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EDITED BY
Guangnian Xiao,
Shanghai Maritime University, China

REVIEWED BY
Zhong Xiao,
Tianjin University, China
Peng Liao,
Southeast University, China

*CORRESPONDENCE
Zhiyi Lei
lei_zhiyi@hhu.edu.cn

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Research on accessibility of port collection and distribution system from the perspective of carbon emissions

Guangsheng Wang[1], Yuheng Song[2], Tong Yu[1], Zhiyi Lei[2]*, Yanhao Yang[1] and Guangyu Huang[2]

[1]CÔTE D'IVOIRE Regional Management Center, China Harbour Engineering Company Ltd, Beijing, China, [2]College of Harbour, Coastal and Offshore Engineering, Hohai University, Nanjing, China

Port accessibility is an important factor in the efficiency of a port collection and distribution systems. And the carbon emission of the collection and transportation system is large, which is an important factor that cannot be ignored when constructing the collection and transportation system. In order to analyze the carbon emission characteristics of the port collection and distribution system, the paper incorporates the carbon emission factor into the accessibility measurement of the port collection and distribution system. To solve the problem of unbalanced demand of each logistics node, the distribution of logistics demand in the system is realized by the method based on the appropriate freight volume. The carbon emission cost factor is introduced, and the accessibility measurement model based on the generalized cost impedance function is constructed. Taking the collection and distribution system of Douala Port in West Africa as an example to verify, the results show that, after adding the carbon emission factor, the accessibility of each logistics node shows different degrees of decline which shows that the addition of the carbon emission factor can be more comprehensive and can reflect the accessibility of the system.

KEYWORDS
port collection and distribution system, multimodal transportation, accessibility, suitable terminal capacity, carbon emissions

1 Introduction

The positive role of the port in the regional economy requires an efficient port collection and distribution system, so as to realize the benign economic interaction between the port and the hinterland. As an important part of the construction of modern transportation system, multimodal operation plays an extremely important role in improving transportation efficiency, reducing freight transportation costs, and realizing energy saving and emission reduction in transportation systems. Combined transportation is also one of the effective solutions to improve the efficiency of the port collection and distribution system (Yang and Guo, 2020; Yang et al., 2021). Further, the efficiency of global ports is the important evolutionary directions for international trade (Xu et al., 2023). However, the port collection and distribution system under the multimodal transport scenario involves various transportation methods, and there are complex and dynamic spatio-temporal dependencies between different areas in the road network (Xiao et al., 2023a). Currently, when describing the collection and distribution system, the technical path of constructing an index system is mainly used (Hu and Wang, 2020; Li and Wang, 2020), but there are some indicators which are still difficult to quantify, and the results are difficult to apply to specific practices such as planning and optimization.

Accessibility is an important concept in transportation geography and economic geography. It was first proposed by Hansen (1959), and it is defined as the size of the opportunity for each node in the transportation network to interact. After that, the concept of accessibility has been applied to research in the field of transportation to describe the degree of transportation connection between different transportation district, in relation to the land use intensity of attractive subregions and the travel time or travel distance between district (Xiao, 1990). In the research field of transportation network such as urban road network and railway network, accessibility is an important indicator to describe system attributes (Zeng et al., 2001; Li and Lu, 2005). The concept of accessibility has also been applied to the research on port collection and distribution systems. Scholars at home and abroad have focused on the collection and distribution systems of land direction and sea direction (Yang and Guo, 2016; Liu et al., 2021) based on time (Liu et al., 2021), distance (Song, 2001), economy and cumulative opportunity (Yang and Guo, 2016) and other factors to construct the accessibility measurement model of the port collection and distribution system. At present, the research on the accessibility measurement of logistics system can be divided into two aspects. On the one hand, the research object is often only for a single logistics mode, without considering the factors of multimodal transport. On the other hand, the cost factor considered is mainly economic and timeliness, which are less involved with environmental factors, especially carbon emission factors. In recent years, however, the swift expansion of transportation industry has resulted in the trend of exponentially growing carbon emission in this industry. One of the significant evidence is in China, where 436.17 million standard coal was consumed in 2018, accounting for 9.24% of the country's total energy consumption, second only to industry level energy consumption. Additionally, characterized by high pollution level, carbon emissions from the transportation industry have gradually become a hot topic of greenhouse gas emissions in China. Judging from the current trend, carbon emission factors are an important factor in transportation system planning (Liu et al., 2021; Zhao and Zhou, 2021), so it is necessary to take the carbon emission factor into consideration (Li and Luo, 2022; Xiao et al., 2023b).

