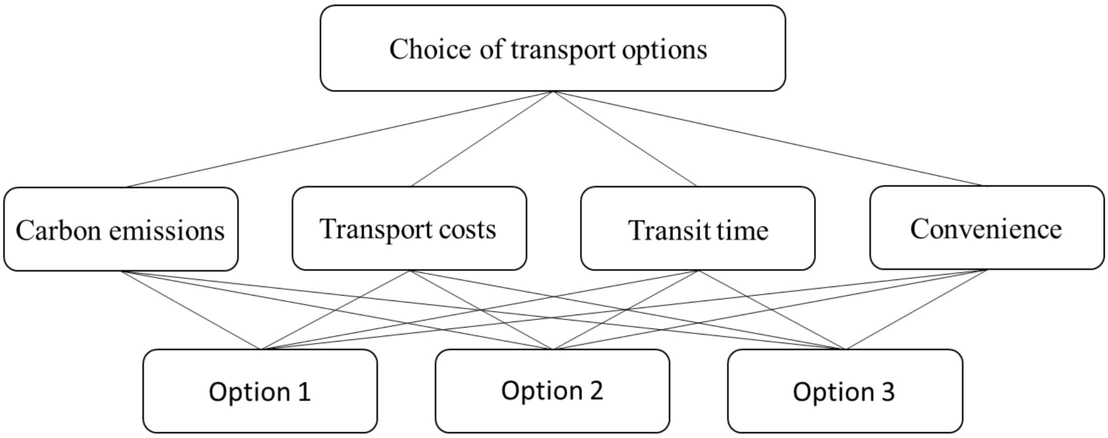

Figure 3 Hierarchy chart

First, the judgment matrix in the hierarchical analysis needs to be obtained using the 1-9 scale, with the criteria for the 1-9 scale shown in the table below.

Table 7 AHP evaluation scale

Compare Standards	Definition	Specific content
1	Equally important	Both elements are of equal importance
3	Slightly important	One of these elements is slightly more important
5	Quite important	Preferring one element over another based on experience
7	Obviously important	A clear preference for one element
9	Absolutely important	A strong preference for one of the two elements

2.4.6.8	A compromise between the above criteria

As this paper needs to give priority to meeting the indicators of carbon emissions, the importance of the carbon emission indicators needs to be evaluated higher than the remaining three indicators when quantifying them. In addition, the importance of the remaining indicators in the indicator layer was ranked quantitatively after referring to a large amount of information and the evaluation of the indicators by some experts; subsequently, the individual solutions were then ranked by hierarchical analysis according to the evaluation of the solutions in the previous part of the paper. The main objective was to calculate the eigenroots and eigenvectors of the judgement matrix.

In summary, the judgement matrix was obtained as shown below. (The respondents of this questionnaire include 10 students of maritime related majors, 10 researchers working in shipping research institutes and 10 teachers working in maritime related universities. 30 questionnaires were distributed in total and 28 valid questionnaires were collected. The final judgment matrix was rounded off after arithmetic averaging.)

Table 8 Comparison between indicator layers (A)

	Carbon emissions	Transport costs	Transit time	Convenience
Carbon emissions	1	3	5	7
Transport costs	1/3	1	5	7
Transit time	1/5	1/5	1	3
Convenience	1/7	1/7	1/3	1

Table 9 Comparison of carbon emissions of alternative options (B)

Carbon emissions	Option 1	Option 2	Option 3
Option 1	1	1/3	1/2
Option 2	3	1	2
Option 3	2	1/2	1

Table 10 Comparison of transport costs of alternative options (C)

Transport costs	Option 1	Option 2	Option 3
Option 1	1	1/3	1/2
Option 2	3	1	2
Option 3	2	1/2	1

Table 11 Comparison of transit time of alternative options (D)

Transit time	Option 1	Option 2	Option 3
Option 1	1	2	1/2
Option 2	1/2	1	1/3
Option 3	2	3	1

Table 12 Comparison of convenience of alternative options (E)

Convenience	Option 1	Option 2	Option 3
Option 1	1	2	3
Option 2	1/2	1	2
Option 3	1/3	1/2	1

In the next step, this paper will use the square root method to process the judgement matrix, firstly multiplying the elements of the judgement matrix by rows to obtain a new vector, secondly finding the nth root of the new vector (n is the order of the matrix), and finally normalising the resulting vector to obtain the weight vector.

