IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 4 June 2024, accepted 19 June 2024, date of publication 24 June 2024, date of current version 1 July 2024.
Digital Object Identifier 10.1109/ACCESS.2024.3417956

RESEARCH ARTICLE

Research on Site Selection of Ship Tank Washing Stations Based on a Biobjective Optimization Model

YONG XU AND KAIZE ZHU
Department of Electronic Commerce, South China University of Technology, Guangzhou 510006, China
Corresponding author: Yong Xu (xuyong@scut.edu.cn)

ABSTRACT This paper presents a biobjective model for locating tank washing stations. The model aims to minimize the total void sailing cost of ships and the facility load deviation of tank washing stations to improve the facility utilization rate and avoid overloading facility services while ensuring that the tank washing demand of the ships carrying hazardous goods in the region can be adequately met. By introducing the "proximity allocation" constraint and assigning the ship to the tank washing station that minimizes the void sailing cost, a more realistic model is set up. This allows for a more accurate estimation of the number of tank washing services at the tank washing station and measurement of the facility load, facilitating the optimization of the siting objective. This paper applies a biobjective optimization siting model to identify a set of Pareto-optimal solutions for the siting of tank washing stations at 79 terminals in 18 port districts in the Pearl River Delta region based on one quarter's data for the demand of tank washing for the ships in the region. The average void sailing cost for a group of better-performing solutions is 11.4 km, while the average tank washing station facility load is 11.8%, which is close to the value of 8% of the optimal solution. In addition, through a sensitivity analysis, it is demonstrated that when the void sailing cost is adjusted according to the tonnage of the ship and the additional cost of travel to a third terminal for tank washing, the total ship void sailing cost in the results of the model will decrease or increase accordingly. The results demonstrate that the model can provide a scientific basis for decision-making regarding the siting of tank washing stations. This ensures the effective utilization of tank washing stations while enhancing the availability of tank washing services.

INDEX TERMS Tank washing station, biobjective optimization, void sailing costs, site selection.

I. INTRODUCTION

When a ship transporting hazardous materials changes cargo during its operation, it is necessary to perform tank washing to prevent any potential chemical reactions between the previous and next cargoes that may result in accidents. This also ensures that the purity of the cargo meets the merchant's demand. It is important to avoid any incompatibility between the types of cargo carried on different voyages. Tank washing is typically conducted either at the tank washing station or by a third-party tank washing service at the terminal. Some ships may also rely on on-board tank washing equipment, although this is only available for a small number of large tankers. Due to high service costs and inconsistent operation standards [1], as well as cases of illegal discharge and disposal of tank-washing wastewater by ships [2], [3], construction of tank-washing stations is necessary to fully satisfy the demand for tank washing in a region and effectively solve the problem of tank-washing water treatment. This is crucial for ensuring the safety of marine shipping of dangerous goods and reducing marine pollution. Planning and selecting sites for tank washing stations can help meet the demand for ship tank

The associate editor coordinating the review of this manuscript and approving it for publication was Mauro Gaggero.

washing and promote effective implementation of regional tank washing operations and the regulation of tank washing water discharge.

Tank washing stations should be located at sites where the demand for tank washing is concentrated [4]. Locating tank wash stations at terminals provides the infrastructure to treat oily waste water and tank wash water and facilitates the berthing of ships. Therefore, the potential location of the tank washing station should be a discrete point, and its location problem type should be considered as a Discrete Facility Location Problem (DFLP). Unlike for the Continuous Facility Location Problem (CFLP), facilities can be located only at a limited number of discrete points in DFLP, usually at certain nodes in the network diagram, while demand points also exist in the network diagram and can be connected to the facility points to form a path. Due to the differences in the form of demand, facility siting objectives and facility siting constraints, the number of different types of DFLP has increased [5], and two of the most prominent DFLP types are as follows [6]:

a. Coverage-based problems (CBPs), including the set coverage location problem (SCLP) and the maximum coverage location problem (MCLP).

b. Median-based problems (MBPs), including the p-median location problem (p-MLP).

Among them, p-MLP is concerned with the selection of the optimal location of P facilities among the given candidate locations in order to minimize the sum of distances from the demand points to the facilities [7], [8]. The p-MLP problem is NP-hard, and the difficulty of solving it increases when it evolves into a problem that considers facility capacity constraints [9]. However, the assumptions of p-MLP regarding the number of facilities and their candidate locations do not accurately reflect reality in certain scenarios [10]. For instance, a high number of facilities may result in a proportional increase in the cost. The most reliable approach to assumptions about the number of facilities is to include them as decision variables in the model, even though this can lead to a rapid increase in the size of the solution space of the problem, which makes it more difficult to solve [11]. A more prevalent methodology is to delineate the number of facilities through budgetary constraints [12], [13]. The objective of p-MLP is to ensure that the layout of facilities seeks to optimize spatial efficiency and accessibility, allowing each demand point to obtain services at a lower cost, which is consistent with the purpose of selecting tank washing stations from the point of view of ship interests.

Currently, research on ship tank washing focuses on the treatment of tank-washing water [14] and the current situation and development of the tank-washing industry [15], [16], [17]. By contrast, few studies on the location of tank washing stations have been reported, and there is a lack of sufficiently abundant case studies or more general and effective methods and models to provide suggestions for the planning of tank washing stations in other regions. Furthermore, current research on the site selection of tank washing stations has focused primarily on reducing the cost of tank washing station construction. The research is conducted at the scale of the harbor, with no further specific selection of the location for the construction of the wash station [18].

In contrast to other problems, the siting of tank washing stations involves ships that are constantly moving and must travel to these stations to complete their washing operations after unloading and leaving the harbor. This presents a problem: if the unloading terminal lacks the tank washing capacity, the ship must visit other tank washing stations to complete the tank washing operation after leaving the harbor, incurring a certain amount of void sailing cost, as the ship still has its next transport task to complete. The existence of a void sailing cost reduces the willingness of the ship to wash tanks, resulting in the completed tank washing station failing to meet the expected number of tank washing services [19]. In the design of tank washing stations, it is crucial to consider the availability of tank washing services and the utilization rate of the stations as key factors. A site cannot be selected only based on reducing the distance or construction costs, as this may not guarantee effective and adequate operation of the stations while minimizing investment. To achieve this goal, it is necessary to utilize optimization models with multiple objectives in the siting of tank washing stations. A number of hierarchical objective and biobjective optimization models have been employed in a number of siting problems to enhance the reliability of the siting solution [20], [21]. These models have been used to provide Pareto optimal solutions for decision-makers, enabling them to select a siting solution based on their preferences or objective weights. Therefore, a model should be proposed to provide an ideal tank washing station siting scheme that offers adequate tank washing services for ships with limited stations while incurring the smallest possible void sailing cost for ships traveling to the tank washing station. This will increase ship willingness to wash tanks, resulting in a greater number of annual tank washing operations at the stations and more efficient use of resources for tank washing services.