Multimodal transport is a process of transport which is completed by two or more kinds of vehicles connecting and transferring each other. Multimodal transport combines various modes of transport such as railway, waterway, highway and air to form an integrated logistics network and provide better transport services for users. Scholars at home and abroad have focused on analyzing the problems of cooperative efficiency and cohesion among different modes of transport in multimodal transport (Zhu, 2010), and devote to improving collaborative efficiency (Kadoono et al., 2004; Marchet et al., 2012). For the optimization of the existing multimodal transport system, scholars pay more attention to the status quo evaluation and improvement measures. Cluster analysis, analytic hierarchy process, systems engineering method (Yang, 2019), fuzzy theory, DEA (Piao et al., 2013) and other methods are widely used in the evaluation model of cooperative ability of multimodal transport system. In addition, taking transportation time and transit time as uncertain variables in the process of multimodal transportation, a multi-objective routing optimization model with cost, time and especially minimum carbon emission as targets is proposed and established.

In order to solve the problems, we propose an accessibility measurement model of port multimodal transport collection and distribution system based on generalized cost impedance function. Secondly, from the perspectives of economy, timeliness and carbon emission, a generalized cost impedance function is constructed as the calculation basis of the evaluation index; finally, the generalized cost impedance is introduced into the accessibility potential model, and a generalized cost impedance of accessibility measure function for cost impedance is proposed. This model can objectively evaluate the influence of transportation mode, route selection and other factors in the port collection and distribution system on the economy, timeliness and environmental friendliness of the collection and distribution plan, and provide theoretical support for the optimization of the port collection and distribution system.

2 Materials and methods

2.1 Scope of research

The core function of the port collection and distribution system is to realize the collection and distribution of goods between the port and the hinterland, so the spatial scope of the study is the logistics nodes within the port and its hinterland. On the other hand, bulk cargo is often transported by the same mode of transportation, such as railways. In order to better reflect the characteristics of multimodal transportation, this paper determines the transportation object as a container, and converts other goods into containers through the appropriate amount of containers. In summary, the object of the research is the port collection and distribution system based on container-based water transportation, highway, railway and multimodal transportation. In addition, this paper defines the accessibility of the port collection and distribution system as the degree of convenience for containers in the hinterland of the port to reach their destination ports by road, rail, water or multimodal transport.

2.2 Construction of the accessibility measure model

Accessibility reflects degree of convenience for goods to reach their destination under a certain transportation infrastructure configuration and transportation organization. Therefore, the layout and scale of infrastructure are important factors that affect accessibility (Rodrigue et al., 2013). In addition, the imbalance in the distribution of freight demand may lead to different flows in each logistics channel, which may affect the efficiency of the logistics system. Therefore, the distribution law of freight demand is also an important factor in calculating accessibility (Chen and Deng, 2019). In summary, the accessibility evaluation mainly includes two stages, one is the distribution of freight demand based on the appropriate freight volume coefficient method to solve the uncertainty of freight demand distribution, and the other is construction of accessibility measurement model based on the generalized cost function.

2.2.1 Freight demand distribution based on appropriate freight volume coefficient method

Before carrying out the accessibility evaluation, it is necessary to estimate the volume of each node. In this paper, the concepts of appropriate freight volume and appropriate freight volume coefficient are introduced, combined with the known total logistics volume, to determine the volume of each node. The calculation of the suitable terminal capacity is an important basis for determining the construction scale, construction sequence, station function, operation nature, station layout and investment amount estimation of the main highway hub.

The appropriate freight volume refers to the throughput of goods entering the transportation hub area and processed by the hub. It is an important basis for determining the level and scale of freight transportation in the hinterland. Goods include all materials transported by road, railway, and waterway, including light cargo, bulk cargo, containers, and even information that enters the hub for processing.