Table 13 Results of the alternative treatment

	Carbon emissions	Transport costs	Transit time	Convenience	Product of lines	Geometric mean	Normalisation
Carbon emissions	1	3	5	7	105.0000	3.2011	0.5403
Transport costs	1/3	1	5	7	11.6667	1.8481	0.3119
Transit time	1/5	1/5	1	3	0.1200	0.5886	0.0993
Convenience	1/7	1/7	1/3	1	0.0068	0.2872	0.0485

Table 14 Weights and Eigenvalues

w	Aw
0.5403	2.3120
0.3119	1.3280
0.0993	0.4152
0.0485	0.2033

From the results of the above table, we can obtain $\mathrm{w} = (0.5403, 0.3119, 0.0993, 0.0485)^T$ as the eigenvector of matrix A. Subsequently, we can also calculate the maximum eigenvalue of the matrix as follows.

$$\lambda = \frac{1}{n}\sum_{i=1}^{n}\frac{[Aw]_i}{nw_i} = 4.2278 \qquad (4.13)$$

The same approach can be used to determine the weights of each judgment matrix in turn in matrices B to E. The calculation results are shown in the table below

Table 15 Weighting of transport options under each indicator

	Carbon emissions	Transport costs	Transit time	Convenience
Option 1	0.1634	0.1634	0.2970	0.5396
Option 2	0.5396	0.5396	0.1634	0.2970
Option 3	0.2970	0.2970	0.5396	0.1634

Next, the model for transport option selection is subjected to a hierarchical total ranking. After calculating the relative importance of the elements at each level, the combined weights of the elements at each level with respect to the system as a whole can be derived from the top level, i.e. a hierarchical total ranking. For the highest level, the result of the single ranking is the result of the total ranking, and therefore the result of the single ranking is also shown in the matrix above.

By multiplying the results of the single ranking of the option weights, with the weights of the options in the indicator layer (the eigenvectors of matrix A), the total hierarchical ranking of the transport options can be calculated, setting the weights of the option elements to a_i and the weights of the elements in the indicator layer to b_i^j respectively The specific calculation results are as follows.

Option 1:

$$w_i = \sum_{j=0}^{4} a_i \cdot b_j^i = \left(0.1634，0.1634，0.2970，0.5396\right)\begin{bmatrix}0.5403\\0.3119\\0.0993\\0.0485\end{bmatrix} = 0.1949$$

(4.14)

Option 2:

$$w_i = \sum_{j=0}^{4} a_i \cdot b_j^i = \left(0.5396，0.5396，0.1634，0.2970\right)\begin{bmatrix}0.5403\\0.3119\\0.0993\\0.0485\end{bmatrix} = 0.4905$$

(4.15)

Option 3:

$$w_i = \sum_{j=0}^{4} a_i \cdot b_j^i = \left(0.2970，0.2970，0.5396，0.1634\right)\begin{bmatrix}0.5403\\0.3119\\0.0993\\0.0485\end{bmatrix} = 0.3146$$

（4.16）

Based on the combined weights calculated for the three transport options, it can be judged that option 2 is the preferred option, with option 3 second and option 1 last.

Consistency test.

In order to ensure the reasonableness of the weights and the accuracy of the calculated results, a consistency test needs to be performed on the calculated maximum characteristic roots, which are calculated as follows.

$$\lambda = \frac{1}{n}\sum_{i=1}^{n}\frac{[Aw]_i}{nw_i} = 4.2278 \qquad (4.17)$$

Calculate the consistency index for this characteristic root

$$\mathrm{C.I.} = \frac{\lambda - n}{n-1} = \frac{4.2278-1}{4-1} = 0.0759 \qquad (4.18)$$

Table 16 Random consistency indicators

Order	1	2	3	4	5	6	7	8	9	10
R.I.	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

According to the table check, we can get the random consistency indicator R.I. = 0.89 for n = 4. Therefore, the consistency ratio C.R. is

$$\mathrm{C.R.} = \frac{C.I.}{R.I.} = 0.0853 \leq 0.1 \qquad (4.19)$$

This matrix consistency test passes and the previous calculations are valid.

4.4. Determination of the optimal option and estimation of carbon emissions

When looking at transport options for a dry port-seaport system with the aim of reducing carbon emissions, the first priority is to ensure that the transport option has the lowest carbon emissions. Secondly, transport costs and transit times are the two areas of greatest concern to shippers, and these two indicators directly influence the level of satisfaction of shippers with the transport solution, and only lastly should the convenience of the transport solution be considered.