This paper attempts to design a biobjective location model based on the classical P-median location model to solve the tank washing station location problem. The model takes the minimization of the ship's void sailing cost as the optimization objective and identifies the minimization of the gap between the amount of tank washing service to be provided by the tank washing station and its designed tank washing capacity, i.e., the minimization of the facility load deviation of the tank washing station, as the second optimization objective. The latter objective ensures that in the modeled site selection scenario, high facility utilization of the tank washing station can be maintained and that the tank washing station does not have to provide tank washing services that grossly exceed its designed tank washing capacity. In addition, a ''neighborhood assignment'' constraint has been added to the model, which requires tank wash stations to be assigned to wash tanks at the station to minimize the void sailing costs incurred by the ship. As this type of assignment is more consistent with the ship's interests, it is more likely to be considered by the majority of ships when selecting a tank washing station, making the model's estimate of the number of tank washing services performed by a tank washing station in the course of its operation more accurate and thus more accurately measuring the utilization of the tank washing station's facilities for the purpose of target optimization. Taking the Pearl River Delta (PRD) region as an example, this paper applies the tank washing station location model and uses the Nondominated Sorting Genetic Algorithm with Elite Strategies (NSGA-II) to determine the Pareto optimal solution, verifying the feasibility and efficacy of the model.

II. METHOD AND MODEL

A. TANK WASHING DEMAND

The International Convention for the Prevention of Pollution from Ships (MARPOL), established by the International Maritime Organization in 1973, sets standards for when ships must conduct tank washing and the associated requirements for such operations. These standards have been refined and implemented in the member countries of the Convention [22]. The Convention classifies cargoes carried by ships into four categories, X, Y, Z, and OS, based on their potential harm to the marine environment and human health. Ships carrying substances of category X or highly viscous or coagulable substances of category Y must undergo mandatory prewashing. This means that ships must perform the tank washing operation either at the port of discharge or at the next port of destination after providing written consent. The Convention outlines the conditions for exemption from mandatory prewashing. This exemption may be granted with the consent of the cargo owner if the cargo to be loaded is the same as or compatible with the cargo to be discharged. Additionally, the ship must have implemented a ventilation procedure in compliance with the code that serves as an alternative to tank washing.

The ship tank washing demand is typically generated when a ship changes incompatible cargoes or when the purity requirements of the cargoes to be carried on the next voyage change. Obtaining relevant data for tank washing demand and its distribution within the region is a prerequisite for selecting the location of the tank washing station. To ensure that the tank washing station location model's objective function is accurate, comprehensive tank washing demand data that reflect the demand generated by ships in the region are needed. These data should include the distribution of different ports and terminals rather than relying solely on the statistics from the Maritime Safety Administration or ports. These statistics may be unreliable because they may not include all tank washing operations [18]. Furthermore, the cost of void sailing to the same tank washing station varies among ships depending on the next destination of the vessel after the completion of the tank washing operation. As a result, the demand for tank washing generated at the same terminal during different voyages of different ships results in varying void sailing costs. It is necessary to differentiate between the costs of different ships.

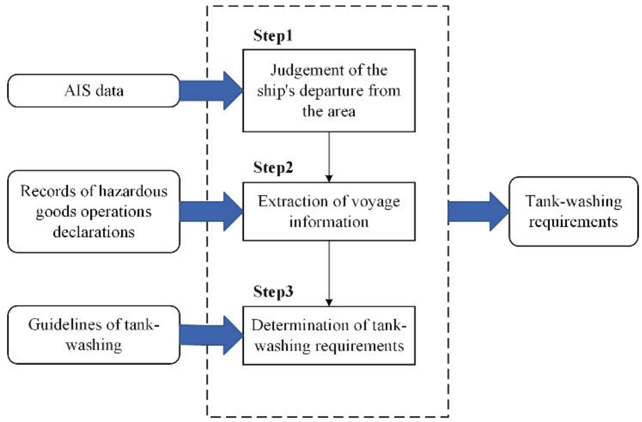

FIGURE 1. Methodology for identifying ship tank washing demand.

To achieve this goal, this paper considers the tank washing demand of the same ship between voyages as separate demand points. The vessel voyage data are extracted, and the tank washing demand is identified using a method based on dangerous goods declaration records and vessel AIS data from existing studies [23]. The method is based on the chemical compatibility guidelines developed by the U.S. Coast Guard (USCG) and the established tank washing regulations for inland waterway vessels in the Yangtze River region. It combines the vessel's voyage information to determine whether the vessel needs to perform tank washing between adjacent voyages [24]. Figure 1 shows the flowchart of the method. The data identifying the need for tank washing can be distinguished across different voyages of various ships. If ship i completes K_i voyages during the study period, the tank washing demand generated by its kth voyage is defined as $D_{i,k}$. When the incompatible cargo types generating tank washing demand between adjacent voyages are known, $D_{i,k}$ will be 1, indicating that the ship needs to perform a tank washing operation at that time. If the ship leaves the study area after completing the voyage or if it is the last voyage in the study time period, it is unclear whether the ship needs to undergo tank washing at this time due to the lack of cargo type information. Therefore, $D_{i,k}$ will be expressed as a probability less than one.

B. VOID SAILING COST

The void sailing cost to a tank washing station at the end of a trip should be calculated as the difference between the distance traveled to and from the tank washing station and the original route. This value reflects the additional distance the ship must travel to reach the tank washing station. According to Equation 1, if the target tank washing station is closer to or at the same distance as the ship's next destination, the void sailing cost will be lower or even zero. This is because the ship will not have to travel a longer distance than the original route to reach the tank washing station for the tank washing operation. In the cases where the ship has sailed away from the study area after completing the voyage, the void sailing cost is determined by the distance traveled directly to the tank washing station at the end of the voyage. This is because the location of the ship's next mooring is unknown.

$$d_{i,k,s} = \begin{cases} \mathrm{ld}_{k,s} + \mathrm{fd}_{k+1,s} - \mathrm{vd}_{k,k+1}, & D_{i,k} = 1 \\ \mathrm{ld}_{k,s}, & D_{i,k} \neq 1 \end{cases} \tag{1}$$

The void sailing cost of ship i to tank washing station s after the end of its k-th voyage is represented by $d_{i,k,s}$. The distances between the first and last berthing terminals of the k-th voyage of ship i and the tank washing station s are represented by $\mathrm{fd}_{k,s}$ and $\mathrm{ld}_{k,s}$, respectively. $\mathrm{vd}_{k,k+1}$ represents the distance between the last berthing terminal of the k-th voyage of ship i and the first berthing terminal of its $k+1$-th voyage. Figure 2 provides a graphical representation of these variables.

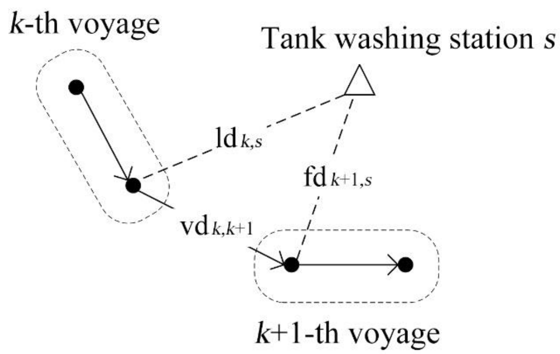

FIGURE 2. **Void sailing cost.**

C. SITE SELECTION MODEL

The mathematical model of the P-median problem aims to identify appropriate locations for P facilities and assign each demand point to a specific facility to minimize transportation costs or distances. The objective function of this problem considers not only the distance or transportation cost between the facility and the demand point but also the demand size at each point as a weight. The location of the facility and the assignment of demand points must consider the special requirements and importance of each demand point. To solve the median P problem, a common strategy is to use the neighborhood assignment principle, which selects the closest facility to each demand point to meet its demand. While this strategy may be simple and easy to implement, it may not always be the optimal solution due to various factors that can affect transportation costs or distance, such as road conditions, traffic flow, and terrain. To minimize total transportation costs, it may be necessary to optimize the location of facilities and the assignment of demand points through more complex methods. Consequently, although the principle of neighborhood allocation facilitates the achievement of the objective of minimizing transport costs or distances under the P-median problem, it is not included as one of the constraints in the model of the P-median problem.