The appropriate freight volume coefficient refers to the proportion of the logistics volume in the designated area to the total freight volume in the large area where it is located. The main factors affecting the appropriate freight volume coefficient include: regional scale service level, location of the freight market, freight traffic conditions, etc. The determination of the appropriate freight volume coefficient requires the judgment of the cargo throughput that enters the transportation hub area and is processed by it (He and Yan, 2002). When determining the appropriate freight volume coefficient in a region, it is not only necessary to evaluate the infrastructure and its own characteristics in the region, but also to study the characteristics of the logistics environment and traffic environment in the large environment in which the region is located, and comprehensively analyze to obtain reasonable and credible results. The relationship between the total logistics volume W_t, the appropriate freight volume W_s and the appropriate freight volume coefficient γ is shown in Equation (1):

$$W_s = \gamma \times W_t \tag{1}$$

Based on Analytic Hierarchy Process (AHP), the paper determines the appropriate freight volume coefficient of each logistics node area. The index system is shown in Table 1. On this basis, a judgment matrix is constructed, and the expert scoring method is used to assign the importance of the two arbitrary elements i and j dominated by the two above criteria according to the scale of 1-9. The freight volume is relative to the target, and the comparison and judgment matrix $A - B$ is constructed as shown in Table 2, where $B1$, $B2$, $B3$ represent regional development, transportation convenience, and transportation economy, respectively. According to the above judgment matrix of container allocation, the corresponding eigenvector is obtained as $W = (A, B, C)^T$. Among them, A, B, C respectively represent the weight values of the three indicators $B1$, $B2$, $B3$. Comparing the importance of the target area and other areas in the country with respect to each criterion, construct a table of judgment matrix $B1$, $B2$, $B3$, and compare the evaluation results of each node with other areas in the country to obtain the weight of the judgment matrix, such as Form shown in Table 3.

In summary, the eigenvectors of the three corresponding indicators of the target area are: $W_1 = (a_1, b_1, c_1, \ldots)^T$、 $W_2 = (a_2, b_2, c_2, \ldots)^T$、 $W_3 = (a_3, b_3, c_3, \ldots)^T$. Among them, a_i, b_i, c_i are the weight values assigned to each area on this item. Finally, according to Equations 2, the appropriate freight volume coefficient of each node can be calculated.

$$\gamma = A \times a_1 + B \times a_2 + C \times a_3 \tag{2}$$

TABLE 1 Regional Container Share Index Indicators.

Object	First-level indicator	Factors
Regional Container Sharing Index	Regional Economic Development Conditions	Regional Resource Endowment
		GDP
		Regional Industrial Structure
		Regional Population Density
		Space Utilization
	Transportation Convenience	Transportation Network Density
		Transport Infrastructure
		Transportation Organization
		Transportation Management
	Transport Economy	Transportation Cost
		Freight Turnover Factor

TABLE 2 Container Allocation Volume Judgement Matrix A-B.

A	B1	B2	B3
B1	1	2	4
B2	1/2	1	2
B3	1/4	1/2	1

2.2.2 Accessibility measurement model based on generalized cost function

The accessibility of the port collection and distribution system is affected by various factors such as location, infrastructure, and management. The accessibility measurement model of a single index cannot fully reflect the actual attributes of the system. In addition, under the combined action of various factors, there may be interactive relationships between elements, and the problem that the accessibility measurement models based on distance and opportunity cost cannot reflect such nonlinear factors will become more prominent. The gravity-based accessibility measurement model (Yang et al., 2019) can reflect many factors. Under this framework, the accessibility of a node not only depends on its location in the system, but also is affected by other nodes in the system. And the influence of each node's own attributes. In summary, this paper will be constructed under the framework of a gravity-based accessibility measure model, as shown in Equation 3.

$$P_i = \sum_{j=1}^{n} \frac{M_j}{C_{ij}^r} \tag{3}$$

where P_i is the accessibility of node i, M_j is the economic quality of node j, r is the impedance attenuation parameter; C_{ij} is the logistics cost from node j to node i.

In the paper, the economic quality of the hinterland logistics nodes is used to characterize the gravitational strength of the hinterland to the port, the logistics cost and time cost are used to characterize the economic factors, and the carbon emission is used to characterize the carbon emission factors. The logistics cost, time cost and environmental cost are constructed as accessibility potential. The impedance function of, constructs the expression of port accessibility as shown in Equation 4.

$$P_i = \frac{s}{n} \sum_{j=1}^{n} \frac{M_j}{g(C_{ij}, E_{ij}, T_{ij})^r} \tag{4}$$

Where P_i is the accessibility of node i. M_j is the economic quality of node j. r is the distance decay coefficient, usually taken as 2 (Yu et al., 2014). s is the model gravity coefficient, under the condition that only a single cargo type of container is considered, each node is homogenized, so takes the value 1. n is the number of source nodes; C_{ij}, E_{ij}, T_{ij} are the logistics cost, time cost, and carbon emission cost between node j and node i, respectively; $g(C_{ij}, E_{ij}, T_{ij})$ is a combination of factors impedance function.