First of all, according to the calculation results in the previous section we can get the following conclusion, in the case of prioritising transport carbon emissions, the transport solution containing intermodal transport is evaluated better than the pure road transport solution, the reason for this phenomenon is the higher carbon emission factor of diesel engines, while the relatively low fuel efficiency of container trucks causes a higher CO2 emission per unit weight of distance transported; Although in people's intuition electric locomotives are greener than internal combustion locomotives, we get a different answer by comparing the CO2 emissions of electric and internal combustion locomotives. Although the carbon emission factor is lower, the higher energy consumption per unit weight of distance traveled results in significantly higher CO2 emissions per unit weight of distance traveled for electric locomotives than for internal combustion locomotives. In addition, by comparing the transport costs and transport times of several options, some conclusions can be drawn. When short-distance transport is carried out, the transport costs of road transport are less than those incurred by rail transport; when long-distance transport is carried out, the transport costs of road transport are greater than those of rail transport, and internal combustion locomotives have an advantage over electric locomotives in terms of transport costs. In terms of time spent on transport, the public-rail transport option for electric locomotives is significantly shorter than the other two transport options. Road transport is more convenient for shippers than multimodal transport. Therefore, the final result that Option 2 is better than Option 3 than Option 1 is in fact more objective and accurate, given the priority given to transport carbon emissions. In conclusion, Option 2 is the best dry port-seaport system transport solution for the purpose of reducing carbon emissions.

Rough estimate of transport carbon emissions.

Assume that there is currently a shipment of 15 TEU containers (individual TEU cargo weighing approximately 22 tonnes) to be transported from Seaport A to Dry Port B. The distance by road from Seaport A to Dry Port B is 300 km, the distance by rail from Seaport A to Collector Station C near Dry Port B is 200 km, and the distance by road from Collector Station C to Dry Port B is 100 km. The assumptions taken are as close as possible to the reality of the situation.

The carbon emissions from each of the three options of transport are

Option 1: $E_1 = 3.51XL_1 = 3.51 * 15 * 300 = 15795$ kgCO2 (4.20)

Option 2: $E_2 = 3.51XL_3 + 0.17XL_2 = 3.51 * 15 * 100 + 0.17 * 15 * 200 = 5775$ kgCO2 (4.21)

Option 3: $E_3 = 3.51XL_3 + 2.43XL_2 = 3.51 * 15 * 100 + 2.43 * 15 * 200 = 12555$ kgCO2 (4.22)

In summary, under this assumption, transport option 3 reduces CO2 emissions by 3,240 kg compared to transport option 1; transport option 2 reduces CO2 emissions by 6,780 kg compared to transport option 3; this translates into a reduction in carbon trading price of US$28.26 and US$59.14 respectively. The calculation of the actual data shows more intuitively that the multimodal option with internal combustion locomotives has a clear advantage in terms of carbon emission reduction compared to other options.

5. An case study on Tianjin Port – Zhengzhou Port system in the field of low carbon transport

5.1. Introduction to the port system

Inland dry ports are inland cargo distribution centres and modern logistics platforms that play an important role in driving the economic development of cities and the regions they radiate. Therefore, in order to strengthen the core competitiveness of the regional economy, it is important to build an international inland port. Imported goods from seaports can be transported to inland ports for consolidation and distribution to all parts of the country. At the same time, export goods from inland cities can be transported to inland ports and transported to European cities via China-European trains; they can also be transported to seaports and transported by sea to European ports for cargo distribution and dispatch; goods from inland cities can also be transshipped through inland ports for customs clearance and inspection, and then transported by railway container trains to seaports for loading and discharging, finally reaching European cities. At present, there are four inland port groups in China, including inland port groups in the northeast, including Harbin, Shenyang, Changchun and other inland ports, Dalian port as its home port; inland port groups in northwest China, including Beijing, Shijiazhuang, Zhengzhou, etc., with Tianjin port as the home port; Bohai Sea port groups mainly include Qingzhou, Zibo, Luoyang and other inland ports, with Qingdao port seaport; inland port groups in the southeast coast, mainly Yiwu, Shaoxing, Nanchang, Kunming and other inland Ningbo, Xiamen and Shenzhen ports as their home ports.

Zhengzhou Port

Zhengzhou International Dry Port is one of the largest waterless inland ports in China. In May 2015, China Railway Zhengzhou Bureau Group Corporation, Qingdao Port, Lianyun Port, Customs and other units jointly set up an iron-sea intermodal service centre at Zhengzhou Railway Container Centre Station, with the aim of extending the port's functions inland to Zhengzhou Railway Container Centre Station and making every effort to build Zhengzhou waterless port. The Zhengzhou Railway Container Centre Station is responsible for cargo acceptance, storage, loading and running of trains; the port side is responsible for cargo reservation, customs clearance, inspection, quarantine and booking. Through the advantages of the railway and the port and the docking of their functions, an economic and fast, low-carbon and environmentally friendly logistics channel between Zhengzhou and the port is constructed.

