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A Co-Scheduling Problem of Ship Lift and Ship Lock at the Three Gorges Dam

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ABSTRACT Due to the unprecedentedly increasing demands of waterway transportation on the Yangtze River during the latest years, traffic congestion at the Three Gorges Dam (TGD) has becoming a serious problem. In busiest seasons, a vessel may need to wait up to 3 days for passing the TGD via the ship lift or the five-stage ship lock. In order to improve the navigation efficiency and the utilization of passing facilities, a co-scheduling problem of ship lift and ship lock at the TGD is modeled in this paper. Besides, the improvement on effectiveness, safety and fairness of the navigation scheduling by introducing the ship lift is taken into account. The mathematical model proposed is, by nature, a two-stage problem, where the first-stage variables determine the assignments of passing facilities and the second-stage variables schedule the vessels. In order to solve the proposed mathematical model, a hybrid metaheuristic algorithm is used at the first stage to determine the allocation of vessels to different passing facilities and to different lockage through the maximization of facility utilization rate. The second-stage problem is then solved by CPLEX. The proposed mathematical model and algorithm are validated through a set of numerical experiments and a case study. The results show both the navigation efficiency and the utilization of passing facilities can be improved by using the proposed methods.

INDEX TERMS Three Gorges Dam, scheduling, co-scheduling, metaheuristics, optimization.

I. INTRODUCTION

The Three Gorges Dam (TGD) is the largest water conservancy and hydropower project in the world [1]. The project not only plays a vital role in flood control and electricity generation, but also determines the navigation capacity of waterway transportation on the Yangtze River [2]. In recent years, due to the rapid economic development along the middle-upper reach of the Yangtze River, the needs of waterway transportation have increased unprecedentedly. As a conjunction point, which connects the upstream reservoir and the downstream waterway, the capacity limitation of the TGD has become a major bottleneck of waterway traffic on the Yangtze River. In 2011, the cargo volume passing the TGD reached more than 100 million tons and exceeded the maximum capacity of the five-stage ship locks, which was 19 years earlier than that of the original planning [3]. In 2018, the total volume passing the TGD was increased to 144 million tons, which resulted in more significant challenges in maintaining the efficiency of navigation scheduling.

Today, vessels may pass the TGD via two facilities, namely, the five-stage ship lock and the ship lift. However, due to the insufficient capacity of both passing facilities, a vessel may need to wait for a long time at the anchorage. Statistics shows the average waiting time has risen from 17 hours to 106 hours during the past seven years [4]. Furthermore, the longest waiting time may be up to 200 hours in the busiest season of waterway transportation. The delay of vessels in passing the TGD causes an average daily cost of approximately 10,000 CNY/vessel. Moreover, the large amount of waiting vessels crowed at the anchorage not only leads to negative environmental impacts, but also increases the risk of accident [5]. Hence, it is of significant importance to optimize the navigation scheduling in order to maximize the utilization of passing facilities and to minimize the delay of vessels in passing the TGD.

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One of the major challenges is lock scheduling problem, which has been considered in many researches [6]–[8]. Zhang *et al.* [9] investigated a co-evolutionary strategy to improve the lockage scheduling of the TGD. Wang *et al.* [10] proposed a data-driven method to predict the stochastic arrivals of vessels at the TGD, and the results were applied to optimize the lock scheduling problem through the minimization of total costs. The proposed method is able to calculate the theoretically maximum number of vessels passing the TGD within a given period, but the result cannot be validated with the vessel placement constraint of lock chambers. Considering the optimization of both lock scheduling and berth allocation at the TGD, Ji *et al.* [11] investigated a mixed integer linear program, and a fuzzy logic based approximation algorithm was developed for solving large problem instances. Taking into account the environmental impacts, Zhao *et al.* [5] formulated an improved optimization model, which combines both lock scheduling and vessel scheduling problems, in order to minimize the overall carbon emissions from the vessels in passing the TGD.

The Three Gorges Project is comprised of two dams, namely, the TGD and the Gezhouba Dam (GD) [12]. The two dams are 38 km apart from each other. Therefore, the co-scheduling problem of the TGD and the GD has been focused from three perspectives: (1) the maximization of throughput; (2) the minimization of waiting time; and (3) the minimization of total costs. Moreover, since the co-scheduling optimization has been proved to be NP-hard [13], [14], the development of efficient heuristics or meta-heuristics has been extensively focused [2], [15], [16]. An early research was given by Xu *et al.* [17], who developed a bi-random multi-objective decision-support model and applied a particle swarm optimization (PSO) to solve the co-scheduling problem of the two dams. Inspired by a flexible manufacturing system (FMS), Zhang *et al.* [18] formulated a mixed integer nonlinear program to optimize both lock operations and dispatch of vessels in the co-scheduling problem of the TGD and the GD. An improved hybrid simulated annealing algorithm was proposed to solve the optimization problem.

Wang *et al.* [19] proposed an optimization model for the co-scheduling problem of the two dams in the Three Gorge Project. The model aims at improving the throughput and the space utilization of lock chambers, while simultaneously minimizing the total waiting time. A series queuing network scheduling algorithm was proposed to group the vessels in passing the two dams and to give priorities in accordance with several pre-defined criteria. Zhang *et al.* [20] developed a rolling horizon procedure to improve the computational efficiency of a co-scheduling problem of the TGD and the GD. Recently, Yuan *et al.* [2] investigated a hybrid chaotic PSO and a set of heuristic-adjusted strategies in order to optimize the grouping of lockage, the dispatch of vessels, and the overall timetable. Ji *et al.* [15] proposed a multi-objective mixed integer nonlinear program for the co-scheduling problem of the TGD and the GD. The model considers the conflicting stakes of both shipping companies and administration of the two dams. An orthogonal design-based non-dominated sorting genetic algorithm III (ONSGA-III) and a heuristic-adjustment strategy were developed to solve the complex optimization problem.

One of the most significant challenges of the co-scheduling problem of the TGD and the GD is capacity imbalance of the two dams. Compared with the TGD, the GD comprises only one-stage ship locks and needs thus much less time to operate. This has caused more delays and a longer waiting time of vessels at the TGD. In order to relieve this congestion problem, the facilities for inland transshipment of cargos via road or railway have been constructed at the TGD. In this regard, Yuan *et al.* [21] formulated a co-scheduling problem for an improved decision making on water-land transshipment at the TGD. The computational results suggest that the waiting time may be reduced and the congestion problem may be relieved with a proper coordination between the two passing modes. Ji *et al.* [22] proposed a bi-objective co-scheduling problem of the two passing modes in order to minimize both waiting time and total cost of shipping companies. The model was solved by a binary Borg multi-objective evolutionary algorithm incorporating with an adaptive large neighborhood search and a multi-order best fit method. Recently, Ji *et al.* [23] investigated a bi-objective co-scheduling problem for the optimization of water-land transshipment decisions at the TGD, which was solved by a modified binary nondominated sorting genetic algorithm II (binary NSGA-II).

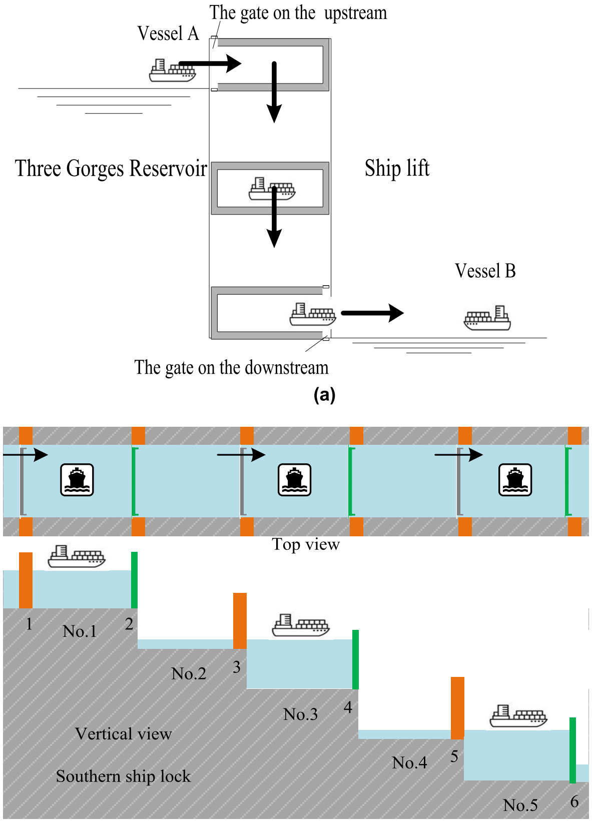
However, due to the extra costs incurred for using water-land transshipment facilities, this passing mode is currently less attractive for shipping companies [11]. Statistics reveals that the cargo volume transported via water-land transshipment facilities has declined in recent years, and the congestion problem at the TGD has not been relieved. To this end, another way to tackle the congestion problem at the TGD is to increase the navigation capacity by opening new passing facilities. In 2016, a ship lift started operations with the aims of relieving the pressure on the five-stage ship lock and of improving the overall navigation capacity. Research focuses have been given to the structural and stability analyses related to the safety issues of the ship lift [24], [25]. Studies have also been done for the emergency response in the lift chamber [26], [27]. However, to our knowledge, the co-scheduling problem of the two passing facilities has not been extensively investigated. Currently, the navigation scheduling of the ship lock and the ship lift belongs to different departments of the Three Gorge Navigation Administration and is thus planned individually. Due to this, even if the utilization of the five-stage ship lock has reached the maximum level in the busiest season, there is still a long queue of vessels waiting to pass the TGD. However, on the other hand, the capacity of the ship lift has not been fully exploited, so the improvement on the overall navigation capacity is insignificant. Therefore, this paper investigates a co-scheduling problem of ship lift and ship lock in order to better solve the congestion problem at the TGD.