However, in comparison to the classical P-median problem, siting a tank washing station presents two additional features:

· Shipowners typically prioritize their own interests when selecting stations for tank washing services, often opting for stations that are closer and more convenient. Therefore, it is important to fully consider their needs during the site selection and planning stage to ensure that the completed tank washing stations are utilized effectively.

· Assigning uniform tank washing schedules to all ships is difficult and impractical. Ships have different routes and schedules, making unified scheduling and management challenging. Additionally, the need for tank washing varies depending on the ship type, route, and cargo, making it difficult to establish a standard assignment.

Considering the first feature, this paper aims to minimize the total void sailing cost of a ship by developing a site selection model within the framework of the P-median model. The objective is to find a site selection scheme that maximizes a ship's willingness to perform tank washing and meets the regional tank washing demand. Considering the second feature, this paper introduces an additional constraint into the site selection model. Specifically, the ship must be assigned to the tank washing station that minimizes its void sailing cost. With this constraint, the site selection model no longer needs to assign the demand point, as the ship at the demand point will be assigned to a fixed facility point to complete the service.

However, the constraint on facility capacity may conflict with this constraint, resulting in a siting problem without a feasible solution. In the case of unconstrained facility capacity, a perfect solution would be to establish tank washing stations at all terminals and determine the designed tank washing capacity of each station based on the demand generated at each terminal. However, this option is unrealistic because the size of the tank washing station is determined by the number of berths at the terminal, the scale size, the tonnage of ships allowed to dock, and the sewage treatment capacity, among other facility conditions. It is important to consider these factors when determining the appropriate tank washing capacity. Facility conditions determine the feasibility and effectiveness of a site selection program. It is crucial to thoroughly investigate and understand these conditions before beginning the site selection process. Therefore, to address the siting problem while adhering to established facility capacity planning requirements, the degree to which the decision variables contravene facility capacity constraints, the gap between the amount of tank washing service to be provided by a tank washing station and its designed tank washing capacity is considered as the second minimization objective of the siting model in this paper.

With the objective of finding Pareto frontier solutions that enable ships to obtain tank washing services at a lower void sailing cost and make the facility loads at each tank

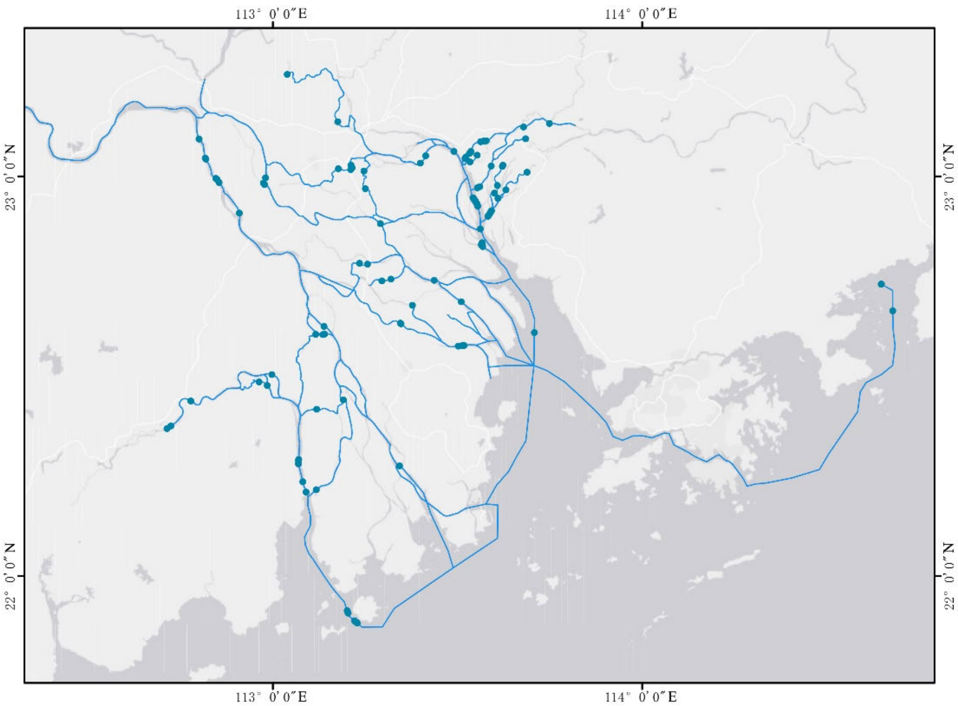

FIGURE 3. Distribution of terminals.

washing station as close as possible to the service capacity of the facility for which it is designed, the siting model is a two-objective optimization problem. It is predicated on a number of underlying assumptions, which are outlined below.

1. All of the ship's tank washing requirements are generated at the quay after unloading, and the generated amount and the location of the ship are known.

2. Each tank washing service of a ship is provided by only one tank washing station, and the ship will choose the tank washing station that minimizes the void sailing cost incurred by itself.

3. The number of tank washing stations is fixed, and their candidate locations are known.

4. The void sailing cost for a ship to travel to a tank washing station is equal to the difference between the distance traveled by the ship under this behavior and the distance traveled by the ship on its original route.

The mathematical model for the tank washing station siting problem is presented below:

$$\min \sum_{s\in S} \sum_{i\in I} \sum_{k=1}^{K_i} y_{i,k,s} D_{i,k} d_{i,k,s} \tag{2}$$

$$\min \sum_{s\in S} \frac{x_s}{q_s} \left| q_s - \sum_{i\in I} \sum_{k=1}^{K_i} y_{i,k,s} D_{i,k} \right| \tag{3}$$

$$\sum_{s\in S} y_{i,k,s} = 1 \, (i \in I, k = 1, 2, \cdots\cdots, K_i) \tag{4}$$

$$\sum_{s\in S} x_s = p \tag{5}$$

$$y_{i,k,s} \le x_s \, (i \in I, k = 1, 2, \cdots\cdots, K_i, s \in S) \tag{6}$$

$$\sum_{s\in S} y_{i,k,s} d_{i,k,s} = \min \left\{ d_{i,k,s} \,|s \in S \right\} \quad (i \in I, k = 1, 2, \cdots\cdots, K_i) \tag{7}$$

$$x_s \in \{0, 1\} \, (s \in S) \tag{8}$$

$$y_{i,k,s} \in \{0, 1\} \, (i \in I, k = 1, 2, \cdots\cdots, K_i, s \in S) \tag{9}$$

Here, S represents the set of candidate tank washing stations, while I represents the set of all ships. $y_{i,k,s}$ indicates whether ship i will go to tank washing station s to fulfill its tank washing demand at the end of its k-th voyage. If yes, $y_{i,k,s}$ is 1; otherwise, it is 0. $D_{i,k}$ represents the tank washing demand generated by ship i at the end of its k-th voyage, and K_i represents the number of voyages generated by ship i. $d_{i,k,s}$ refers to the distance that ship i travels to reach tank washing station s at the end of its kth voyage. The variable x_s indicates whether the tank washing station is constructed at the candidate tank washing station s. If it is constructed at s, x_s is equal to 1; otherwise, it is equal to 0. q_s represents the design annual tank washing capacity of the tank washing station constructed at s, and p represents the number of the tank washing stations to be sited.