2.2.3 Impedance function

2.2.3.1 Economic cost factor

The economic cost factor reflects the influence of the spatial distance of transportation on the travel cost. This paper involves road, railway, water transportation and multimodal transportation. Therefore, the collection and distribution system of the port is divided into several sections k according to the transportation mode. The logistics cost of road segment k to determine its transportation mode is as Equation 5.

$$C_{free,k}^{i} = d_k f^i q_k \tag{5}$$

where $C_{free,k}^{i}$ is the freight cost of road section k under the condition of transportation mode i. d_k is the length of the section k. f^i is the cost of transportation mode i.

2.2.3.2 Time factor

The time factor is determined by factors such as infrastructure capacity and transportation mode. Common time impedance functions are mainly aimed at road transportation, such as the BPR road resistance function (Zhang et al., 2008) and the vehicle speed-flow model (Wang et al., 2006). However, this paper needs to consider a variety of transportation modes, and the influencing factors of time impedance are relatively complex. Therefore, in this paper, under the framework of BPR function, a time impedance function suitable for multimodal transportation is constructed.

2.2.3.2.1 Highway Impedance

The paper adopts the original form of the BPR function, as Equation 6.

$$t_k = t_{free,k}[1 + \theta_1 (\frac{q_k}{F_k})^{\theta_2}] \tag{6}$$

Where t_k is the transport time. $t_{free,k}$ is the free flow travel time of the road section k, which is equal to the ratio of the length of the road section to the free flow speed. q_k is the cargo flow on the road section k; F_k is the traffic capacity of the road section k; θ_1, θ_2 are the time cost fitting parameters of the BPR function, generally 0.15, 2.5 (Zhang et al., 2008).

TABLE 3 Container allocation judgment matrix B1.

B1	Area 1	Area 2	Area 3	......
Area 1				
Area 2				
Area 3				
......				

2.2.3.2.2 Railway impedance

The railway transport capacity mainly depends on the train running diagram of the railway, and its impedance has rigid constraints: when the railway transport capacity meets the freight volume demand of the road section, its impedance is approximately 1, and the impact of the freight volume on the transport time is only reflected in the loading and unloading process. The transportation process has no effect; when the transportation capacity of the current operation chart cannot meet the demand for freight volume, the transportation volume exceeding the transportation capacity will not be able to be transported by railway, and its impedance is approximately infinite, so the railway impedance is shown in Equation 7.

$$t_k = \theta_3 t_{k,free} \tag{7}$$

where θ_3 is the decision coefficient, when the railway transportation capacity meets the freight demand, it is taken as 1, otherwise, it is taken as infinity.

2.2.3.2.3 Waterway Impedance

For waterway transportation, canalization is the decisive factor for waterway resistance. If the channel is not channelized, the water transportation impedance is similar to road transportation, and there is an elastic relationship between flow and time; if the channel is channelized, there is a rigid interval at the channelized hub. When the channelized hub cannot meet the navigation demand, the impedance of the waterway is approximately infinite. The waterway transport impedance function is as Equation 8.

$$t_k = t_{free,k}[\theta_4 + \theta_5(\frac{q_k}{F_k})^{\theta_6}] \tag{8}$$

Where θ_4 is the decision coefficient, when the transportation capacity meets the demand of freight volume, it is taken as 1, otherwise, it is taken as infinity. θ_5 and θ_6 are the time-cost fitting parameters of the BPR function. Considering that the water transport has a larger unit volume but lower speed than road transport, and is less sensitive to congestion, combined with the relevant trial calculation results in the paper. So based on the recommended value of the highway BPR function, it is further reduced, taking 0.1, 1.5 (Zhang et al., 2008).

2.2.3.2.4 Multimodal Impedance

The conversion time between different transportation modes should be much shorter than the transportation time, and this paper has divided the collection and distribution system into different sections according to the transportation mode, so the replacement impedance of multimodal transportation is not additionally considered. The multimodal transport impedance formula is shown in Equation 9.

$$T = \sum_{k=1}^{m} t_k^{car/rail/ship} \tag{9}$$

where m is the total number of road segments from logistics node j to port i.

2.2.3.3 Carbon emission factor

Carbon emission factor refers to the amount of greenhouse gases produced by energy consumption per unit mass converted into carbon dioxide. It includes the total amount of carbon dioxide converted from the greenhouse gases emitted by each process of mining, processing and using per unit mass of energy.