Due to the high computational complexity of a scheduling or co-scheduling problem, approximation methods, especially the hybrid ones with a combination of several heuristics and metaheuristics, have become the mainstream of solving these optimization problems. In this regard, several hybrid methods have recently been developed in order to solve the complex optimization problems in a wide variety of industries. Hybrid heuristic approaches [28], as their name suggested, incorporate different heuristic strategies [29], [30] and/or exact methods [31] into the main structure of a metaheuristic in order to improve the quality of solution and, at the same time, to accelerate the convergence speed. Considering the traffic uncertainty of a multi-period network design problem, D'Andreagiovanni *et al.* [31] proposed an improved ant colony optimization (ACO) method, which incorporates with a modified relaxation induced neighborhood search, in order to find high quality solutions within a short time. Gambardella *et al.* [32] analyzed the drawbacks and suggested two directions to improve a general framework of the ACO. Zhao *et al.* [33] developed a two-stage exact method to solve large problem instances of a single-machine scheduling problem. To optimize a hospital emergency department layout problem, Zuo *et al.* [34] improved a Tabu search (TS) through the incorporation of a local search heuristic. Wang and Lu [35] proposed a memetic algorithm with competition mechanism to solve a capacitated green vehicle routing problem, where multiple operators were employed to enhance the local search. For solving an economic power dispatch optimization problem, Zhao *et al.* [36] improved the efficiency and robustness of a traditional cuckoo search algorithm by using a self-adaptive step size and a set of neighbor-study strategies. Guo *et al.* [37] proposed two scatter search algorithms with different combination operators to optimize the disassembly sequence of complex products.

In this paper, a hybrid method is developed to improve the assignments of passing facilities and the grouping of vessels to different lockage in the co-scheduling problem of the TGD. The scientific contributions that differentiate the current research from the previous ones are summarized as follows:

1) A new mixed integer program is formulated for the co-scheduling problem of ship lift and ship lock at the TGD, which aims at optimizing the vessel scheduling and the utilization of both passing facilities.
2) The model also considers the improvement of effectiveness, safety and fairness of the navigation scheduling by the introduction of the ship lift.
3) A novel hybrid method is proposed to effectively and efficiently solve the complex optimization problem.
4) Managerial implications of the co-scheduling of both ship lift and ship lock at the TGD are discussed through a set of computational experiments and a case study with practical data.

The rest of the paper is organized as follows. Section II gives the problem description. The mathematical model for the co-scheduling problem of ship lift and ship lock is formulated in section III. Section IV develops a hybrid solution method to solve the proposed model. Sections V and VI present a set of numerical experiments and a case study in order to show the effectiveness and applicability of the proposed model and solution method. Finally, section VII concludes the paper and gives further outlooks.



(a)

(b)

FIGURE 1. Operations of (a) the ship lift (b) the five-stage ship lock.

II. PROBLEM DESCRIPTION

A. THE PASSING FACILITIES AT THE TGD

Two passing facilities, namely, the ship lift and the five-stage ship lock, are used in order to overcome the 175 m water level difference between the two sides of the TGD. The ship lift, as its name suggested, is a vertical-hoisting elevator and can lift a vessel up to 3000 tons within its lift chamber to pass the TGD. This process takes approximately 40 to 60 minutes in one direction, and the lift chamber can only accommodate one vessel each time. Figure 1(a) shows the ship lift operations. First, a vessel (A) from the upstream enters the lift chamber. After disconnected with the gate on the upstream, the vessel is vertically elevated down at 0.2 m/s [38] until it reaches the same water level on the other side of the TGD. The lift chamber will be re-connected with the gate on the downstream, and the vessel will leave the lift chamber. The operation will

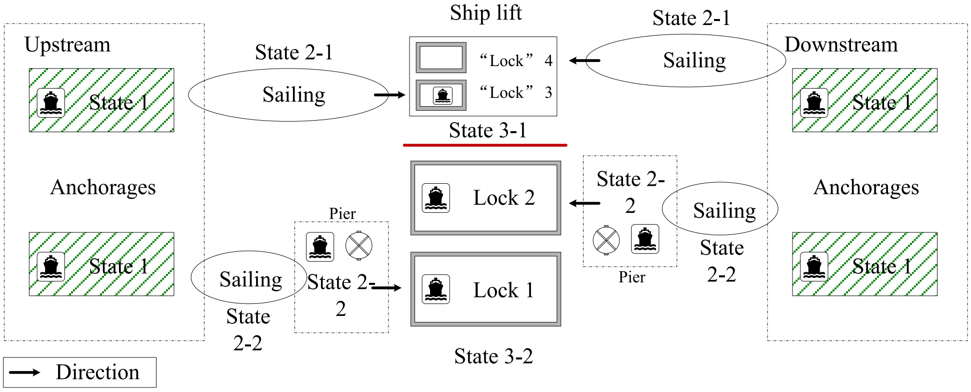


FIGURE 2. The passage procedures via both ship lift and five-stage ship lock at the TGD.

then be performed in the opposite direction in order to lift another vessel to the upstream reservoir. For safety sake, the vessel speed in this process cannot exceed 1 m/s [38] when entering or exiting the lift chamber. Sometimes, due to traffic imbalance, the ship lift operations may be adjusted accordingly. For example, performing two or several adjacent operations in the same direction. In this case, the interval between two operations is 0.5 hours.

Medium and large vessels, which are more than 3000 tons, need to use the five-stage ship lock to pass the TGD. The five-stage ship lock is a dual-track facility that enables the passage of vessels from both sides of the TGD can be performed in parallel. The southern route serves vessels from the upstream reservoir, and the northern route is for vessels from the downstream waterway. Figure 1(b) shows the operations of the ship lock, where each vessel in a lock chamber is the simplification of a group of vessels assigned to the same lockage. The vessels go through all the five lock chambers one by one in order to overcome the large water level difference. In the lockage, the maximum vessel speed for entering or exiting the ship lock is 1 m/s [38], and the maximum vessel speed for moving between two adjacent lock chambers is 0.6 m/s [38]. Compared with the ship lift, the five-stage ship lock has a larger chamber capacity that allows for more than four vessels in each group to pass the TGD. However, the lockage operations are more time consuming, which require at least 2.5 hours. Furthermore, the interval between two adjacent lockage is approximately 1.5 hours.

B. THE CO-SCHEDULING PROBLEM

With two passing facilities scheduled at the same time, the co-scheduling problem is more complex than a single lock scheduling problem. First, based on the co-scheduling rules, vessels are assigned to different passing facilities (ship lock or ship lift). After which, the sequences of vessels in passing the TGD via both facilities are determined. In this phase, the vessels assigned to the five-stage ship lock are further grouped for lockage operations. Figure 2 illustrates the passage procedures via both the ship lift and the five-stage ship lock. State 1 is the initial stage, at which vessels arrive at the anchorage and wait for the orders to pass the TGD. The vessels start the second stage (state 2) when an order is given, by which the passing facility is assigned. Then, the vessels head accordingly for respective passing facilities. When the ship lift is assigned (state 2-1), a vessel sails directly to the ship lift for the passage in state 3-1. In order to simplify the problem formulation, the ship lift is considered as a bi-directional one-stage ship lock with only one lock chamber, and it allows the passage of a vessel in one direction each time. When the vessels are assigned to the five-stage ship lock, they first sail to and queue at the pier before starting the lockage in state 3-2. Due to the capacity limitations of both passing facilities in the busiest season, a large number of vessels may need to wait for a long time in state 1. On the other hand, the queues at the pier may be due to the tardiness in states 3-1 and 3-2. In other words, the number of vessels waiting at the pier is dependent on the operational efficiency of the two passing facilities. Hence, the co-scheduling problem aims, through an improved operational planning and navigation scheduling, at maximizing the capacity utilization of both passing facilities and at minimizing the total waiting times of vessels.

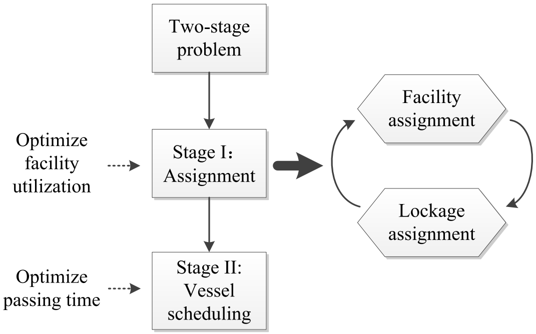


FIGURE 3. The two stages of the co-scheduling problem.

C. THE TWO-STAGE PROBLEM STRUCTURE

The co-scheduling of both ship lift and ship lock at the TGD is, by nature, a two-stage problem, as shown in Figure 3. With the aim of maximizing facility utilizations, the first-stage

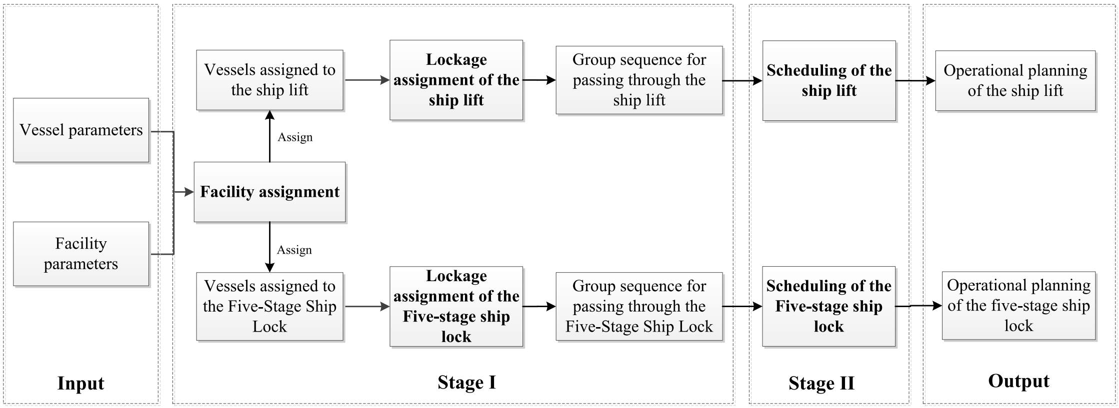


FIGURE 4. The model's structure of the co-scheduling problem.

problem determines the assignment of vessels to the two facilities, the grouping of vessels in the lockage, and the sequence of each group in passage. The second-stage problem optimizes the scheduling of each group of vessels in the passage of the TGD via both facilities in order to minimize the tardiness in states 2 and 3 and to improve the overall efficiency.