The model employs several constraints to optimize the tank washing station allocation. Constraint 4 guarantees that each demand point is met by a tank washing station, while constraint 5 limits the total number of tank washing stations

TABLE 1. Statistics on ship tank washing demand.

Data	Value
Number of cargo type changes (times)	842
demands for tank washing (times)	460

to p. Constraint 6 ensures that each demand point is not met by a station without a tank washing station, and constraint 7 ensures that each demand point is met by a station that minimizes the void sailing cost. The two objective functions aim to minimize the void sailing cost and the deviation of facility loading at the tank washing stations.

III. CASE STUDY

A. RESEARCH DATA

This study focuses on the PRD region, including the PRD region and some of its neighboring areas. The PRD region has a well-developed water system and excellent shipping conditions, with many river and ocean-going vessels engaged in domestic and foreign trade. The demand for petrochemical product loading and unloading operations at the ports of the PRD region has been increasing due to the expansion of the energy, chemical, and pharmaceutical industries. This has led to an increased demand for tank washing in the transportation of petrochemical products due to the changes in the cargo type and other reasons. Currently, the PRD region lacks tank washing stations, and some inland waterway terminals have inadequate capacity to receive and treat pollutants from ships [25], [26]. Ships typically hire third-party cleaning services to wash their cabins at the wharf, hindering the standardization of regulations for tank washing and wastewater treatment. This also results in inadequate supervision by the Maritime Safety Administration and port authorities. The construction of a tank washing station can ensure that the tank washing demands of the ships in the region are satisfied in a timely manner. In the long run, this approach can further guarantee the transportation safety of hazardous chemical ships and reduce the pollution of oceans or inland water sources due to unknown destinations of tank-washing water or improper treatment.

The aim of this case study is to offer a solution for siting tank washing stations in the PRD region that reduces both the total void sailing cost and the burden on the tank washing station facility. The objective function's decision variables in the siting model include the tank washing demand and void sailing cost. These variables were obtained by processing data from the voyage records of the ships in the study area between January 1, 2018, and March 31, 2018. The tank washing demand was generated by cargo types that changed between voyages. This work has been performed in related studies [23]. Table 1 shows that the tank washing demand represented approximately 7.4% of the recorded ship operations in the study area during the specified time period. To distinguish the tank washing demand of ships at various terminals and calculate the void sailing cost to travel to tank washing stations, this paper utilizes terminal names and coordinate information from Chinaports.com. Additionally, satellite remote sensing images were compared to calibrate the locations of 79 terminals in 18 port areas within the study area. The distribution of these terminals in the PRD waterway network is shown in Figure 3. The calculation of the void sailing cost involves measuring the distance between two points. This distance is determined as the length of the shortest path for a ship traveling between these two points in the fairway network. The shortest path is determined using the Dijkstra algorithm. Dijkstra's algorithm is a breadth-first algorithm that divides all of the points in the network into two sets: labeled and unlabeled points. It starts from the starting point and, based on the greedy strategy, searches for the point with the shortest path distance from the starting point in the set of unlabeled points. It then labels that point until all of the points are labeled or stops with the end point labeled when the starting and ending points of the route are clear. Dijkstra's algorithm is an efficient and easy-to-implement solution for finding the shortest path in a sparse channel network graph with no negatively weighted edges.

B. RESULTS

Based on the operation of existing tank washing stations, this paper establishes that the annual tank washing capacity of a tank washing station is 400 times per year. Therefore, the designed tank washing capacity should be 100 times for a quarter time period. The ships generated a total tank washing demand of 460 times in one quarter. To minimize the number of tank washing stations while meeting demand, the number of tank washing stations should be set to five. To solve the tank washing station siting problem under these parameters, this paper uses the NSGA-II algorithm. A multiobjective optimization problem should have a series of optimal solutions and often requires the use of heuristic algorithms, such as genetic algorithms, to solve it because its solution space is usually large [27]. The Nondominated Sorting Genetic Algorithm (NSGA) is a genetic algorithm designed based on the concept of Pareto optimality for solving this type of problem. Compared to general GA, the NSGA incorporates a stratification operation based on the dominance relationship between individuals prior to executing the selection operator. This allows superior individuals to have a greater likelihood of being inherited by the next generation. NSGA-II introduces an elite strategy to ensure that satisfactory solutions are not lost and to improve solution quality while reducing algorithm time complexity [28]. This allows the algorithm to be used in various problem scenarios [29]. Figures 4 and 5 show the variation in the evaluation metrics of hypervolume (HV) and spacing (Spacing) during the solution process of this paper using the NSGA-II under the settings of a population size of 50 and number of iterations of 100. The HV metric measures the size of the region dominated by the set of nondominated solutions. A larger HV indicates better comprehensive performance of the algorithm. The spacing metric measures the smallest distance from each solution to the others of the standard deviation. A smaller spacing indicates a more homogeneous solution set.

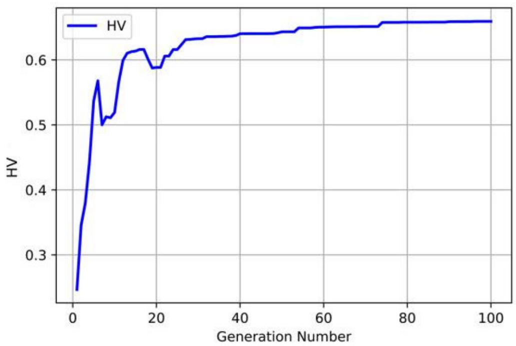

FIGURE 4. HV trace plot.

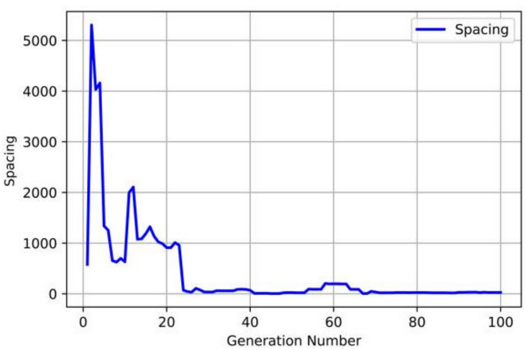

FIGURE 5. Spacing trace plot.

The solutions on the Pareto frontier obtained using this algorithm for the siting problem in this case are displayed in Figure 6. To facilitate the interpretation of these solutions, they are clustered using hierarchical clustering (HC). The cluster spacing is defined as the average of the distances of the points within the cluster, while the point spacing is defined as the Euclidean distance between two points after the coordinate normalization process. After clustering with a threshold value of 0.5 for cluster spacing, these solutions can be classified into three groups. Group A's siting solution can achieve a lower average void sailing cost (total void sailing cost/total tank washing demand), indicating a greater willingness of the ship to complete the tank washing operation. However, the average difference between a tank washing station's requirement to provide the tank washing service and its designed tank washing capacity exceeds 20%. This suggests that some tank washing stations may experience a certain degree of overload beyond their design service capacity or that some berths may remain idle. In contrast to Group A and Group B, Group C solutions successfully maintain the facility load deviation of the tank washing stations at less than 10% but result in higher average void sailing costs. For Group C, the average void sailing cost is 31.5 km. This means that, on average, the ship must travel more than 30 additional km for each tank washing operation to reach the tank washing station. Group B has a lower average facility load deviation (below 20%) and average void sailing cost (below 17 km), which is more consistent with the objectives of this study.