Zhengzhou Port and China-European Liner

As an important platform and carrier to promote high-level opening up, the China-Europe Class Train (Zhengzhou) has continued to accelerate its pace of development. The first China-European Express (Zhengzhou) started in July 2013. Over the years, based on the advantages of Henan's transportation location, the CEBS (Zhengzhou) has experienced the transformation from "point-to-point" to "hub-to-hub", and has initially formed an international logistics and trade route "connecting domestic and overseas, radiating east and west". The international logistics and trade corridors have been formed. Outside of China, CEB (Zhengzhou) has taken Hamburg, Munich, Liege and Moscow as its primary hubs, and Paris, Prague, Warsaw, Malaszewicz and Brest as its secondary hubs, increasing the number of foreign container depots to 46 and spreading the network to more than 130 cities in more than 30 countries in the EU, Russia and Central Asia.

Tianjin Port

Tianjin Port, located in Binhai New Area, Tianjin, China, is situated at the western end of Bohai Bay, backed by Xiongan New Area, radiating inland hinterland in Northeast, North China and Northwest China, connecting Northeast Asia with Central and West Asia, and is the maritime gateway to Beijing, Tianjin and Hebei, the eastern starting point of China-Mongolia-Russia Economic Corridor, an important node of the New Asia-Europe Continental Bridge, and also a strategic pivot point of the 21st Century Maritime Silk Road. Tianjin Port intersects with the Beijing-Harbin Railway, the Beijing-Shanghai Railway and the Beijing-Tianjin Intercity Railway, and is connected to the Beijing-Guangzhou Railway, the Beijing-Kowloon Railway, the Beijing-Bao Railway, the Beijing-Chengdu Railway, the Jingtong Railway, the Longhai Railway, the Baolan Railway and the Lanzhou-Xinjiang Railway, which are connected to the national railway network. It will reach Beijing, Inner Mongolia and Northeast China in the north, East China and South China in the south, and connect the western and northwestern inland areas in the west, which in turn will connect Mongolia, Russia and European countries. China has made the building of the New Asia-Europe Continental Bridge and the implementation of the "One Belt and One Road" strategy the focus of deepening its opening up to the outside world, and the port of Tianjin is in the position of the bridgehead of the Asia-Europe Continental Bridge, and is also an important strategic city along the "One Belt and One Road"; with the revitalisation of the northeast, the rise of central China, and the development of the west With the implementation of the strategies for the revitalisation of the Northeast, the rise of the Central Region and the development of the West, the economy of the hinterland radiated by the Port of Tianjin has been developing, and the "Beijing Economic Circle", "Beijing-Tianjin-Hebei City Cluster", "Tianjin Free Trade Zone" and other related With the introduction of concepts such as "Beijing Economic Circle", "Beijing-Tianjin-Hebei City Cluster" and "Tianjin Free Trade Zone", the Port of Tianjin is in an important strategic position to drive the development of the north and China.

Tianjin Port - Zhengzhou Port System

At present, Tianjin Port has set up the Tianjin Port Zhengzhou Marketing Centre, focusing on promoting the construction of waterless ports in Puyang and other areas in northern Henan Province, vigorously unlocking the multimodal logistics corridor, building a two-way logistics service system with Zhengzhou Railway Bureau, and jointly promoting the "Silk Road Economic Belt" and the "21st Century Maritime Silk Road "The company is also working with the Zhengzhou Railway Bureau to build a two-way logistics service system and promote the development of the Silk Road Economic Belt and the 21st Century Maritime Silk Road. Ltd., Zhengzhou Container Center Station, China Railway Express Zhengzhou Branch and other enterprises to form the Zhongyuan Railway Multimodal Transport Consortium signed a framework agreement to work closely around the implementation of major national strategies and the development plan of modern logistics in the Central Plains Economic Zone, expand the scope of business services of iron and sea transport on both sides of the cooperation, innovate the form of transport organization, and actively promote the opening of intermodal transport services to Tianjin port and neighboring cities in the central region. The agreement will also provide for the opening of circular trains from major cities in the central region to Tianjin Port and surrounding areas. Taking this opportunity, in November 2017, the first railway freight train loaded with Haima auto parts and mould abrasives left Zhengzhou Container Centre Station and was sent to Tianjin Port. This not only marks the official opening and operation of the sea-rail intermodal train between the two places, but also marks a major key breakthrough for Tianjin Port Group Company in its efforts to build a logistics system in the Central Plains region and promote the coordinated economic development of the East, Central and West regions.