In this paper, two types of tardiness are taken into account, namely, buffer time and reaction time. Buffer time is the waiting time between the arrival of vessels at the pier or a lock chamber and the operation of the lock chamber. For example, the vessels may need to wait at the pier before the completion of operations at the first lock chamber for the previous group of vessels. In addition, buffer time also accounts for the waiting time of the vessels that enter a lock chamber earlier than the rest of the same group. Reaction time calculates the vessel movement from one lock chamber to another. In this process, the delay of one vessel may interrupt the whole group's movement and may increase total reaction time. Consequently, the buffer time of next group will also be increased.

III. MATHEMATICAL MODEL

The co-scheduling problem is formulated as a two-stage mathematical model that aims at improving the effectiveness of navigation scheduling and the utilization of passing facilities at the TGD in the busiest season. Figure 4 illustrates the two-stage structure of the model. The first-stage model determines the assignments of facilities and lockage, and the vessel scheduling is optimized in the second stage.

A. NOTATIONS

The sets, parameters, and decision variables in the mathematical model are first given as follow:

Sets:

O	Set of vessels scheduled in the given period and $\lvert O\rvert$ is the number of elements in this set.
V_1	Set of vessels assigned to the ship lift in the given period and $\lvert V_1\rvert$ is the number of elements in this set.
V_2	Set of vessels assigned to the five-stage ship lock in the given period and $\lvert V_2\rvert$ is the number of elements in this set.
K	Set of the groups of vessels assigned to the five-stage ship lock, indexed by k. $\lvert K\rvert$ is the number of elements in this set.
N	Set of the lock chambers, indexed by n.
P	Set of the groups of vessels assigned the ship lift, indexed by p. $\lvert P\rvert$ is the number of elements in this set.

Parameters:

l_i, w_i	Length and width of vessel i, $\forall i \in O$.
ton_i	Tonnage of vessel i, $\forall i \in O$.
$Draft_i$	Draft of vessel i, $\forall i \in O$.
L_1, W_1	Length and width of the lock chamber.
L_2, W_2	Length and width of the lift chamber.
$Draft_1$, $Draft_2$	Required draft of the lock chamber and the lift chamber.
$Cost_1$, $Cost_2$	Operating cost of the ship lock and the ship lift.
$Cost_{max}$	Budget constraint of the passing facility operations.
$safety_{dis}$	Safety distance for vessels in the lock chamber.
$safety_{int}$	Safety interval between the departures of two vessels in the lock chamber.
R_1, R_2	Requirement of the space utilization at the ship lock and ship lift.
t_{lock}^{gate}, t_{lift}^{gate}	Gate operating time at the ship lock and the ship lift.
ot	Operating time of the lock chamber.
du	Operating time of the ship lift.
ft	Operation time of the ship lift with empty load.
A_i	Arrival time of vessel i at the anchorages, $\forall i \in O$.
A'_{pi}, A'_{ki}	Arrival time of vessel i at the ship lift and the five-stage ship lock, $\forall i \in O$.

st_d, ct_d	Start and end times of the given period.
γ	Requirement of the minimum interval between the operations of two adjacent groups at the same lock chamber.

Variables of the first-stage problem:

U_{ki}	Binary variable, if $U_{ki} = 1$, vessel i is assigned to the ship lock in group k and if $U_{ki} = 0$, otherwise. $\forall i \in O, \forall k \in K$.
U'_{pi}	Binary variable, if $U'_{pi} = 1$, vessel i is assigned to the ship lift in group p and if $U'_{pi} = 0$, otherwise. $\forall i \in O, \forall p \in P$.
Z_{kij}	Binary variable, if $Z_{kij} = 1$, vessel i and j are assigned to the same group in passing the TGD via the ship lock and if $Z_{kij} = 0$, otherwise. $\forall i, j \in V_2, i \neq j, \forall k \in K$.
x_i, y_i	Integer variables that define the x and y positions of vessel i in the lock chamber. $\forall i \in V_2$.
ls_{ij}	Binary variable, if $ls_{ij} = 1$, vessel i is on the left-hand side of vessel j and if $ls_{ij} = 0$, vessel i is on the right-hand side of vessel j. $\forall i, j \in V_2, i \neq j$.
fs_{ij}	Binary variable, if $fs_{ij} = 1$, vessel i is in front of vessel j and if $fs_{ij} = 0$, vessel i is behind vessel j. $\forall i, j \in V_2, i \neq j$.

Variables of the second-stage problem:

bt_{pi}	The buffer time of the p^{th} group passing via the ship lift, $\forall p \in P, \forall i \in V_1$.
wt_{nki}	The buffer time of vessel i in the k^{th} group passing via ship lock at lock chamber n. $\forall k \in K, \forall i \in V_2, \forall n \in N$.
rt_{nki}	The reaction time of vessel i in the k^{th} group passing via ship lock at lock chamber n. $\forall k \in K, \forall i \in V_2, \forall n \in N$.
st_{nk}, ct_{nk}	The start time and completion time of the operation of lock chamber n for group k. $\forall k \in K, \forall n \in N$.
st_{pi}, ct_{pi}	The start time and completion time of the operation of the ship lift for group p. $\forall k \in K, \forall p \in V_1$.
et_{pi}	The entering time of vessel i in group p to the ship lift. $\forall p \in P, \forall i \in V_1$.
et_{nki}	The entering time of vessel i in group k to the n^{th} lock chamber. $\forall k \in K, \forall i \in V_2, \forall n \in N$.
lt_{ki}	The leaving time of vessel i in group k from the ship lock. $\forall k \in K, \forall i \in V_2$.
lt'_{pi}	The leaving time of vessel i in group p from the ship lift. $\forall p \in P, \forall i \in V_1$.
δ_p	Binary parameter determines the direction of two adjacent ship lift operations. If $\delta_p = 1$, the ship lift operates in the opposite direction and if $\delta_p = 0$, otherwise. $\forall p \in P$.

B. THE FIRST-STAGE PROBLEM

In the first stage, the vessels are assigned to different passing facilities and are then grouped. The objective function (1) aims at maximizing the overall utilizations (OU) of the two passing facilities, which are proportional to the number of facility operations and the average utilization rate (AUR) of chamber space. Eq. (2) sets up the maximum amount of the operating cost. Herein, we take into account of two scenarios, namely, congestion and non-congestion. In the non-congestion scenario, the total number of facility operations within a given period is a fixed number determined by the operating cost constraint, so Eq. (1) can be converted to the optimization of the AUR. In the congestion scenario, which is focused in this paper, the operating cost constraint can be relaxed in order to enable a maximum number of vessels to pass the TGD. In this case, the optimization of the AUR may result in a sub-optimal solution. For instance, the model may suggest the passing facilities are only used for one time within the given period so that the space utilization can be maximized by selecting the best combination from all waiting vessels. However, this is obviously not the global optimal solution in this case. Thus, both the number of facility operations and the AUR of chamber space should be maximized. In addition, the OUs of ship lift and ship lock are combined with a weighted sum in Eq. (1), where $Weight_{shiplock} + Weight_{shiplift} = 1$. In this co-scheduling problem, different weights may be given to the two passing facilities in order to balance their workloads.

$$\text{Maximize } OU = (Weight_{Shiplock}\sum_{i\in O}\sum_{k\in K}\frac{U_{ki}l_iw_i}{L_1W_1} + Weight_{Shiplift}\sum_{i\in O}\sum_{p\in P}\frac{U'_{pi}l_iw_i}{L_2W_2}) \tag{1}$$

$$\sum_{k\in K}U_{ki}Cost_1 + \sum_{p\in P}U'_{pi}Cost_2 \le Cost_{max}. \tag{2}$$

The first-stage problem is subjected to constraints (3-24).