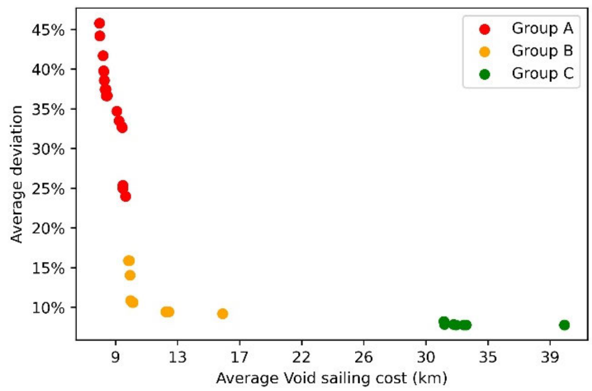

FIGURE 6. Pareto frontier solution.

Table 2 presents the mean statistics for facility load deviation and void sailing cost across all samples in the three group solutions. In comparison to the Group B solution, the Group A solution did not significantly reduce the average void sailing cost by placing the tank washing stations closer to the terminals where a larger portion of the tank washing demand is generated. However, this approach did result in a higher facility loading deviation for each tank washing station. On the other hand, the Group C solution was designed to reduce the facility loading deviation of the tank washing stations by distributing them more evenly, but this resulted in a much higher average void sailing cost for the ships traveling to each tank washing station. The mean cost of sailing without cargo to each tank washing station is significantly higher. In this case, the sum of the designed tank washing capacity of each washing station slightly exceeds the regional tank washing demand, resulting in an imbalance between supply and demand. As a result, the average deviation of the facility loading can only reach a minimum value of 8% in the best case. Some samples in Group B have an average deviation of the facility loading that is close enough to reach this value.

Specifically, siting schemes for all solutions in Group B include terminals in the four locations shown in Figure 7, and the siting schemes for solutions in Group A and Group C also include multiple terminals at these four locations. Location p_1 is the location of Huizhou Port, location p_2 is in the Lisha Island operation area of Dongguan Port, location p_3 is in Jiangmen Port, and location p_4 is in Gaolan Port of Zhuhai.

TABLE 2. Statistics for the set of solutions.

Group	Facility load deviation	Average void sailing cost
A	35.4%	8.4 km
B	11.8%	11.4 km
C	8.1%	33.5 km

p_1, p_2 and p_4 are the clusters of large petrochemical terminals, so that most of the tank washing demand in the PRD region will be generated at the terminals in this location; p_3 is located in the mainstream region of the Pearl River Basin, the Xijiang River, downstream of the Pearl River Basin, which is one of the locations that ships frequently pass through when going out to sea or entering the mainstream of the Xijiang River. In fact, the petrochemical terminals in these four locations all belong to the same port area or port, and selecting different terminals in each location does not lead to a significant change in the target value of the location model. Therefore, ideally the construction of tank washing stations should be planned at these four locations, and factors such as the infrastructure conditions of each terminal and the construction cost should be further considered when selecting the specific location of the tank washing stations; this which will ensure that the final location selection of the tank washing stations meets the requirements of the actual situation and will be implemented effectively.

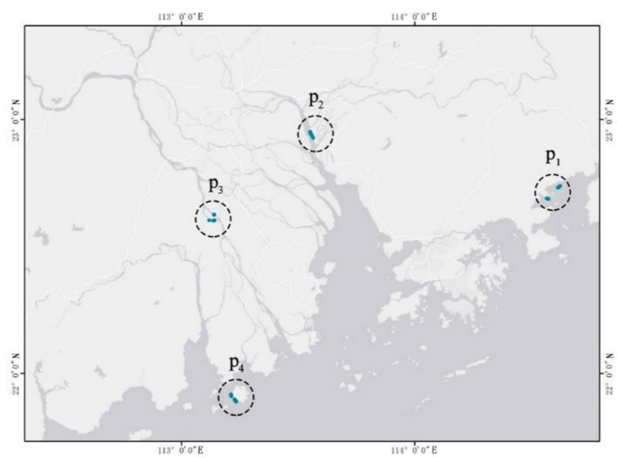

FIGURE 7. The most frequent locations in the solution set.

C. RESULTS COMPARISON

The P-median model was employed to analyze the case, resulting in a site selection solution with an average facility load deviation of 8% for the tank washing station and an average void sailing cost of 28.5 km. Compared with this result, the biobjective optimization model proposed in this paper can find more Pareto frontier solutions, as shown in Figure 8. As mentioned above, Group B solutions have lower facility load deviations, and for majority of these solutions, the average void sailing cost can reach less than half of the corresponding values of the solutions of the P-median model. This suggests that the biobjective optimization model can provide site selection decision-makers with more site selection options that are more consistent with the interests of the ship and do not violate the limitations on the size of the tank washing station that can be constructed at each location rather than having only a single site selection option.

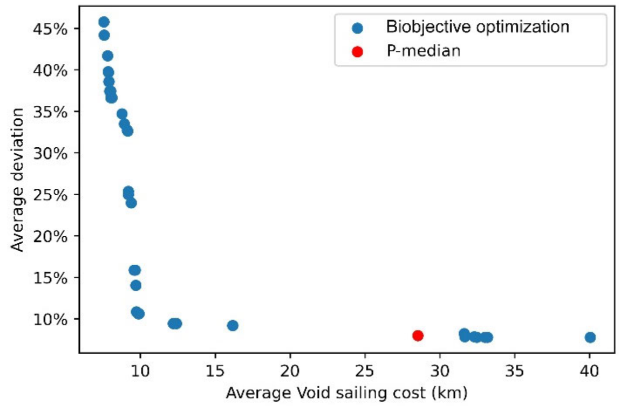

FIGURE 8. Result comparison.

Figure 9 presents a comparison between the facility distribution locations of a Group B solution and the results of the P-median model. The corresponding values of the average facility load deviation and the average void sailing cost are shown in Table 3. Figure 9 shows that the two models have the same site locations at Gaolan Port of Zhuhai and Huizhou Port, while the distributions of the other three locations differ.

TABLE 3. Statistics on the result comparison.