In the paper, the unit energy consumption of each transportation mode is converted into carbon emissions, and carbon emissions are used as carbon emission cost factors, and the carbon emission cost impedance function is shown in Equation 10

$$e_k = d_k q_k C P_c \tag{10}$$

Where e_k is the carbon emission factor. P_c is the unit carbon tax. C is the unit carbon emission, referring to China's statistical caliber of carbon emissions for road, railway and waterway transportation, the emission coefficient of converting standard coal into carbon is 2.7, and the unit carbon emission of each transportation mode is shown in Table 4.

2.2.3.4 Generalized cost impedance function

For the economic cost factor and the carbon emission cost factor, the fundamental source is the fuel consumed in the transportation process, and the fuel consumption is proportional to the transportation time, so the logistics cost and the environmental cost also increase linearly with the transportation time. In summary, the generalized cost impedance is constructed as shown in Equation 11.

$$g(C_{ij}, E_{ij}, T_{ij}) = \sum_{k=1}^{m} t_k(\alpha c_k + \beta e_k) \tag{11}$$

Where α, β are the standardization coefficients, and the Z-Score method is used to determine the standardization coefficients.

2.2.4 Accessibility measurement model based on generalized cost impedance

Based on the above factors a generalized cost impedance function is constructed, as shown in Equation 12.

$$P_i = \frac{s}{n}\sum_{j=1}^{n} \frac{M_j}{[\sum_{k=1}^{m} t_k(\alpha c_k + \beta e_k)]^r} \tag{12}$$

TABLE 4 Carbon emissions of different modes of transport.

Model	Highway	Railway	Waterway
Converted CO^2 emissions per unit (kg/10^4t·km)	574.6	43.4	215.7
Converted carbon emissions per unit of transportation (kg/10^4t·km)	156.7	11.8	58.9
Carbon emissions per unit of container (t/10^4TEU·km)	2.74	0.21	1.03

Where α, β are the variables that reflect the impedance. When $\beta = 0$, only the logistics cost factor and the time cost factor play a role in the impedance function; when α, β are the corresponding standardized coefficients, the economic, time and environmental costs factors work together. In order to verify the effect of the environmental cost factor, we will calculate the port accessibility of the collection and distribution system according to the above two schemes.

In order to facilitate the construction of the model, the port collection and distribution system is abstracted into a topological structure consisting of port hubs, logistics nodes and logistics sections. Based on the Dijkstra algorithm, according to the attributes of passing capacity, transportation mode, existing load and path length, the collection and distribution system of the port is divided into several independent sections. At the same time, the incremental allocation method (Feng et al., 2022) is adopted to eliminate the influence of the cargo sequence in different hinterlands. According to the incremental distribution method, the accessibility measurement model of the port collection and distribution system is shown in Equation 13. Where δ is the number of times of incremental distribution of node logistics flow.

$$P_i = \frac{s}{n}\sum_{i=1}^{\delta}\sum_{j=1}^{n}\frac{M_j/\delta}{\left[\sum_{k=1}^{m}t_k(\alpha c_k + \beta e_k)\right]^r} \tag{13}$$

3 Case studies

In order to verify the impact of carbon emission factors on the accessibility measurement model, this paper selects the Douala port located in the Gulf of Guinea in Africa as a case for verification. The port of Douala is adjacent to the northwest side of the Gulf of Guinea and is the largest port in Cameroon. Currently, the port of Douala is considering upgrading the collection and distribution system. According to the preliminary investigation, the hinterland of Douala Port mainly includes 6 countries including Chad and the Central African Republic, as shown in Figure 1.

Firstly, the appropriate freight volume coefficient and container freight demand of each node are calculated based on the generation coefficient method. Combined with the infrastructure of the country where the logistics node is located (Africa Union, 2012), the appropriate freight volume coefficient and container transportation demand of each node are calculated as shown in Table 5. Among them, the appropriate freight volume coefficient of the Douala port node is 1.