1) FACILITY ASSIGNMENT

Eqs. (3) guarantee only one passing mode is selected for each vessel scheduled in the given period. Eqs. (4-5) calculate the number of vessels assigned to different passing facilities, and Eq. (6) calculates the total amount of vessels scheduled in this period.

$$\sum_{k\in K}U_{ki} + \sum_{p\in P}U'_{pi} = 1, \quad \forall i \in O \tag{3}$$

$$\sum_{i\in O}\sum_{k\in K}U_{ki} = |V_2| \tag{4}$$

$$\sum_{i\in O}\sum_{p\in P}U'_{pi} = |V_1| \tag{5}$$

$$|V_1| + |V_2| = |O|. \tag{6}$$

2) LOCKAGE ASSGINMENT OF THE SHIP LIFT

Eqs. (7) guarantee all the vessels assigned to the ship lift within the given period will be scheduled to pass the TGD. Eqs. (8) restrict only one vessel can be assigned to the ship lift each time. Constraints (9) require the tonnage of the

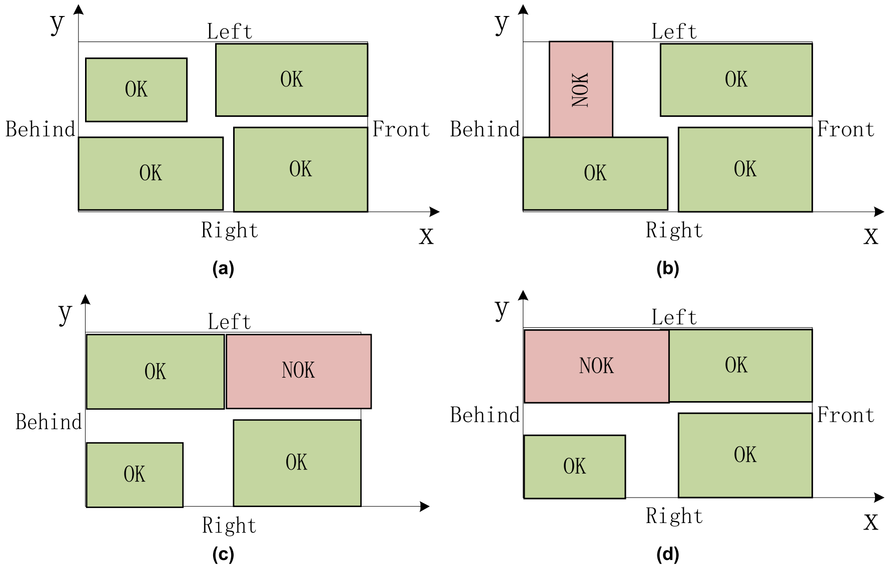


FIGURE 5. **Illustration of the vessel placement problem in a lock chamber: (a) The vessel placement is feasible. (b) The vessel placement is infeasible due to the violation of the heading direction requirement. (c) The vessel placement is infeasible due to the violation of the chamber space requirement. (d) The vessel placement is infeasible due to the violation of the safety distance requirement. (OK: the placement of a vessel is OK with the given requirement; NOK: the placement of a vessel is not OK).**

vessels assigned to the ship lift cannot exceed 3000 tons. Eqs. (10) impose a draft constraint in the lift chamber. Constraints (11-12) guarantee the sizes of the vessels in each group fulfill the respective requirements on length and width. Constraints (13) ensure the minimum AUR requirement is satisfied. In order to improve the fairness of the scheduling, constraints (14) impose a first-come-first-serve (FCFS) rule in assigning the vessels to the ship lift [39], which gives priorities to the earliest arrived vessels.

$$\sum_{p\in P} U'_{pi} = 1, \quad \forall i \in V_1 \tag{7}$$

$$\sum_{i\in V_1} U'_{pi} = 1, \quad \forall p \in P \tag{8}$$

$$U'_{pi} ton_i \le 3000, \quad \forall i \in V_1, \ \forall p \in P \tag{9}$$

$$U'_{pi} draft_i \le Draft_{2,}, \quad \forall i \in V_1, \ \forall p \in P \tag{10}$$

$$l_i + 2safety_{dis} \le L_2, \quad \forall i \in V_1 \tag{11}$$

$$w_i + 2safety_{dis} \le W_2, \quad \forall i \in V_1 \tag{12}$$

$$\frac{l_i w_i}{L_2 W_2} \ge R_2, \quad \forall i \in V_1 \tag{13}$$

$$U'_{pi} \ge U'_{pj}, \quad \forall i,j \in V_1 \cap \left(A_j \ge A_i\right), \ \forall p \in P. \tag{14}$$

3) LOCKAGE ASSIGNMENT OF THE FIVE-STAGE SHIP LOCK

The lockage assignment of the five-stage ship lock determines the grouping of vessels in the lockage under chamber space limitations. It can be considered as a two-dimensional (2D) bin-packing problem, where the vessels are simplified as rectangular items that are to be put into a bin (lock chamber) [40]. Moreover, the vessels need to head for the same direction in passing the ship lock and the draft requirements at each lock chamber should be fulfilled. Figure 5 illustrates the vessel placement problem in a lock chamber. The coordinates of the lower-left corner x_i and y_i are used to calculate the position of a vessel in the lock chamber. Eqs. (15) require all the vessels assigned to the ship lock will be scheduled in passing the TGD. Constraints (16) select a group of vessels in the same lockage. Constraints (17-23) are the vessel placement requirements. Constraints (17-18) restrict that a lock chamber cannot accommodate more vessels than its size and the safety requirement allow. Constraints (19) ensure the draft requirement is satisfied at the lock chamber. Constraints (20-23) determine the positions of the vessels in the same lockage. In this process, a safety distance must be maintained between two adjacent vessels. Constraints (46) impose a minimum requirement on the AUR of a lock chamber.

$$\sum_{k\in K} U_{ki} = 1, \quad \forall i \in V_2 \tag{15}$$

$$U_{ki}U_{kj} \le Z_{kij}, , \forall i,j \in V_2 \cap i \ne j, \quad \forall k \in K \tag{16}$$

$$safety_{dis} \le x_i U_{ki} \le L_1 - l_i - safety_{dis}, \quad \forall i \in V_2, \ \forall k \in K \tag{17}$$

$$safety_{dis} \le y_i U_{ki} \le W_1 - w_i - safety_{dis}, \quad \forall i \in V_2, \ \forall k \in K \tag{18}$$

$$U_{ki} draft_i \le Draft_2, \quad \forall i \in V_2, \ \forall k \in K \tag{19}$$

$$Z_{kij}\left(x_i - x_j - l_j - safety_{dis}\right) \ge 0, \quad \forall k \in K, \quad \forall i,j \in V_2 \cap fs_{ij} = 1 \tag{20}$$

$$Z_{kij}\left(x_j - x_i - l_i - safety_{dis}\right) \ge 0, \quad \forall k \in K, \forall i,j \in V_2 \cap fs_{ij} = 0 \tag{21}$$

$$Z_{kij}\left(y_i - y_j - w_j - safety_{dis}\right) \geq 0, \quad \forall k \in K, \quad \forall i,j \in V_2 \cap ls_{ij} = 1 \tag{22}$$

$$Z_{kij}\left(y_j - y_i - w_i - safety_{dis}\right) \geq 0, \quad \forall k \in K, \quad \forall i,j \in V_2 \cap ls_{ij} = 0 \tag{23}$$

$$\frac{\sum_{i\in V_2} l_i w_i U_{ki}}{L_1 W_1} \geq R_1, \quad \forall k \in K. \tag{24}$$

C. THE SECOND-STAGE PROBLEM

In the second stage, facility operations and vessels are scheduled in order to minimize the overall tardiness. In this paper, the optimization of the navigation scheduling in one direction is considered. The objectives of the second-stage problems are given in Eqs. (25) and (26). Eq. (25) aims at minimizing the total elapsed time for all vessels, which comprises the operating time, the buffer time, and the reaction time. Because the operating time of the lock chambers and the ship lift are considered to be constants in the passage process, Eq. (25) can be simplified by only taking into account the other two tardiness, as shown in Eq. (26).

$$\text{Minimize } \textit{Total elapsed time} = \sum_{i\in O}\left[\sum_{k\in K} U_{ki}\left(lt_{ki} - A'_{ki}\right) + \sum_{p\in P} U'_{pi}\left(lt'_{pi} - A'_{pi}\right)\right] \tag{25}$$

$$\text{Minimize } \textit{Tardiness} = \left[\sum_{n\in N}\sum_{k\in K}\sum_{i\in V_2}\left(wt_{nki} + rt_{nki}\right) + \sum_{p\in P}\sum_{i\in V_1} bt_{pi}\right]. \tag{26}$$

The second-stage model is restricted by constraints (27-46).

1) TARDINESS

Eqs. (27-28) calculate the buffer time of a vessel assigned to the ship lock. Eqs. (29) calculate the buffer time of a vessel assigned to the ship lift. The reaction time of a vessel moving from one chamber to the next is calculated by Eqs. (30).

$$wt_{1ki} = st_{1k} - A'_{ki}, \quad \forall i \in V_2, \ \forall k \in K \tag{27}$$

$$wt_{nki} = st_{nk} - et_{nki}, \quad \forall i \in V_2, \ \forall k \in K, \ \forall n \in N \cap n \neq 1 \tag{28}$$

$$bt_{pi} = \left(st_{pi} - A'_{pi}\right), \quad \forall i \in V_1, \ \forall p \in P \tag{29}$$

$$rt_{nki} = et_{(n+1)ki} - ct_{nk}, \quad \forall i \in V_2, \quad \forall k \in K, \forall n \in N \cap n \leq 4. \tag{30}$$

2) SCHEDULING OF THE SHIP LIFT

Constraints (31-37) are the scheduling requirements of the ship lift. Constraints (31) ensure the entering time cannot not be earlier than the arrival time of a vessel. Constraints (32) require the operation of the ship lift cannot be started before a vessel has entered the lift chamber. Eqs. (33) calculate the completion time. Constraints (34) are the leaving time requirement. The ship lift is operated for both upstream and downstream directions, and the start of the operation on one direction is thus dependent on the completion of that on the other direction. In this regard, constraints (35) are the time interval requirements of two adjunct operations at the same direction. Constraints (36-37) define the earliest start time and the latest finish time of the period under investigation.