Model	Facility load deviation	Average void sailing cost
P-median	8%	28.5 km
Biobjective optimization	9.4%	12.5 km

D. SENSITIVITY ANALYSIS

In this paper, the additional distance that the ship must travel to a tank washing station is considered as the void sailing cost, and for all ships the cost is measured using this distance; however, this may not fully reflect the actual situation. Since the engine power of a large ship is much greater than that of a small ship, a large ship will use more fuel to travel the same distance, and the cost to the shipowner will be greater. A more reasonable approach would be to consider the tonnage of the vessel and assign a larger coefficient to the void sailing cost of a larger tonnage vessel. Specifically, the model's objective function for minimizing void sailing costs can be adjusted as follows:

$$\min \sum_{s \in S} \sum_{i \in I} \sum_{k=1}^{K_i} y_{i,k,s} D_{i,k} d_{i,k,s} g_i \tag{10}$$

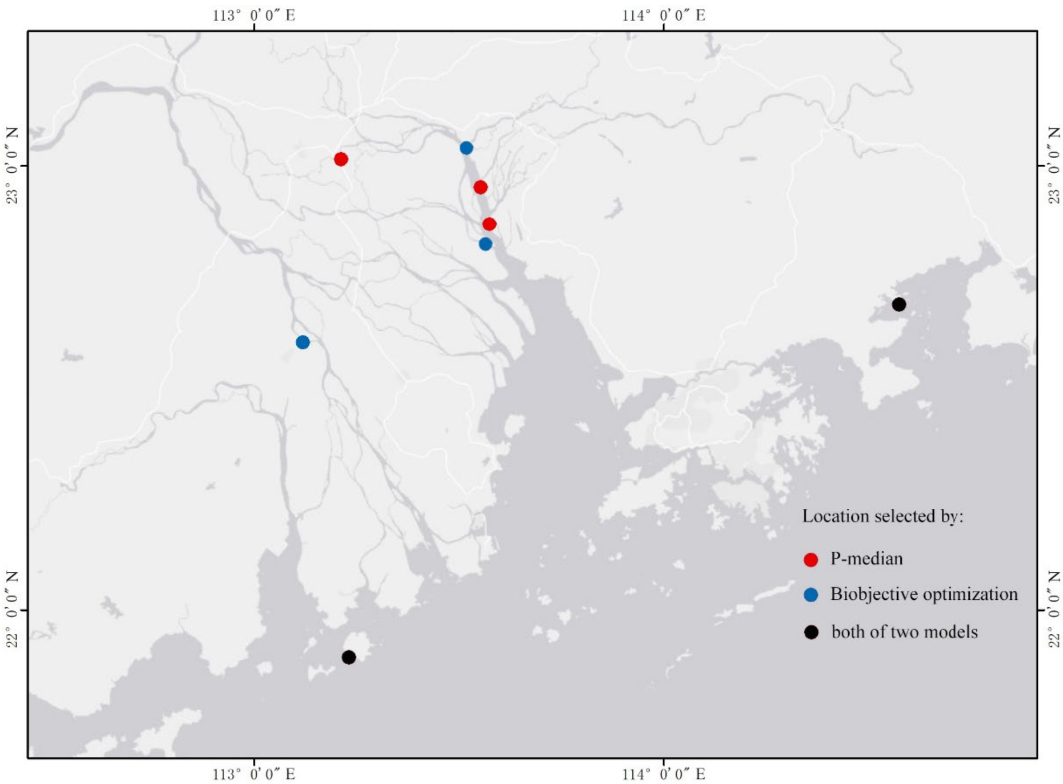

FIGURE 9. Comparison of site locations.

TABLE 4. Values of the tonnage factor for ships of different tonnages.

Gross tonnage of ship (t)	Value
(0,1000]	0.5
(1000,3000]	1
(3000,10000]	1.5
(10000,+∞)	2

where g_i is the tonnage coefficient of ship i, the values of which are given in the table below:

In addition, a situation where the ship receives the tank washing service at the terminal of discharge or at the next terminal of destination is the most desirable situation for both the ship and the port, as in this case, the ship no longer must travel to a third terminal. Voyages to a third terminal not only create additional idling distance for the ship but also require more time and manpower for the ship to make declarations at the third terminal and coordinate the berthing of the ship, which should be taken into account in the void sailing costs. To achieve this, a fixed cost coefficient must be added to the objective function of minimizing the void sailing cost in the model, which takes into account the additional operating cost of the ship to complete the tank washing process at the third terminal, as shown in the following equation:

$$\min \sum_{s \in S} \sum_{i \in I} \sum_{k=1}^{K_i} y_{i,k,s} D_{i,k} d_{i,k,s} + t_{i,k,s} C \tag{11}$$

C is a fixed value, and its value should depend on the situation of the ship; here, it is taken as 10. $t_{i,k,s}$ indicates whether the tank washing station s to which ship i moves after its kth voyage is located in the unloading terminal of its kth voyage or in the starting terminal of its $k+1$th voyage; if this occurs, then it is taken as 0; otherwise, it is taken as 1.

After adjusting the objective function according to the above two types of adjustments, the location model is solved, and the results are shown in Figure 10.

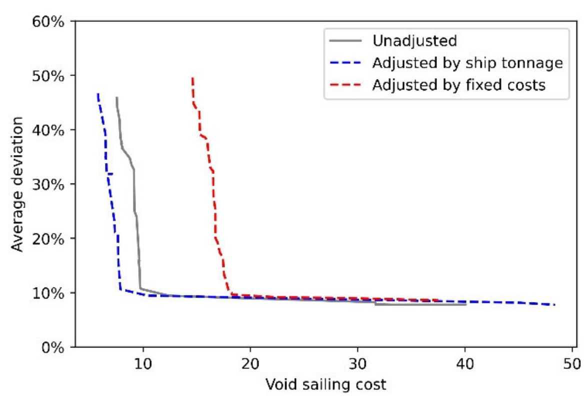

FIGURE 10. Sensitivity analysis results.

It is observed that following the adjustment based on the tonnage of the ship, the shape of the Pareto front solution has not changed significantly, but the overall direction of the void sailing cost is shifted to a smaller direction. This is because the cargo holds of large ships are larger and contain more cargo than those of small ships, and it more time is required to complete the tank washing operation after cargo exchange. Therefore, the ship owner prefers to carry a fixed type of cargo or fewer types of compatible cargo to avoid the possible need for tank washing, and the tank washing demand generated by ships accounts for a smaller proportion of the total tank washing demand in the region. After adjusting for fixed costs, the shape of the Pareto frontier solutions remained largely unchanged. However, the average sailing costs for the entire solution set increased slightly by less than the value specified in Equation 9. This suggests that there are still many cases where ships do not complete tank washing at the discharge terminal or the next destination terminal unless more tank washing stations are provided. However, $t_{i,k,s}$ in Equation 9 is differentiated by different terminals, and in fact, there may be no additional operating cost for a ship to complete berthing and deberthing between different terminals in the same port because the ship can apply to the same port management and complete berthing and deberthing operations within the port. Therefore, Equation 9 can further consider the differentiation of $t_{i,k,s}$ at the scale of the port instead of the terminal.

IV. CONCLUSION AND DISCUSSION

With the continuous development of the shipping industry, the demand for the transportation of dangerous goods is increasing, and the importance of tank washing as a key step in ensuring the safe transportation of dangerous goods cannot be ignored. The construction of a tank washing station is an important measure to meet the demand for tank washing in the region and solve the problem of receiving tank-washing wastewater from ships, so that the planning and site selection of a tank washing station must be carried out. The location of the tank washing station should fully consider the tank washing demand and the void sailing cost of ships to improve the availability of the tank washing service and the utilization rate of the facilities of the tank washing station. Due to the requirements of basic conditions such as sewage facilities, the layout of tank washing stations should be based on the distribution of petrochemical terminals in the region. The willingness of ships to wash tanks is also essential because it determines the utilization rate of the tank-washing stations and the practical capability to enforce the relevant tank washing regulations; the latter is an important part of ensuring the effective implementation of tank washing operations and regulating the discharge of tank-washing wastewater.