5.2. Data collection and assumptions

Port throughput

Port throughput is an important measure of direct and indirect carbon emissions from ports. Based on the Ministry of Transport of China and a summary of information available online, data on cargo throughput and container throughput for this dry port-seaport system in recent years, as well as data on container freight between the two ports, were obtained as shown in the table below.

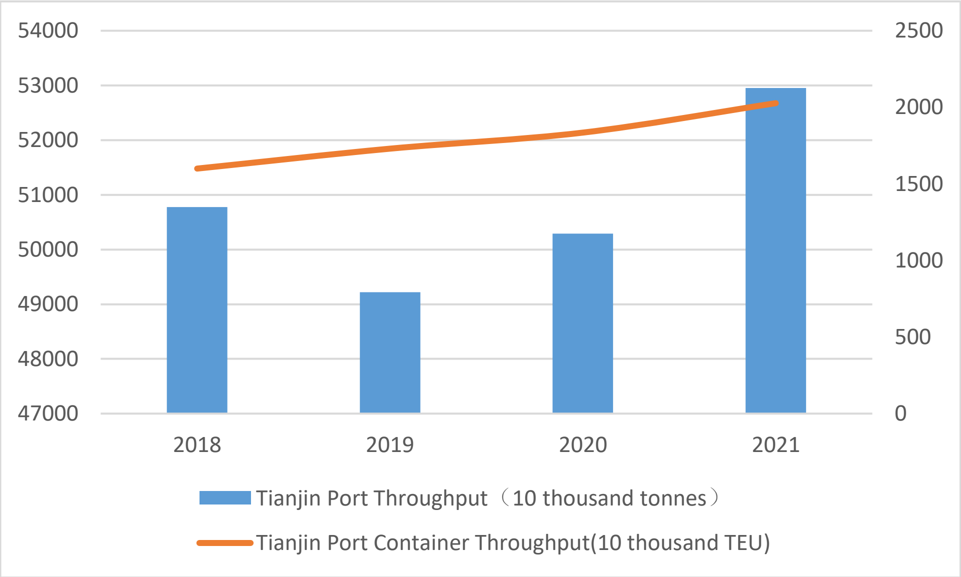

Figure 4 Tianjin Port Throughput
Data source: Ministry of Transport of China

Table 17 Tianjin Port Throughput

Year	Tianjin Port Throughput（10 thousand tonnes）	Tianjin Port Container Throughput(10 thousand TEU)
2017	50284	-
2018	50774	1600
2019	49220	1730
2020	50290	1835

2021	52954	2027

Data source: Ministry of Transport of China

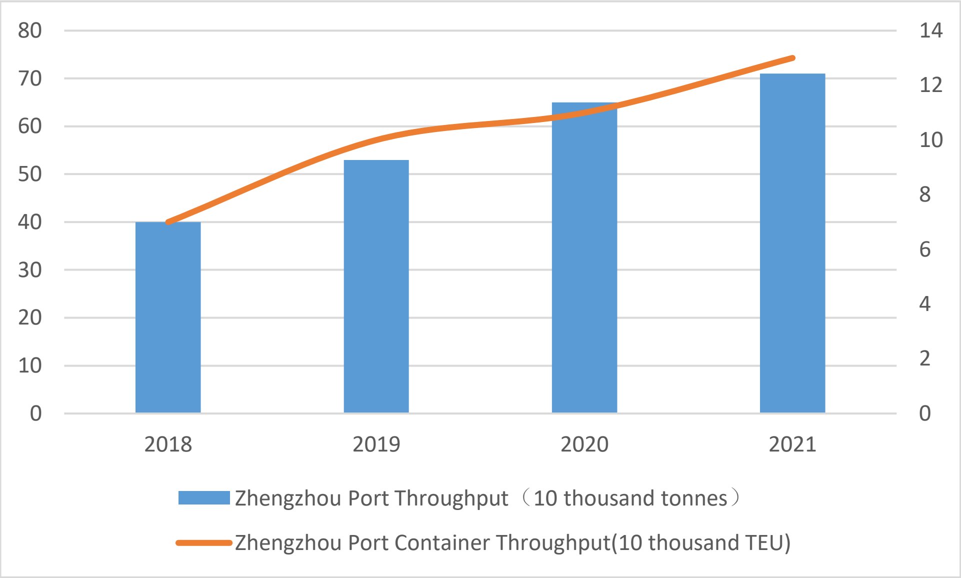

Figure 5 Zhengzhou Port Throughput

Data source: Ministry of Transport of China

Table 18 Zhengzhou Port Throughput

Year	Zhengzhou Port Throughput（10 thousand tonnes）	Zhengzhou Port Container Throughput(10 thousand TEU)
2017	-	-
2018	40	7
2019	53	10
2020	65	11
2021	71	15