$$et_{pi} \geq A'_{pi}, \quad \forall i \in V_1, \ \forall p \in P \tag{31}$$

$$st_{pi} \geq et_{pi} + t_{lift}^{gate}, \quad \forall i \in V_1, \ \forall p \in P \tag{32}$$

$$ct_{pi} = st_{pi} + du, \forall i \in V_1, \forall p \in P \tag{33}$$

$$lt'_{pi} \geq ct_{pi} + t_{lift}^{gate}, \forall i \in V_1, \forall p \in P \tag{34}$$

$$et_{(p+1)i} \geq lt'_{pi} + du\delta_{p+1} + ft\left(1 - \delta_{p+1}\right) + 2t_{lift}^{gate} \forall i,j \in V_1 \cap i \neq j, \forall p \in P \tag{35}$$

$$et_{1i} \geq st_d + t_{lift}^{gate}, \quad \forall i \in V_1 \tag{36}$$

$$lt'_{|P|i} + t_{lift}^{gate} \leq ct_d, \quad \forall i \in V_1. \tag{37}$$

3) SCHEDULING OF THE FIVE-STAGE SHIP LOCK

Constraints (38-46) are the scheduling requirements related to the ship lock operations. Constraints (38) ensure the operation cannot be started before all the vessels have entered the lock chamber. Eqs. (39) calculate the completion time of the k^{th} group of vessels at chamber n. Constraints (40) require a minimum interval of two adjacent groups. Constraints (41) require a vessel cannot enter the next lock chamber before the gate is opened. Constraints (42) impose a safety interval between two adjacent vessels in movement. Constraints (43-44) specify the relationships between the entering time and the exiting time. Constraints (45-46) give the earliest start time and the latest finish time. In addition, the decision variables need to fulfill the respective binary and non-negative requirements.

$$st_{nk} \geq et_{nki} + t_{lock}^{gate}, \quad \forall i \in V_2, \ \forall k \in K, \ \forall n \in N \tag{38}$$

$$ct_{nk} = st_{nk} + ot, \quad \forall k \in K, \ \forall n \in N \tag{39}$$

$$st_{n(k+1)} \geq st_{nk} + \gamma \times ot, \quad \forall n \in N, \quad \forall k \in K \cap k < |K| \tag{40}$$

$$et_{(n+1)ki} \geq ct_{nk} + t_{lock}^{gate}, \quad \forall i \in V_2, \ \forall k \in K, \quad \forall n \in N \cap n \leq 4 \tag{41}$$

$$et_{nkj} - safety_{int} \geq Z_{kij} fs_{ij} et_{nki}, \quad \forall i,j \in V_2 \cap i < j, \quad \forall k \in K, \ \forall n \in N \tag{42}$$

$$et_{1ki} \geq A'_{ki}, \forall i \in V_2, \quad \forall k \in K \tag{43}$$

$$lt_{ki} \geq ct_{5k} + t_{lock}^{gate}, \forall i \in V_2, \quad \forall k \in K \tag{44}$$

$$et_{11i} \geq st_d + t_{lock}^{gate}, \quad \forall i \in V_2 \tag{45}$$

$$lt_{|K|i} + t_{lock}^{gate} \leq ct_d, \quad \forall i \in V_2. \tag{46}$$

IV. SOLUTION METHOD

The proposed mathematical model is a two-stage problem. The first-stage problem determines the assignment of passing facilities and the grouping of lockage. To maximize the utilization of chamber space through the optimal placement of vessels, the grouping is modeled based on a bin-packing problem, which is NP-hard in the strong sense [41], [42]. Due to the high computational complexity, heuristics and metaheuristics are more effective and flexible to solve this kind of optimization problems [12], [43], [44]. In this paper, we developed a hybrid metaheuristic to solve the first-stage problem. Initially, the binary quantum inspired gravitational search algorithm (BQIGSA) is used to determine the assignment of passing facilities. In this step, the feasibility of the ship lift is checked when a vessel is assigned to it, and the vessels whose tonnages are more than 3000 will be rejected and be re-assigned to the ship lock. The vessel sequence for passing the ship lift is determined by the FCFS rule. For the vessels assigned to the five-stage ship lock, the multi-order best-fit Tabu search (MOBFTS) algorithm is used to maximize the facility utilization through the grouping of vessels in an optimal way. In this step, the fitness of swarm is obtained each time, which drives the BQIGSA to the next iteration until the stopping criteria are fulfilled. With the decisions obtained from the first-stage problem, the second-stage problem, which determines the scheduling of passing facilities and vessels, is solved by CPLEX. Figure 6 presents the algorithmic framework for solving the two-stage co-scheduling problem at the TGD.

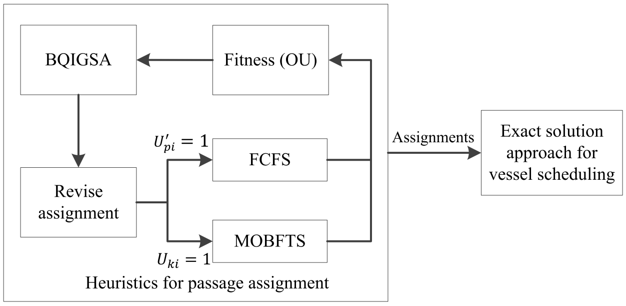


FIGURE 6. **Framework of the proposed solution method.**

A. BINARY QUANTUM INSPIRED GRAVITATIONAL SEARCH ALGORITHM FOR FACILITY ASSIGNMENT

1) BINARY GRAVITATIONAL SEARCH ALGORITHM

The binary gravitational search algorithm (BGSA) is a swarm intelligence algorithm with binary coding [45], which is developed based on the law of motion and Newtonian gravity [46]. Eq. (47) shows an example of encoding for the assignment of passing facilities, where "0" is to assign a vessel to the ship lift and "1" is for the assignment to the ship lock.

$$X = [0\ 1\ 1\ 1\ 0\ 1\ 0\ 1\ 1\ 1] \tag{47}$$

The initial position of a swarm is randomly generated, for example, as shown in Eq. (47). Then, the fitness and the mass of the swarm are calculated by Eqs. (48-49). The basic idea of the GSA is to simulate the movement of an agent that is affected by other agents in the search space due to the Newtonian gravity [47]. For instance, as illustrated in Figure 7, the agent 1 accelerates towards the direction of the total forces applied by the other agents. In accordance with Rashedi *et al.* [46], Eqs. (50-52) calculate the total forces applied to an agent based on Newtonian law of gravity, where $R_{ij}(t)$ is the Euclidean distance between two agents at time t. Eq. (53) calculates the acceleration based on Newtonian law of motion. The swarm updates the solutions obtained with accelerations until the pre-defined stopping criterion is met.

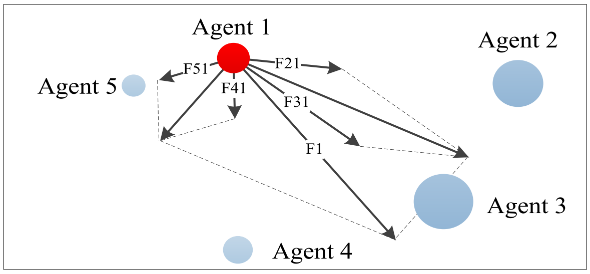


FIGURE 7. **Agent movement due to the forces applied from other agents.**

$$M_i(t) = \frac{fit_i(t) - worst(t)}{\sum_{j=1}^{N}[fit_j(t) - worst(t)]} \tag{48}$$

$$worst(t) = \min_{j\in\{1,2,\ldots,N\}} fit_j(t) \tag{49}$$

$$R_{ij}(t) = \left\| X_j(t), X_i(t) \right\|_2 \tag{50}$$

$$F_{ij}^d(t) = G(t)\frac{M_j(t)\,M_i(t)}{R_{ij}(t)+\varepsilon}(x_j^d - x_i^d) \tag{51}$$

$$F_i^d(t) = \sum_{j\in kbest, j\neq i} rand_j G(t)\frac{M_j(t)\,M_i(t)}{R_{ij}(t)+\varepsilon}(x_j^d - x_i^d) \tag{52}$$

$$a_i^d(t) = \frac{F_i^d(t)}{M_i(t)} = \sum_{j\in kbest, j\neq i} rand_j G(t)\frac{M_j(t)\left(x_j^d - x_i^d\right)}{R_{ij}(t)+\varepsilon}. \tag{53}$$

where:

t	–Time t;
ε	– A very small number;
N	– The size of population (agents);
$M_i(t)$	– Mass of agent i at time t;
$fit_i(t)$	– The fitness value of agent i at time t, which is the objective value of Eq. (1);
$R_{ij}(t)$	– Euclidean distance between agents i and j;
$G(t)$	– Gravitational constant at time t;
$F_{ij}^d(t)$	– The force applied to agent i by agent j at time t;
x_i^d	– The position of agent i in the dimension d, $x_i^d \in \{0, 1\}$;
$X_i(t)$	– Position of agent i in the search space at time t;
$kbest$	– The set of the first K agents with the best fitness value and biggest mass;
$rand_j$	– Uniformly distributed random numbers in the interval [0, 1].