For the convenience of analysis, the paper abstracts different collection and distribution schemes into the form of topological network diagrams, as shown in Figure 2, the line segment lengths and node positions in the figure only represent the topological properties of the system, and do not represent the actual mileage of the road segment and nodes. space coordinates. The outward flow of arrows in Figure 2 is the outbound flow diverted from Nigeria to

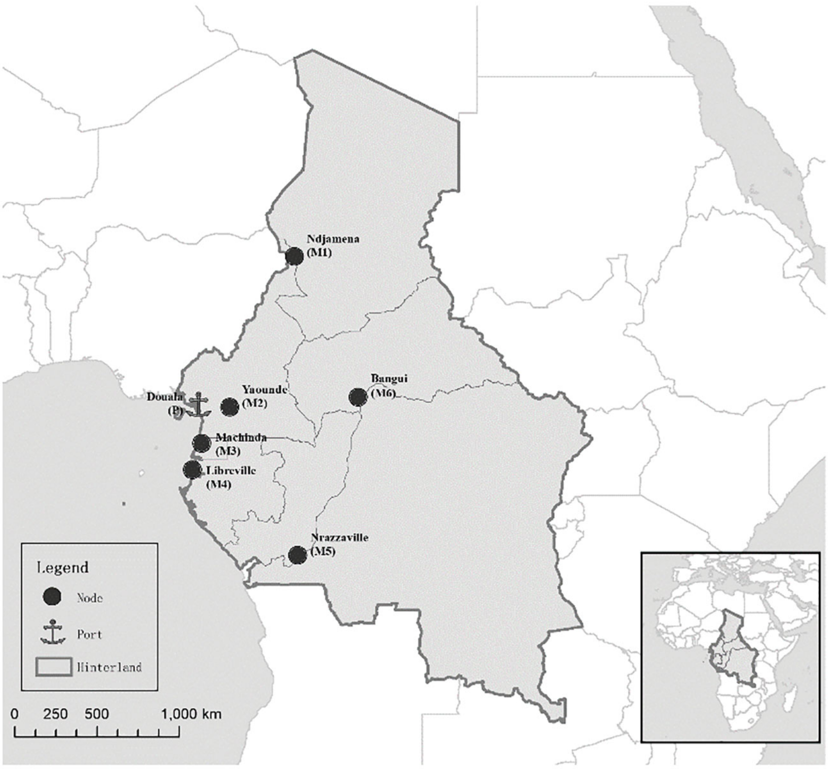


FIGURE 1
The spatial extent of this study.

TABLE 5 Container generation nodes and generation volumes.

Node	Volume of import and export containers (Million TEU)	Appropriate Freight Volume Coefficient	Cargo Volume (Million TEU)
Douala(P)	400	1.000	400
Ndjamena (M1)	150	0.7637	115
Yaounde (M2)	600	0.4473	268
Machinda (M3)	300	0.7857	236
Libreville (M4)	350	0.6753	236
Nrazzaville (M5)	2400	0.7507	1802
Bangui (M6)	100	0.7282	73

Douala Port. In plan a, Nigerian containers are transferred to Douala Port (P) via the road network of C1. In plan b, Nigeria Transshipment from Port Harcourt to Douala. In addition, there are no canalization junctions in the waterway transportation reaches involved in the collection and distribution system. In the paper, an elastic model is used, that is, a value of 1 is used for impedance calculation.

3.1 Accessibility analysis

Based on the two planning schemes of the collection and distribution system, two scenarios were set whether to consider carbon emission factors, and a total of 4 groups of experiments were designed. The experimental results are shown in Figure 3.

The results show that there is no obvious linear correlation between the economic quality of the node and the accessibility of the destination node, that is, under the action of the impedance function, the accessibility potential of the destination node and the economic quality of the source node exists nonlinear relation. From the perspective of port, the accessibility potential of Plan b (road-rail-waterway plan) compared to Plan a (road-rail combination plan) is significantly improved in both scenarios, where only logistics costs and time are considered in the case of cost, scheme b is 5.1% higher than Plan a. When considering the combined effect of economic, time and environmental costs, Plan b is 6.3% higher than Plan a. It can be seen that the collection and distribution of road-rail-waterway transport system has significantly improved the port's economy, timeliness and carbon emission reduction. From the perspective of users, the accessibility potential of most logistics nodes in Plan b has been improved by about 20%. Among them, Bangui (M6) has the most significant improvement of 173% and 196%. Influenced by the distribution flow of container freight volume, the accessibility potential of Bata (M3) and Libreville (M4) has a slight decline ranging from 3% to 9%.