To this end, this paper proposes a biobjective site selection model based on the classical P-median problem. The model aims to minimize the void sailing cost of ships while ensuring that the loading deviation of the tank washing station is minimized to improve the utilization of the tank washing station. By distinguishing the tank washing demand of different ships on different voyages and their corresponding void sailing costs to different tank washing stations, by taking into account the "neighborhood allocation" constraint in terms of void sailing costs, and by minimizing the total void sailing cost of the ship and the facility loading of the tank washing station, the model can provide a more realistic estimate of the number of tank washings to be provided by each tank washing station. By minimizing the total void sailing cost of the ship and the deviation of the facility load of the tank wash, the model can optimize the siting plan that is more consistent with the interest of the ship's owner based on a more balanced approach that is more consistent with the construction conditions of each siting point.

To assess the practical applicability and reliability of the proposed model, this study employs a biobjective optimization framework to identify a set of Pareto-optimal solutions for locating tank washing stations across 79 terminals distributed in 18 port districts within the PRD region. This analysis is based on quarterly data for the ship tank washing demand in the specified area. Among the solutions obtained, a subset exhibiting superior performance has an average void sailing cost of 11.4 km for ships, while the average utilization rate of tank washing stations is 11.8%, which is near the 8% threshold of the optimal solution. Additionally, a sensitivity analysis is conducted to investigate the impact of varying void sailing costs based on ship tonnage and incremental costs incurred by the vessels traveling to a third terminal for tank washing. This analysis reveals that adjustments in these factors lead to a corresponding decrease or increase in the total void sailing cost calculated by the model. The obtained results can support the planning and location of tank washing stations in the PRD region and provide useful reference information for the location of washing stations in other regions. Consequently, this research offers some management suggestions for the siting and planning of tank washing stations based on these results.

First, positioning the tank washing station at a cluster of petrochemical terminals or at a strategic intersection within the canal network presents numerous benefits that significantly enhance its operational efficiency and reduce costs for shipping companies. This placement enables a vast majority of ships to conduct their tank washing operations locally, immediately after discharging their cargo at the port of destination. This eliminates the need for the ships to travel long distances to remote tank washing facilities, thus saving significant time and fuel. Moreover, by locating the tank washing station closer to the original voyage routes, ships can minimize the void sailing time, which is the time period when a ship is traveling without cargo. Reducing the void sailing time not only saves fuel costs but also improves the overall efficiency of the shipping fleet. This, in turn, leads to reduced emissions and more environmentally sustainable operation. This suggests that siting the tank washing station at these locations is a feasible and reasonable location strategy.

Second, it is recommended that the location of tank washing stations be considered from the perspective of the ship's interests, as they represent a kind of public facility. This should be given primary consideration in the construction planning stage to meet the requirements of ships for washing tanks. Since ships are continuously on different voyages, focusing on the void sailing costs incurred by travel to tank washing stations between voyages is an approach to consider the interests of ships in a morespecific manner compared to simply considering the sailing distance.

Third, given the multiplicity of objectives involved in the siting of a ship's tank washing station, a series of Pareto-optimal solutions can be identified by applying a multiobjective optimization model. It is recommended that management implement a comprehensive assessment system to quantify the impact of different siting options on the total cost, facility utilization and service quality. This will enable the management to make informed decisions about the relative importance of the different objectives, ensuring that the decision meets both the economic efficiency and the sustainability requirements of the facility's services.

The problem of siting tank washing stations can be approached from various perspectives, and this paper aims to provide a solution that considers the interests of the ship. However, further optimization and research are necessary to address the following points:

· Distinguishing between the need for tank washing and the cost of void sailing at the ship voyage scale results in a large number of decision variables for the siting model. The complexity of the problem stems from the sheer number of decision variables required to differentiate between tank washing needs and the cost of void sailing based on the ship's voyage scale. This complexity can be mitigated by exploring heuristic algorithms that offer higher efficiency in handling large-scale problems. Such algorithms would be particularly useful in adapting the siting model to more complex scenarios involving larger quantities of planning units. If algorithms with sufficient performance for solving complex siting problems are available, further consideration can be given to adding planning for the number of tank washing stations to the model for processing.

· This paper assumes that a ship chooses the tank washing station with the lowest void sailing cost for tank washing. However, limitations on the tonnage of ships that can call at the berths in the marina and the draught restrictions on channel access may prevent some large-tonnage ships from reaching certain locations. To address this, the model can be enhanced by incorporating the data for the ship docking and navigation restrictions, which can then be incorporated as constraints within the model to produce more reliable and feasible results.

· Ships may choose to change cargo types more frequently following an increase in the availability of tank washing services at the discharge port, which may in turn lead to changes in the demand for tank washing and the generation of tank-washing wastewater in the region. To consider this situation more comprehensively, future research can incorporate dynamic decisions or game modeling to further explore different outcomes. Through these models, the decisions and interactions between different stakeholders can be simulated to more accurately predict the changes in the tank washing requirements and thus further adjust the options for siting the tank washing stations.

· The site selection results of the model require further data analysis to provide management suggestions. For example, statistics for the amount and type of tank-washing wastewater generated by each tank-washing station would be beneficial. The model's requirement data include static information on cargo types and ships which can be obtained. The statistical results will also assist port authorities in obtaining a preliminary understanding of the wastewater treatment facilities available at the terminals located at the ship tank washing station sites.

REFERENCES

[1] J. Chen, "Yangtze river ship washing: Change bringing problems," *China Waterway*, vol. 618, no. 5, pp. 17–18, 2019, doi: 10.13646/j.cnki.42-1395/u.2019.05.005.

[2] Guangdong Maritime Safety Administraion of the People's Republic of China. *Zhuhai Maritime Safety Bureau promotes the Rectification of the Industry of Detecting the Concentration of Wash Water on Board Ships*. Accessed: Jun. 4, 2024. [Online]. Available: https://m.thepaper.cn/baijiahao_4631391

[3] Jinshan Maritime Safety Administraion of the People's Republic of China. *Jinshan Maritime Safety Administraion Investigated and Dealt With the Case of Illegal Discharge of Wash Water From Ships*. Accessed: Jun. 4, 2024. [Online]. Available: http://www.zgsyb.com/news.html?aid=667025

[4] C. Cong and X. Wang, "Ozone-aerated biofilter for treatment of harbour chemical tank washing wastewater," *Environ. Sci. Technol.*, vol. 32, no. 10, pp. 141–144, 2009, doi: 10.3969/j.issn.1003-6504.2009.10.033.

[5] C. Liu and R.-C. Chen, "Research on pollution prevention and control of tank washing water," in *Proc. 6th Int. Conf. Transp. Inf. Saf. (ICTIS)*, Wuhan, China, Oct. 2021, pp. 1–4.

[6] D. Zhang, "Thoughts on the status quo and development countermeasures of tank washing stations for bulk liquid dangerous chemical tanks on the Yangtze river main line," in *Proc. Int. Conf. Frontier Comput., Theory, Technol. Appl.*, Singapore, 2020, pp. 1–9.