Algorithm 1 State Declaration

```
Input: $\alpha_i^d$, $\beta_i^d$
Output: $x_i^d$
  if $rand(0, 1) < (\alpha_i^2)$ then
    $x_i^d = 0$
  else
    $x_i^d = 1$
  end if
```

2) BQIGSA

The BQIGSA is a novel metaheuristic for binary encoding problems [47], which incorporates the BGSA [45] and the quantum inspired system. A recent research has revealed that BQIGSA has a high exploration capability and has outperformed the classic BGSA as well as other metaheuristics, e.g., genetic algorithm (GA), binary particle swarm algorithm (BPSA), etc. [47]. In the BQIGSA, the quantum inspired system with quantum bit (Q-bit) and Q-gate can be regard as a probability system. Then, the BGSA is improved with two steps: 1) encoding solution with Q-bit; 2) update solution with Q-gate [48]. Eq. (54) formulates a Q-bit, where α and β are the probability of the states "0"and "1". Their values follow the relationship given in Eq. (55) [49]. A general encoded solution of an agent i is presented in Eq. (56). For instance, the right-hand side of Eq. (57) is obtained with Algorithm 1, where the random number is 0.5.

$$q = \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \tag{54}$$

$$|\alpha|^2 + |\beta|^2 = 1 \tag{55}$$

$$Q_i = \begin{bmatrix} \alpha_i^1 & \alpha_i^2 & \alpha_i^3 & & \alpha_i^d & & \alpha_i^n \\ \beta_i^1 & \beta_i^2 & \beta_i^3 & \ldots & \beta_i^d & \ldots & \beta_i^n \end{bmatrix} \tag{56}$$

$$Q = \begin{bmatrix} \frac{1}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{6}}{3} \\ \frac{\sqrt{3}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{3}}{3} \end{bmatrix} \gg X = [110] \tag{57}$$

Another fundamental concept adopted from quantum computing is Q-gate, which is an operator for the variation and change of Q-bit states in order to drive individuals moving towards the global optimum [50]. A Q-gate uses the state of a Q-bit as the input and updates the state of a Q-bit to $(\check{\alpha}, \check{\beta})$ that satisfies $\check{\alpha}^2 + \check{\beta}^2 = 1$ [51]. Among a variety of single Q-gates that can be used to change the state of a Q-bit, the rotation Q-gate (RQ-gate) is the most extensively used one in hybrid metaheuristics due to its effectiveness and capability [52]. Eq. (58) defines a RQ-gate. The rotation angle is calculated in Eq. (59), which is dependent on the angular velocity and the sign of a Q-bit. Eqs. (60-61) calculate the angular velocity and the velocity at time *t+1*, respectively. The BQIGSA is given in Algorithm 2.

Algorithm 2 BQIGSA

```
Initialize swarm position with Q-bit
Acceleration, linear and angular velocities are sot to 0
while gravitational constant is non-negative do
    Evaluate fitness and mass of swarm
    Update force and acceleration of each agent
    Update linear and angular velocities
    Update Q-bit with R.Q-gate
    Update swarm position
    Update gravitational constant
end while
Output: Best position
```

$$\begin{bmatrix} \alpha_i^d(t+1) \\ \beta_i^d(t+1) \end{bmatrix} = \begin{bmatrix} cos(\Delta\theta^d) & -sin(\Delta\theta^d) \\ sin(\Delta\theta^d) & cos(\Delta\theta^d) \end{bmatrix} \begin{bmatrix} \alpha_i^d(t) \\ \beta_i^d(t) \end{bmatrix} \tag{58}$$

$$\Delta\theta_i^d = \begin{cases} \omega_i^d\,(t+1)\,\Delta t, & if\ \alpha_i^d\,(t)\,\beta_i^d\,(t) \geq 0 \\ -\omega_i^d\,(t+1)\,\Delta t, & if\ \alpha_i^d\,(t)\,\beta_i^d\,(t) < 0 \end{cases} \tag{59}$$

$$\omega_i^d\,(t+1) = \frac{v_i^d\,(t+1)}{r} \tag{60}$$

$$v_i^d\,(t+1) = rand_i \times v_i^d\,(t) + a_i^d\,(t)\,\Delta t. \tag{61}$$

where:

$\Delta\theta_{\text{i}}^{\text{d}}$	– Rotation angle of d^{th} Q-bit of Q_i at time t;
$\omega_i^d(t+1)$	– Angular velocity of d^{th} Q-bit of Q_i at time *(t+1)*;
$v_i^d(t+1)$	– Velocity of d^{th} Q-bit of Q_i at time *(t+1)*;
r	– Radius of the circular system;
$rand_i$	– Uniformly distributed random numbers in the interval [0, 1].

B. MULTI-ORDER BEST-FIT TABU SEARCH ALGORITHM FOR LOCKAGE ASSIGNMENT

The multi-order best-fit Tabu search (MOBFTS) algorithm incorporates the traditional multi-order best-fit (MOBF) heuristic into a Tabu search (TS) in order to find the global optimum for the grouping of vessels in lockage, where the TS takes the lockage assignment determined by the MOBF as an original solution and searches its neighborhood. The best-fit (BF) heuristic was derived from a 2D orthogonal strip packing problem [53]. In order to solve an orthogonal stock-cutting problem, a new placement heuristic with BF was proposed by Burke *et al.* [54]. Apart from the use of strip packing algorithms in several similar problems [55], Verstichel *et al.* [56] developed a MOBF algorithm for vessel placement, which uses the dimensions of width, length and surface area as criteria to determine the vessel sequence in lockage. The optimal result of a MOBF can be significantly improved by extending a single ordering to multiple ones [56]. The MOBF is presented as follow:

Step 1: The vessels are initially sequenced by decreasing width, which is the first-ordering criterion.

Step 2: Search for available space from the front most of the chamber and update the gap information.

Step 3: If a vessel can be placed on the left-hand side of the gap under constraints (17-23), it is moved up in the sequence to fill the gap, and step 2 is then repeated. Otherwise, continue with the next step.

Step 4: If a vessel can be placed on the right-hand side of the gap under constraints (17-23), it is moved up in the sequence to fill the gap, and step 2 is then repeated. Otherwise, continue with step 5.

Step 5: Give a new sequence by decreasing length, which is used as the second-ordering criterion, and repeat steps 2-4.

Step 6: If the second-ordering criterion fails to improve the vessel placement, the third-ordering criterion: surface area is then used to repeat steps 2-4.

Step 7: If the third-ordering criterion fails to improve the vessel placement, the algorithm will return to Step 1 and will start the vessel placement of a new group of lockage.

The TS is a neighborhood search metaheuristic, which is able to search the neighborhoods beyond the boundaries of local optimality and feasibility [57]. In the MOBFTS algorithm, the TS is used to improve the optimal solution from the MOBF heuristic, which may be trapped in a local optimum. The TS searches the neighborhoods around the optimal solution obtained by the MOBF. The candidates selected are stored in a tabu list, which is continuously updated during the search iterations in order to find the global optimum. In this process, the quality of the optimal result obtained by the TS is dependent on the MOBF outputs. In addition, it is also affected by tabu length, swap and frequency. The MOBFTS heuristic is given in algorithm 3. At the beginning, the solution is initialized from the MOBF. If the best solution cannot be improved in the current neighborhood, the algorithm will choose a random solution from the feasible set "A" to gernerate a neighborhood for the next iteration. The best solution is defined by $S_b = [v_{b1}, v_{b2}, \ldots, v_{bk}, \ldots, v_{bn}]$, where the elements represent a group of vessels in a lockage. The neighborhood is searched by the following four steps:

Step 1: Calculate the utilization ratio of each element, and then the elements are sequenced with ascending order of the utilization ratio.

Step 2: Select the first $(n+1)$ elements as a swap set, where n is the size of the neighborhood.

Step 3: The first element v_{bk} is moved out from the set and is considered an element in the neighborhood.

Step 4: The element v_{b2} becomes now the first element in the set. Then, the vessels in the set and the elements in the neighborhood are swaped in order to improve the optimal solution. For instance: $N_s^1 = [v_{b1}, v_{b2} + 1, \ldots, v_{bk} - 1, \ldots, v_{bn}]$. The elements of the swap set can be used once.

Algorithm 3 MOBFTS

```
tabulist = $\emptyset$, A = $\emptyset$, N$_b$ = $\emptyset$, S$_b$ = $\emptyset$, F(S$_b$) = $\emptyset$
Initialize S$_0$ by MOBF
while not stopping criterion do
    for i = 1 to n do
        Search neighborhood $N_b$ around $S_b$,($S_c$)
        if neighborhood is infeasible then
            rearrange the neighborhood by MOBF
        end if
    end for
    Evaluate fitness of neighborhood $F(N_b)$
    Update feasible solution set A
    if $maxF(N_b) > F(S_b)$ then
        Update $S_b$,$F(S_b)$ and tabulist
    else
        Choose a solution $S_c$ from A
    end if
end while
Output: $S_b$, $F(S_b)$
```

V. COMPUTATIONAL EXPERIMENTS

In this section, computational experiments are given to show the effectiveness of the algorithm in both lockage assignment and facility assignment problems.

A. LOCKAGE ASSIGNMENT PROBLEM

First, three methods including an exact method, a simple heuristic, and the MOBFTS, were used to solve the vessel grouping and lockage assignment problem. Due to the fact that the ship lift can only accommodate one vessel each time, its space utilization cannot be significantly improved. Thus, in the comparison, the objective function is simplified to the optimization of the chamber space utilization of the five-stage ship lock under constraints (15-24).

The model is first solved by CPLEX. Then, the FCFS is used as a simple heuristic to optimize the lockage assignment by the following three steps:

Step 1: Determine the sequence of vessels based on the FCFS rule.

Step 2: Group the vessels to a lockage one by one according to the sequence until the feasibility requirement given by constraints (17-23) becomes invalid.

Step 3: Group the vessels to a new lockage and repeat Steps 2 and 3 until all the vessels are assigned to a lockage.

Finally, the MOBFTS is used to solve the same problem instances.

Table 1 shows the computational results. The data of vessels is generated based on real-world data, which is described in Section VI. The optimal results of each instance are bolded in the table. Considering the optimality, the exact method finds the best results for the vessel placement problem. Compared with the FCFS heuristic, the MOBFTS has a better AUR. This implies the use of the FCFS rule in lockage assignment may improve the fairness of scheduling

TABLE 1. Computational results.