In the road-rail combined plan, there are local bottlenecks in the collection and distribution system, and the cost of roads is higher than that of railways. Therefore, the container logistics of M6 and P relies heavily on the logistics channels of M6-C3-M2-P. When the M2-P section is oversaturated and crowded, a small amount of container cargo flow will flow through the M6-C3-M5-P channel, while the M5-P section still has some capacity remaining. The distribution of logistics flows is obviously unbalanced; in the road-rail-water combined transport scheme, the construction of water transport sections makes up for the original connectivity bottleneck, and water transport has cost advantages over road transport in terms of economy and environmental friendliness, the container

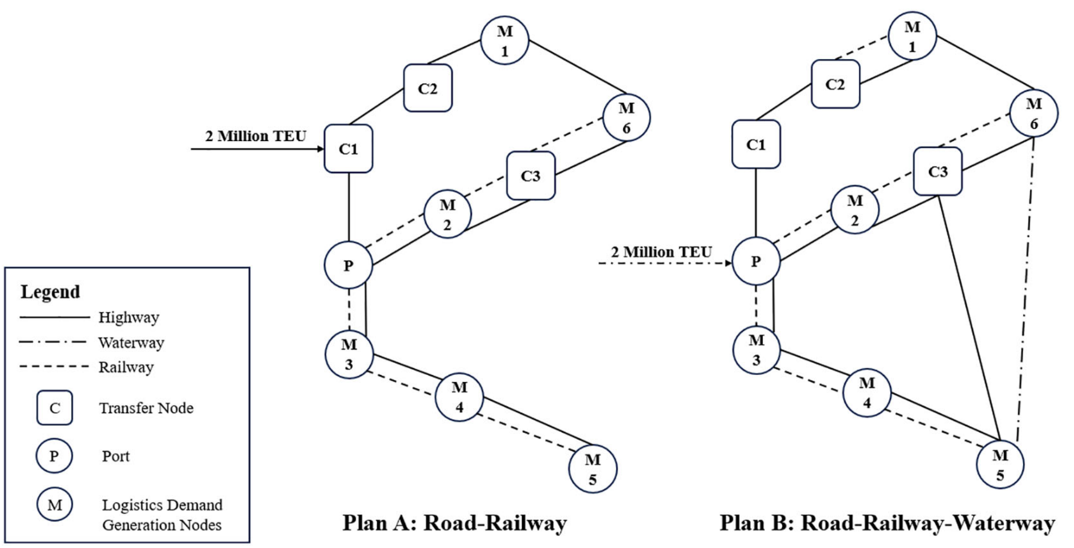
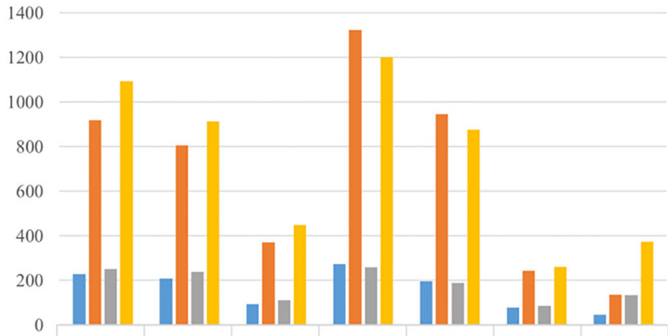


FIGURE 2
Topological network diagram of the planning scheme of the collection and distribution system.



	P	M1	M2	M3	M4	M5	M6
Plan A & With Carbon Factor	229.57	207.46	92.46	273.21	195.61	79.72	45.35
Plan A & Without Carbon Factor	918.27	805.88	369.82	1322.31	946.75	244.14	136.79
Plan B & With Carbon Factor	249.96	239.08	111.98	258.81	188.68	84.95	134.43
Plan B & Without Carbon Factor	1092.82	913.37	447.92	1200.62	875.32	260.15	373.4

FIGURE 3
Comparison of accessibility.

generation volume of M6 is evenly distributed to port P through the two channels M6-C3-M2-P and M6-M5-M4-P, although the local flow of the M4-M3-P section increases, resulting in the availability of M4 and M3. The accessibility potential decreased slightly, but for the collection and distribution system as a whole, the flow distribution was more balanced, and the performance of the collection and distribution system was better.

In addition, in the dynamic process of container flow distribution, due to the inflexibility of railway transportation impedance, and the logistics cost and environmental cost of railway transportation impedance are far less than road transportation, when there is a multimodal transportation option at the node, the railway transportation is often preferred. Instead of roads, railway transportation sections are the first to reach saturation in the collection and distribution system. It can be seen that when the freight volume in the collection and distribution system reaches a certain standard, the generalized cost performance of railway transportation is more significant than that of road transportation, that is, multimodal transportation should be given priority in the construction of regional logistics systems, especially sea transportation. The railway transportation mode will give full play to the advantages of railway transportation.