Data source: Ministry of Transport of China

Table 19 Zhengzhou Port - Tianjin Port Container Volume

Year	Zhengzhou Port - Tianjin Port Container Volume(10 thousand TEU)
2017	-
2018	3
2019	3
2020	3
2021	4

Data source: Ministry of Transport of China

Transport distance

There are two main modes of transport from Tianjin Port to Zhengzhou Port, namely road transport and railway transport. In the calculation of railway transport, as there is no direct railway line from Tianjin to Zhengzhou, Tianjin Port needs to transport the goods from Tianjin Port to Beijing West Station first, and then to Zhengzhou Station via Beijing-Guangzhou railway line, according to the calculation of the transport distance of the two modes of transport as shown in the table below.

Table 20 Transport distance

	Road transport	Rail transport
Road distance	698KM	143KM
Rail distance	-	681KM

Source: Ministry of Transport of China

Energy related data

According to the statistical bulletin on the development of the transport sector in the People's Republic of China, the unit consumption data for port enterprises is 2.6 tce/10 thousand tonne. The energy data includes the electricity consumption data for each port in addition to the carbon emission factors for each energy source mentioned in the third part of the paper. The section on port electricity consumption lacks more specific statistics, so assumptions need to be made on a case-by-case basis.

In general, the annual electricity consumption of an inland dry port is much smaller than that of its home seaport, which is typically around 4 million kWh per year.

5.3. Determination of transport options and estimation of transport carbon emissions

According to the conclusions reached in Part IV of the paper, the intermodal option of internal combustion locomotives with road transport is the best option for reducing carbon emissions from transport in the dry port-seaport system. Therefore, this paper will use the data for 2021 as an example to compare the transport carbon emissions of the whole system when all road transport is used between dry ports and seaports, when internal combustion locomotives are intermodal with road transport, and when electric locomotives are intermodal with road transport, respectively.

Annual transport carbon emissions of the system when all road transport is used

$$E_1 = 3.51 \times 4000000 \times 698 = 9.80 \times 10^9 kgCO2 = 9.80 \times 10^6 tCO2$$

(5.1)

Annual transport carbon emissions of a system using all internal combustion locomotives in intermodal transport with road transport

$$E_2 = 3.51 \times 4000000 \times 143 + 0.17 \times 4000000 \times 681 = 2.47 \times 10^9 kgCO$$
$$= 2.47 \times 10^6 tCO2$$

(5.2)

Annual transport carbon emissions of the system when all electric locomotives are used in multimodal transport with road transport

$$E_3 = 3.51 \times 4000000 \times 143 + 2.43 \times 4000000 \times 681 = 8.63 \times 10^9 kgCO$$
$$= 8.63 \times 10^6 tCO2$$

(5.3)

It can be seen that the results of the calculations are the same as the conclusions obtained in Part 4 of the paper, further proving that an intermodal solution of internal combustion locomotives and road transport is the best solution to reduce the carbon emissions of transport in the port system. If the dry port-seaport system had previously been entirely road-based and was then replaced with an intermodal system of internal combustion locomotives and road transport, annual CO2 emissions would be reduced by approximately 7.3 million tonnes. However, at this stage, road freight is still the dominant mode of transport in China. If we assume that the proportion of road transport before the system is 70% and the proportion of intermodal transport with internal combustion locomotives and road transport is 30%, and if the proportion of road transport is then reduced to 50%, the final annual reduction in CO2 emissions will be approximately 1.47 million tonnes.

5.4. Estimation and conclusion of total system carbon emissions

The previous part of this chapter focused on the effect of the choice of different transport modes on the reduction of emissions in the dry port-seaport system, i.e. the reduction of other emission types of CO2. This part of the paper will specifically estimate the direct and indirect CO2 emissions from the port side of this dry port-seaport system throughout the year and make a summary for the reduction of this part of the port's CO2 emissions.

Estimated annual CO2 emissions from the seaport.

Estimates based on the data collected above indicate that the annual CO2 emissions from the port of Tianjin are approximately as follows.

$$E_s = E_1 = \mathrm{X} \cdot \mathrm{Y} \cdot \mathrm{Z} = 52954 \ \times 2.6 \ \times 2.493 \ = 3.43 \times 10^5 \ \ \mathrm{tCO2} \tag{5.4}$$

Estimated annual CO2 emissions from the dry port.