[7] H. Lin, B. Li, and P. Xu, "Study on location allocation of tank-cleaning station for transportation vessels along Yangtze river main stream based on linear system concept," *Logistics Technol.*, vol. 36, no. 6, pp. 112–115, 2017, doi: 10.3969/j.issn.1005-152X.2017.06.026.

[8] J. Xue, C. Chen, X. Zhang, and Y. Wang, "Analysis of the operation of the Nantong wash station and suggestions for its promotion and application," in *Proc. Annu. Conf. Maritime Manage. Inland Waterway Maritime Committee China Nautical Soc.*, Chongqing, China, 2023, pp. 69–72.

[9] *Guidelines for the Design of Inland River Tank Washing Station Wharf, JTS/T 173-2019*, Ministry Transp. People's Republic China, China, 2019.

[10] M. L. Brandeau and S. S. Chiu, "An overview of representative problems in location research," *Manage. Sci.*, vol. 35, no. 6, pp. 645–674, Jun. 1989, doi: 10.1287/mnsc.35.6.645.

[11] S. L. Hakimi, "Optimum locations of switching centers and the absolute centers and medians of a graph," *Operations Res.*, vol. 12, no. 3, pp. 450–459, Jun. 1964, doi: 10.1287/opre.12.3.450.

[12] R. L. Church and C. S. ReVelle, "Theoretical and computational links between the p-median, location set-covering, and the maximal covering location problem," *Geographical Anal.*, vol. 8, no. 4, pp. 406–415, Oct. 1976, doi: 10.1111/j.1538-4632.1976.tb00547.x.

[13] *International Convention for the Prevention of Pollution from Ships*, MARPOL, International Maritime Org., London, U.K., 1973.

[14] Y. Xu, K. Zhu, and H. Zhong, "Estimation method of regional tank-washing wastewater quantity based on multi-source data," *Sustainability*, vol. 16, no. 1, p. 118, Dec. 2023, doi: 10.3390/su16010118.

[15] Changjiang River Administration of Navigational Affairs MOT. *Guidelines on Tank Washing for River Trade Ships Carrying Bulk Liquid Dangerous Goods on the Mainline of the Yangtze River (for Trial Implementation)*. Accessed: Jun. 4, 2024. [Online]. Available: https://cjhy.mot.gov.cn/zwgg_2890/zhjgg_2892/202308/P020230802387446421245.pdf

[16] Z. Sun, "Research on deepening treatment scheme of water pollutants from inland river ships in Guangdong province," *Transp. Energy Conservation Environ. Protection*, vol. 18, no. 5, pp. 25–30, 2022, doi: 10.3969/j.issn.1673-6478.2022.05.006.

[17] X. Wu, "Analysis of the problem of receiving, transferring and disposing of water pollutants from ships and proposals for countermeasures," *Pearl River Water Transp.*, vol. 18, no. 2, p. 36, 2020, doi: 10.14125/j.cnki.zjsy.2020.18.036.

[18] C. M. Fonseca and P. J. Fleming, "An overview of evolutionary algorithms in multiobjective optimization," *Evol. Comput.*, vol. 3, no. 1, pp. 1–16, Mar. 1995, doi: 10.1162/evco.1995.3.1.1.

[19] K. Deb, S. Agrawal, A. Pratap, and T. Meyarivan, "A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II," *IEEE Trans. Evol. Comput.*, vol. 6, no. 2, pp. 182–197, Jul. 2002, doi: 10.1007/3-540-45356-3.

[20] S. Verma, M. Pant, and V. Snasel, "A comprehensive review on NSGA-II for multi-objective combinatorial optimization problems," *IEEE Access*, vol. 9, pp. 57757–57791, 2021, doi: 10.1109/ACCESS.2021.3070634.

[21] S. Octarina, F. M. Puspita, and S. S. Supadi, "Models and heuristic algorithms for solving discrete location problems of temporary disposal places in Palembang city," *IAENG Int. J. Appl. Math.*, vol. 52, no. 2, pp. 1–11, Jun. 2022.

[22] W. Wu, Z. Cao, B. Zhang, Y. Guo, M. Du, Q. Zheng, Z. Bai, and Z. Shi, "Safe and efficient tank cleaning of liquid cargo tankers: A review," *Ships Offshore Struct.*, vol. 19, no. 2, pp. 263–281, Feb. 2024.

[23] R. Zhao, Y. Xiao, and R. Luo, "Discrete-continuous model for facility location problem with capacity-cost relation constraints," *Comput. Ind. Eng.*, vol. 185, Jul. 2023, Art. no. 109661.

[24] J. Brimberg, N. Mladenovic, and S. Salhi, "The multi-source weber problem with constant opening cost," *J. Oper. Res. Soc.*, vol. 55, no. 6, pp. 640–646, Jun. 2004.

[25] R. H. Pearce and M. Forbes, "Disaggregated benders decomposition and branch-and-cut for solving the budget-constrained dynamic uncapacitated facility location and network design problem," *Eur. J. Oper. Res.*, vol. 270, no. 1, pp. 78–88, Oct. 2018.

[26] R. Lotfi, A. Mostafaeipour, N. Mardani, and S. Mardani, "Investigation of wind farm location planning by considering budget constraints," *Int. J. Sustain. Energy*, vol. 37, no. 8, pp. 799–817, Sep. 2018.

[27] M. Albareda-Sambola, M. Landete, J. F. Monge, and J. L. Sainz-Pardo, "An exact approach for the reliable fixed-charge location problem with capacity constraints," *Eur. J. Oper. Res.*, vol. 311, no. 1, pp. 24–35, Nov. 2023.

[28] S. Mancini, M. Gansterer, and C. Triki, "Locker box location planning under uncertainty in demand and capacity availability," *Omega*, vol. 120, Oct. 2023, Art. no. 102910.

[29] Y. Zhou and G. M. Lee, "A bi-objective medical relief shelter location problem considering coverage ratios," *Int. J. Ind. Eng.*, vol. 27, no. 6, pp. 971–988, 2020.

YONG XU was born in Xiushui, Jiangxi, China, in 1967. He received the bachelor's degree in automation from Donghua University, in 1988, the master's degree in control theory and control engineering from Beijing Institute of Technology, in 1994, and the Ph.D. degree in control theory and control engineering from Beijing Institute of Technology, in 2000.

From 1988 to 1991, he was an Assistant Engineer with Jiujiang Chemical Fibre Factory, Jiangxi. From 1994 to 1997, he was an Engineer with Beijing Tianlong Electronic Engineering Company. From 2000 to 2005, he was a Senior Engineer with SunteK Technology Company Ltd. Since 2005, he has been an Associate Professor with the South China University of Technology. He has authored three books, more than 30 articles, and holds one patent and three software copyrights. His research interests include electronic payments, internet finance, fintech, and personalized recommendations.

Dr. Xu received the Third Prize of Guangdong Science and Technology Award, in 2004, the Third Prize of Science and Technology of the North Industries Group, in 2002, the First Prize of Guangzhou Science and Technology Progress Award, in 2003, the Third Prize of Guangzhou Science and Technology Progress Award, in 2002, and the Second Prize of Beijing Institute of Technology Excellent Scientific and Technological Achievements, in 2005.

KAIZE ZHU received the B.S. degree in logistics engineering from the South China University of Technology, Guangzhou, China, in 2021, where he is currently pursuing the M.S. degree in logistics engineering and management. His research interests include tank washing for dangerous goods ships and ship behavior recognition.