Vessels	CPLEX		FCFS		MOBFTS	
	AUR	CPU time(s)	AUR	CPU time(s)	AUR	CPU time(s)
10	**0.5869**	13.2	**0.5869**	0.01	**0.5869**	0.01
20	**0.6618**	225.3	0.5515	0.04	**0.6618**	0.09
30	**0.7231**	1745.7	0.5625	0.09	0.6328	0.14
50	**0.7039**	3863.3	0.6033	0.12	0.6497	0.19

with the sacrifices on facility utilization and efficiency. Conversely, the MOBFTS aims at maximally filling the gap of a lock chamber and finds thus a better solution. Even though better results were obtained by CPLEX, the computational time increases exponentially with the increase of problem size. In this regard, the searching speed of the two heuristics is much quicker. The results have shown, taking into account both optimality gap and computational efficiency, the MOBFTS is capable to generate reasonably good lockage assignment decisions for large problem instances within a very short time.

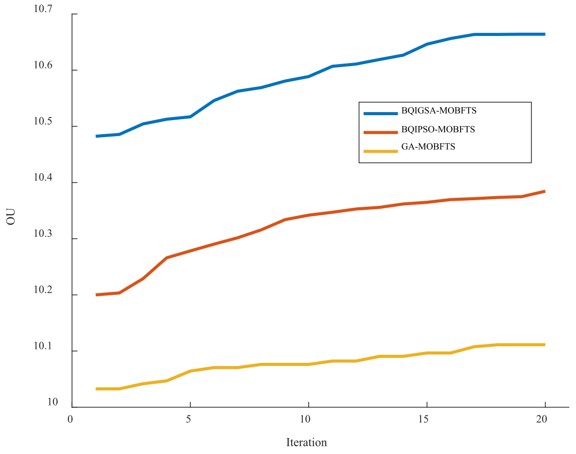


FIGURE 8. Comparison of the three hybrid algorithms.

B. FACILITY ASSIGNMENT PROBLEM

In order to solve the facility assignment problem, we tested three hybrid algorithmic structures that incoperate the MOBFTS into three swarm intelligence and evoluation algorithms, namely, the GA, the binary quantum-inspired particle swarm optimization (BQIPSO), and the BQIGSA. The problem size was set to 88 vessels in one direction. The size of population in both algorithms was set to 80, and the iterations was set 20. Figure 8 compares the optimal facility utilization obtained from the three hybrid algorithms. The results have illustrated the BQIGSA drastically outperforms the other two counterparts. It is also noted that the quanmtum inspired system may enlarge the searching space for the optimization of both the BGSA and the PSO. However, the convergence speed of the BQIPSO is slower than that of the BQIGSA.

TABLE 2. Historical data of the navigation scheduling of the TGD on a daily basis.

Passing facilities	Average number of vessels scheduled	Average number of vessels in a group	Number of operations	*AUR* (%)
Southern ship lock for vessels from the upstream	63.8	3.9	16.4	70%
Northern ship lock for vessels from the downstream	57.6	3.9	14.6	70%
Ship lift for vessels from the upstream	4.1	1.0	4.1	63.5%
Ship lift for vessels from the downstream	5.6	1.0	5.6	64.5%

VI. CASE STUDY

This section provides a case study in order to show the application of the proposed mathematical model and solution approach in improving the navigation scheduling of the TGD. For comparison purpose, the historical data of the navigation scheduling of the TGD is first given in accordance with Administration [4] and Wang *et al.* [19]. As shown in Table 2, the average number of vessels passing the TGD from the upstream via the five-stage ship lock is more than that from the downstream. However, on the other hand, more vessels pass the TGD from the downstream to the upstream via the ship lift. In addition, three indicators are used for performance evaluation:

1) Overall utilization (OU) of passing facilities, calculated by Eq. (1).
2) Average utilization rate of the lift chamber space ($AUR_{shiplift}$), calculated by Eq. (62).
3) Average utilization rate of the lock chamber space ($AUR_{shiplock}$), calculated by Eq. (63).

$$AUR_{shiplift} = |P|^{-1} \sum_{i \in O} \sum_{p \in P} \frac{U'_{pi} l_i w_i}{L_1 W_1} \times 100\% \tag{62}$$

$$AUR_{shiplock} = |K|^{-1} \sum_{i \in O} \sum_{k \in K} \frac{U_{ki} l_i w_i}{L_1 W_1} \times 100\%. \tag{63}$$

As shown in Eq. (1), the OU is determined by the number of operations and the AUR of the passing facilities within the given period. Hence, the information related to the AUR is important and can be used to analyze the reasons of the change of the OU in different scheduling plans.

A. GENERATION OF PARAMETERS

In the case study, the performance of the navigation scheduling is evaluated on a daily basis. We considered the vessels from the upstream of the Yangtze River, and the minimum requirement on the space utilization rate of lift chamber and lock chamber were set to 0.6 and 0.65, respectively. Based on

TABLE 3. Parameter intervals and chamber sizes of the passing facilities.

Length of vessel	82m – 107m
Width of vessel	14m – 18.2m
Draft of vessel	2.8m – 3.8m
Tonnage of vessel	1,500tons – 6,000tons
Chamber of ship lift	120*18*3.5m (length*width*depth)
Chamber of ship lock	280*34*5m (length*width*depth)

historical data from Administration [58] and China [59], Table 3 presents the parameter intervals of vessels and the chamber sizes of the passing facilities. Five benchmark values were defined according to the range of tonnage: 2000 tons, 2500 tons, 3000 tons, 4500 tons and 5000 tons. The distribution of the vessels generated from these benchmark values was 12.5%, 12.5%, 18.75%, 18.75% and 37.5%, respectively. The arrival time of vessels at the anchorage was assumed to follow Poisson Distribution, and the average number of arrival was set to 5 vessels per hour [4]. For simplicity sake, only the navigation scheduling of the vessels from the upstream was optimized, and the daily amount of vessels scheduled was set to 80. To implement the proposed algorithm, the initial gravity constant and the tabu length were set to 100 and 7, respectively. The weight combination was set to 0.5 and 0.5. The hybrid metaheuristic for the first-stage problem was coded and tested in MATLAB 2016a, and the second-stage problem was solved by CPLEX.

B. RESULT AND DISCUSSIONS OF THE FIRST-STAGE PROBLEM

First, nine scenarios with different combinations of agents and iterations were tested. Each scenario was repeatedly solved for eight times in order to maintain a high stability. The average result of each scenario is given in Table 4. In general, the computational time required is directly related to both the number of agents and the iterations. It is also noted that the scenarios with larger values on both the number of agents and the iterations may obtain a higher AUR of the ship lock. Furthermore, compared with the number of agents, the iterations show a stronger influence on the AUR of the ship lock.

Under the current navigation scheduling and the given weight combination, the OU of the two passing facilities at the TGD is 7.04. The optimal scheduling has shown a better utilization of the two passing facilities. This can be explained by two reasons. First, compared with the current navigation scheduling, even if the $AUR_{shiplift}$ is at the same level, the utilization of the ship lift increases significantly due to the fact that more operations are scheduled in the optimal solution. Second, the utilization of the five-stage ship lock is also improved due to the significant increase on the $AUR_{shiplock}$. It is noted, compared with the current navigation, the number of vessels assigned to each group is at the same level in the optimal scheduling. However, due to the frequent use of the ship lift, more vessels under 3000 tonnage are assigned to the ship lift, so larger vessels are grouped in passing the TGD via the ship lock so that the AUR can be improved. Taking into account different combinations, scenarios 1, 5 and 8 lead to better utilizations of the two passing facilities than the other scenarios. In addition, due to the larger AUR of the lock chamber, the algorithm shows a trend to assign more vessels to the ship lock in the searching process, so a proper combination of $Weight_{shiplock}$ and $Weight_{shiplift}$ can balance the selection of passing facilities and optimize the weighted OU.

It is of interest to investigate the impact of different weight combinations on the operations of the ship lift. Table 5 shows the sensitivity analysis for scenarios 1, 5 and 8 with respect to four weight combinations, which yield the best OU of the passing facilities. The number of operations of the ship lift ranges from 9 to 11 throughout the test scenarios, and the OU ranges from 8 to 11. Besides, the influence from the utilization of the ship lock on the OU is relatively insignificant. Thus, it was not taken into the analysis. Compared with scenario 1, the computational time required by scenarios 5 and 8 are much larger in the sensitivity analysis. On the other hand, the number of operations of the ship lift obtained in scenario 8 has the best stability due to the smaller standard deviations. In addition, the results obtained in scenarios 1 and 8 show a higher utilization of the ship lift than the other scenarios. Therefore, considering both the quality of solution and the computational performance, the number of agents and the iterations in the case study were set to 80 and 20, respectively. The weight of the utilization of the ship lift was given to 0.7.

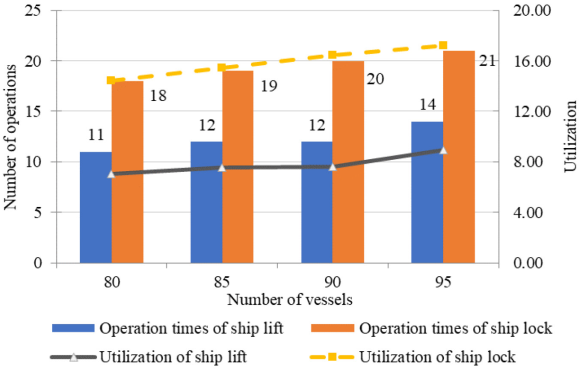


FIGURE 9. The number of operations and the utilization of passing facilities in different scenarios.

Next, another three scenarios with increased number of vessels at 85, 90 and 95 were tested in order to determine the maximum capacity of the passing facilities within the given period and to evaluate the performance of the proposed algorithm. In this set of experiments, the constraints of the latest finish time were relaxed in order to avoid infeasible solutions and to yield meaningful results for comparison, where the exceeded vessels would be scheduled in the next consecutive period. Figures 9 and 10 illustrate the influence from the number of operations and the AURs on the utilization of both ship lift and ship lock. In general, the AURs of both passing facilities are relatively stable, and the increase on

TABLE 4. Experimental results of the test scenarios.