Estimates based on the data collected above indicate that the annual CO2 emissions from the port of Zhengzhou are approximately as follows.

$$\begin{aligned} E_d = E_1 + E_2 &= \mathrm{X} \cdot \mathrm{Y} \cdot \mathrm{Z} + K \cdot 0.0004Z \\ &= 71 \times 2.6 \times 2.493 + 4 \times 10^6 \times 0.0004 \times 2.493 \\ &= 4.45 \times 10^3 \ \ \mathrm{tCO2} \end{aligned} \tag{5.5}$$

Based on the estimated data above, it can be seen that the CO2 emissions from the port's own operations and storage are not significant compared to those from transport, both in dry ports and seaports. Therefore, the choice of a suitable multimodal transport solution has a significant effect on reducing the total carbon emissions of the entire dry port-seaport system. If the previous assumptions are followed, assuming that the system previously had a 70% share of road transport and a 30% share of intermodal transport with internal combustion locomotives and road transport, and if the share of road transport decreases to 50% thereafter, the reduction in CO2 emissions for the system as a proportion of the overall system CO2 emissions can be calculated as

$$\mathrm{R} = 1.47 \times 10^{6} \div (7.6 \times 10^{6} + 3.43 \times 10^{5} + 4.45 \times 10^{3}) \times 100\% = 18.50\% \tag{5.6}$$

5.5. Cases for carbon emission reduction in dry port-seaport systems

Although the use of appropriate transport modes and transport structures can reduce carbon emissions in the dry port-seaport system to a greater extent and more effectively, it is also important to reduce carbon emissions from the seaport and the dry port itself to reduce the carbon emissions of the whole system, and some large ports at home and abroad have their own advanced and excellent methods of reducing emissions, which are suitable for study and reference by seaports and inland dry ports at home and abroad.

1) Integration of wind, storage and load at Tianjin Port

The Tianjin Port grid-connected smart green energy system adopts the "self-generation, surplus power online" model and consists of two parts: wind power and photovoltaic, of which the wind power project adopts the model of the 2022 Beijing Green Winter Olympics supporting project, with a total installed capacity of 9MW and two wind turbines with a single capacity of 4.5MW, which is expected to generate about The photovoltaic project adopts the BIPV PV system with a total installed capacity of

1.43MW, which is expected to generate about 1078 hours of electricity per year, with an average annual power generation of about 1.409 million kWh. The total annual power generation capacity will reach 23.302 million kWh after the system is connected to the grid, which will save about 7,340 tonnes of standard coal and reduce carbon dioxide emissions by about 20,000 tonnes. Through the construction of the intelligent green energy system, the intelligent container terminal in Section C of Tianjin Port's Beijiang Port Area has become the first zero-carbon terminal in the world to use 100% electric energy, with all the sources of electric energy being wind power, photovoltaic and other green electric energy, and all the green electric energy is self-produced and self-sufficient.

2) Hydrogen-powered rail crane at Shandong Port

The hydrogen-powered automated rail crane, independently developed and integrated by Shandong Port, has now been put into large-scale use on the automated terminal at Qingdao Port. The crane is the world's first hydrogen-powered automated rail crane, powered by China's self-developed hydrogen fuel cell unit, which not only reduces the self-weight of the equipment, but also improves the power generation efficiency and achieves completely zero emission. According to the calculation, the power mode of hydrogen fuel cell plus lithium battery pack has achieved the optimal use of energy feed-back, which has reduced the power consumption of the crane by about 3.6% per box; saved the purchase cost of power equipment by about 20% for a single machine, reduced carbon dioxide emission by about 20,000 tonnes and sulphur dioxide emission by about 697 tonnes per year.

3) Rotterdam optimises its distribution system

The Port of Rotterdam attaches great importance to the ecological environment and sustainable development of the port, and is vigorously promoting the development of the port in the direction of low carbon, energy saving and environmental protection. The Port of Rotterdam has implemented the strategic plan "Transformation of transport modes" to optimise the port's collection and distribution system and to guide the transformation of road transport modes into waterways, railways and other clean transport modes to reduce road traffic congestion and environmental pollution. Actively promote the use of electric container dispatch vehicles, clean water and land engines, and shore power technology, and establish pollution control zones for ships to significantly reduce CO2 emissions in port areas. Implemented the Inland Waterway Transport Incentive Scheme, which provides financial subsidies for inland waterway transport vessels that meet specifications. A special freight train between the Port of Rotterdam and Germany has been introduced to increase the proportion of sea and rail transport. At present, the Port of Rotterdam has a water-to-water transhipment ratio of over 50% and inland waterway traffic accounts for over 20% of the total volume.