3.2 Analysis of carbon emission reduction effect

As shown in Figure 3, the accessibility potential of each node considering the carbon emission cost factor is lower than that without considering the carbon emission cost factor, that is, after considering the carbon emission cost factor, the accessibility potential of each node in scheme a and b were significantly reduced. Among them: the M3 and M4 nodes in the scheme a with the most obvious decline, with a drop of about 79%; and the M6 with a significant drop in the scheme b, with a drop of about 64%. From the perspective of collection and distribution, the main transportation mode of M3 and M4 nodes in scheme a is road-rail combined transportation. According to the distribution of cargo flow, the railway capacity of M3 and M4 has basically reached saturation, and the remaining container cargo flow in the channel mainly passes through Road transport; in scheme b, the collection and distribution type of M6 is multimodal transport by road, rail, and water, in which the capabilities of waterways and railways are fully utilized, and waterways replace roads to undertake a considerable part of the transportation capacity. Although the time cost of inland water transportation is higher than that of road transportation, its environmental cost and economic cost are far lower than road transportation, and its generalized cost is lower without considering the timeliness of goods.

Further analysis of the performance of M6 node in scheme b is as follows: When the carbon emission cost factor is not considered, the increase of M6 is 173%, which is mainly due to the construction of water transportation channels, which improves the regional connectivity bottleneck, solves the problems of channel congestion and unreasonable flow distribution, and improves the way of collection and distribution. It also greatly reduces the time cost of the system; when the carbon emission cost factor is considered, the increase in M6 reaches 196%, which further illustrates the advantages of water transportation in terms of environmental friendliness and economic rationality compared with road transportation. Therefore, considering the cost of carbon emissions, the generalized cost of waterway is lower than that of road transportation, which means that the advantages of waterway resources should be fully considered in the planning of the port collection and distribution system.

In summary, compared with the general accessibility measurement method, the accessibility evaluation method of the port collection and distribution system constructed in the paper can solve the accessibility analysis under the condition that the logistics requirements of each logistics node are different, and can solve the problem of accessibility analysis. A more objective and reasonable evaluation of the economic rationality, timeliness and environmental friendliness of the collection and distribution system has quantitative support for the evaluation and optimization of the collection and distribution system planning scheme.

4 Conclusion

The paper proposes a model for measuring the accessibility of port collection and distribution systems considering carbon emissions. Firstly, the logistics demand of each node is calculated based on the generation coefficient method to solve the inhomogeneity and difference in the spatial distribution of logistics demand. Secondly, using the time impedance function suitable for railway and waterway transportation, and based on the traditional accessibility measure based on economic cost and time cost, the carbon emission cost factor is introduced, and the port collection and distribution transportation based on the generalized cost impedance function is constructed. System accessibility measurement model. The model can be used in the feasibility analysis and planning stage of the port collection and distribution system.

It is verified by the upgrading and transformation plan of the collection and distribution transportation of Douala port in the Gulf of Guinea. The results show that the advantages of waterway transportation and railway transportation are more significantly reflected after adding the carbon emission cost factor. When the cargo has low requirements for timeliness and the freight volume reaches a large scale, the construction of railways and the development of water transport resources should be fully considered in the planning of the collection and distribution system, so as to give full play to the advantages of the economic and environmental friendliness of railway transport and inland waterway shipping. The experimental results also show that the accessibility measurement method of port collection and distribution system considering carbon emissions can more objectively reflect the comprehensive effects of economy, timeliness and environmental friendliness, and is more in line with the requirements of low-carbon logistics and sustainable development. However, to extend the conclusions to other cases, further quantitative analysis is necessary. For instance, sensitivity analysis of α and β indicators will help reveal the specific processes in which carbon factors affect accessibility.

Data availability statement

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

Author contributions

GW: Conceptualization, Investigation, Project administration, Writing – original draft. YS: Conceptualization, Data curation, Formal Analysis, Methodology, Writing – original draft. TY: Conceptualization, Investigation, Writing – review & editing. ZL: Formal Analysis, Methodology, Project administration, Validation, Writing – original draft. YY: Data curation, Investigation, Writing – review & editing. GH: Data curation, Validation, Writing – review & editing.

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Conflict of interest

Authors GW, TY and YY were employed by the company China Harbour Engineering Company Ltd.

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

Publisher's note

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