6. Conclusions and Outlook

6.1. Conclusions

This dissertation studies the centralised classification of carbon emissions from ports, and through a review of relevant data, summarises the methods for estimating carbon dioxide emissions generated at seaports, dry ports and in the cargo transportation phase. Three common transport options between dry ports and seaports are then proposed through hypotheses. The four indicators of carbon emissions, transport costs, transit time and transport convenience are compared and ranked for the three transport options, and the optimal transport option is identified using hierarchical analysis. Finally, the correctness and reliability of the optimal transport scheme were verified using Tianjin port and Zhengzhou port as a case study, and the approximate emission reduction effect of the scheme on the whole system was estimated. The main work and conclusions of this paper are as follows.

(1) The carbon emission factors for container trucks, internal combustion locomotives and electric locomotives were clarified through the collection and calculation of carbon emission factors for various fuels and fuel consumption data for various vehicles in Part III of this dissertation. The paper concludes that for the same weight distance, the CO2 emissions from internal combustion locomotives are much less than those from electric locomotives and less than those from container trucks.

(2) This dissertation presents three transport options commonly used between dry ports and seaports, and compares and ranks the four indicators of carbon emissions, transport costs, transit time and transport convenience of the three transport options. It is clarified that the transport method of internal combustion locomotive and road intermodal transport has the lowest carbon emission among several transport methods; when short-distance transport is carried out, the transport cost of road transport is less

than that incurred by railway transport, and when long-distance transport is carried out, the transport cost of road transport is greater than that of railway transport; the electric locomotive and road transport intermodal transport has a greater advantage in terms of transport time; by means of hierarchical analysis, it is concluded that the transport method of internal combustion locomotive and road transport intermodal transport is the optimal solution in the case of giving priority to carbon emissions.

(3) In this dissertation, the carbon emissions of the entire Tianjin-Zhengzhou port system were estimated by collecting data on cargo, energy consumption and transport modes of the two ports. The results show that when the proportion of road transport is reduced and internal combustion locomotives are used as an alternative to road intermodal transport, the effect on the overall carbon emissions of the system is significant. When the proportion of road transport is reduced from 70% to 50%, it is possible to reduce the overall system CO2 emissions by approximately 18%. Further evidence of the reliability of the conclusions in the previous section of the article.

6.2. Outlook

This dissertation analyses the effect of the choice of transport mode and transport structure on the reduction of CO2 emissions in the seaport-dry port system and examines the impact of the choice of transport mode between dry ports and home ports on carbon emissions. However, the issue of carbon emission reduction between seaports and dry ports is a highly complex one, and the research in this paper has the following shortcomings.

(1) Due to the lack of specific data and statistics, it is relatively difficult to quantify the extent to which carbon emission reduction measures (e.g. wind power, onshore

power, new energy spreader, etc.) used by dry ports and seaports themselves have an impact on the overall dry port-seaport system.

(2) In this dissertation, the importance of the four indicators of carbon emissions, transport costs, transit time and convenience of transport is rated in the construction of the indicator layer of the hierarchical analysis method, and the survey method chosen is a questionnaire survey. The population involved ranges from maritime students to experts in the shipping industry. The sample size of the questionnaire could be increased to ensure the objectivity of the results.

(3) In this dissertation, the carbon emissions of the whole Tianjin port-Zhengzhou port system were estimated by collecting data on cargo, energy consumption and transportation modes of the two ports. However, there are no clear statistics on the actual carbon emissions of each port company at this stage. The choice of specific carbon emission reduction methods should also be considered in relation to the actual situation of the ports.

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Appendix

Hierarchical Analysis Research Questionnaire

Dear Teacher & Student:

I am a current graduate student in the World Maritime University's MSc programme. I am studying the issue of carbon emission reduction from transport in dry port-seaport systems. In order to determine the weighting of four evaluation indicators of the importance of transport options: carbon emissions, transport costs, transport time and transport convenience. I sincerely request that you take a moment of your valuable time to complete the following questionnaire. I hope you will comment on the importance of the four indicators from the perspective of the shipper. The questionnaire is scored on a scale of 1-9, with the meaning of each scale explained below.

Compare Standards	Definition	Specific content
1	Equally important	Both elements are of equal importance
3	Slightly important	One of these elements is slightly more important
5	Quite important	Preferring one element over another based on experience
7	Obviously important	A clear preference for one element
9	Absolutely important	A strong preference for one of the two elements

2.4.6.8	A compromise between the above criteria

	Carbon emissions	Transport costs	Transit time	Convenience
Carbon emissions				
Transport costs				
Transit time				
Convenience				

Comparison between indicator layers