Scenarios	Number of agents	Iterations	Ship lift		Ship lock			Weighted *OU*	CPU time (s)
			Number of operations	*AUR (%)*	Number of operations	Average number of vessels in a group	*AUR (%)*		
1	20	20	10.25	63.41%	17.88	3.90	80.78%	10.47	5.41
2	30	20	9.25	63.37%	18.00	3.93	80.79%	10.20	8.30
3	40	25	8.88	64.01%	18.13	3.93	81.52%	10.23	15.40
4	40	30	8.50	64.40%	18.00	3.97	81.65%	10.09	19.00
5	50	20	9.88	63.75%	18.00	3.90	81.42%	10.48	15.60
6	50	50	7.00	64.96%	18.63	3.92	81.71%	9.88	39.50
7	50	70	5.25	66.01%	19.00	3.93	81.67%	9.49	57.30
8	80	20	9.13	63.89%	18.00	3.93	82.04%	10.30	26.20
9	100	20	7.75	64.25%	18.38	3.93	81.92%	10.02	30.00

TABLE 5. Sensitivity analysis.

Scenarios	Weight of ship lift	Number of operations of the ship lift	Standard deviation	Utilization of the ship lift	Utilization of the ship lock	Weighted *OU*	CPU time (s)
1	0.5	10.25	1.9203	3.25	7.22	10.47	5.41
	0.6	9.25	1.5612	3.54	5.86	9.40	6.20
	0.7	10.38	0.9922	4.59	4.39	8.98	5.46
	0.8	10.75	0.8292	5.46	2.83	8.28	5.76
5	0.5	9.88	1.8998	3.15	7.33	10.48	15.60
	0.6	9.75	1.4790	3.73	5.82	9.55	14.60
	0.7	10.38	1.2183	4.63	4.35	8.99	14.30
	0.8	9.88	0.9270	5.05	2.93	8.04	14.20
8	0.5	9.13	1.2686	2.92	7.38	10.30	26.20
	0.6	10.38	1.2183	3.97	5.82	9.79	23.10
	0.7	10.75	0.6614	4.82	4.37	9.19	23.20
	0.8	10.00	0.5000	5.11	2.93	8.04	22.90

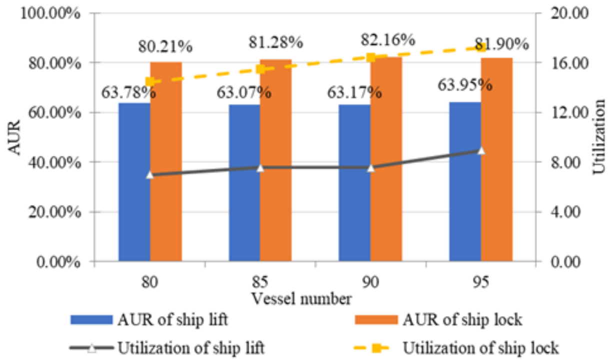


FIGURE 10. The AUR and the utilization of passing facilities in different scenarios.

the utilization is mainly due to the increased number of operations. With the increase on the amount of vessels, the number of operations of both ship lift and ship lock is gradually increased in order to deal with a larger amount of vessels for passing the TGD. Considering the operating time limitation of the given period, the maximum number of operations of the ship lift and the ship lock are 12 and 19, respectively. Therefore, the maximum daily amount scheduled to pass the TGD cannot exceed 88 vessels. It is noted the number of vessels in the last operation of the scenario with 90 vessels is 2.

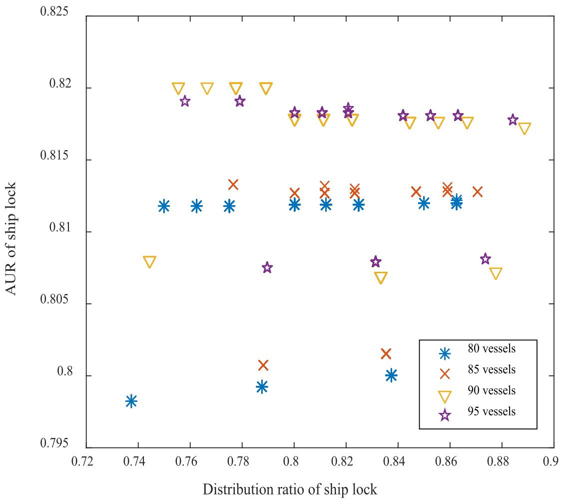
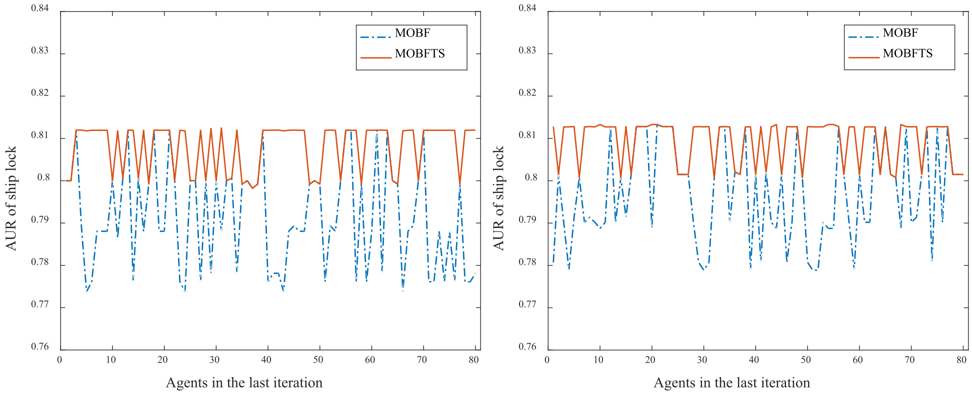
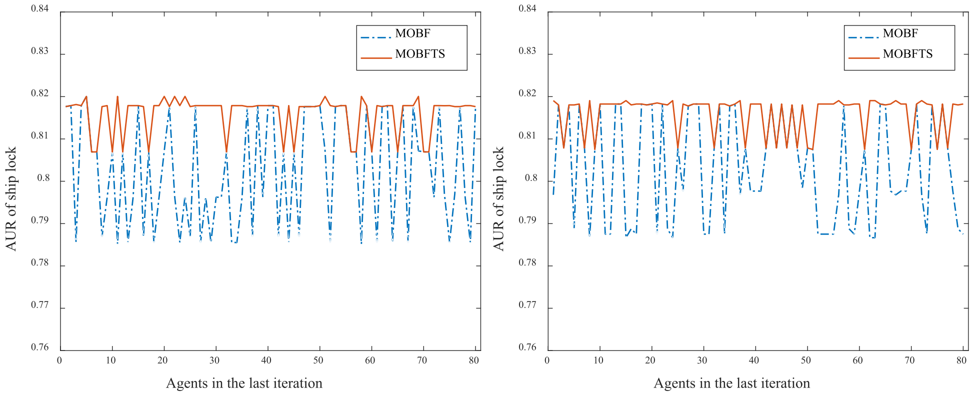


FIGURE 11. Correlation between the distribution ratio and the AUR of the ship lock.



80 vessels **85 vessels**



90 vessels **95 vessels**

FIGURE 12. **Comparison of the AUR of the ship lock calculated by the MOBF and the MOBFTS in the last iteration.**

The different distribution ratio and placement of vessels have more impact on the AUR of the ship lock compared with that on the ship lift. Figure 11 shows the correlation between the distribution ratio and the AUR of the ship lock, which includes the agents of four instances in the last iteration. The distribution ratio is the ratio of vessels assigned to the five-stage ship lock within the scheduling period. As shown, a high level of performance and stability of the AUR of the ship lock can be maintained by the proposed algorithm in the experiments. The best performance may be achieved when the distribution ratio ranges from 75% to 80%. Figure 12 compares the AURs of the ship lock obtained by the MOBF and the MOBFTS in the last iteration. The result shows, through the incorporation of a TS algorithm, the performance of the optimal result obtained by the MOBF is more stable, and the quality of solution can be improved by approximately 2.1%.

C. RESULT AND DISCUSSIONS OF THE SECOND-STAGE PROBLEM

The objective of the second-stage problem is to improve the efficiency of navigation scheduling by minimizing the tardiness. Currently, the navigation scheduling of the ship lock and the ship lift are done individually, which leads to sub-optimal planning and inefficient use of both passing facilities. Historical data shows more vessels are allocated to the five-stage ship lock in today's navigation scheduling, and the average capacity utilization of the ship lift is only 41.67%. Furthermore, due to the insufficient use of the ship lift, the operations are inefficient and, on average, only five times are operated in one direction per day. Figure 13 presents the comparison between the current scheduling and the optimal scheduling. As shown, with the optimal scheduling, the weighted OU can be improved by 89.4%, and the total number of vessels scheduled can be increased by 29.6%. The significant increase on the utilization of the passing facilities is mainly due to the increased amount of vessels scheduled and a better grouping of vessels for improving the AURs. Even though the total amount of vessels in the optimal scheduling is increased, the total tardiness of vessels can still be reduced by 2.7%, which reveals a further reduction on the average waiting time of the vessels. This has shown the effectiveness of the proposed method in the optimization of the navigation scheduling at the TGD.

In order to better understand the results of the experiments, the operations of the ship lift in the two scheduling plans are first analyzed. In the optimal scheduling, the utilization of the ship lift is increased by 191.2%. The AUR of the ship lift cannot be significantly improved, because only one vessel can

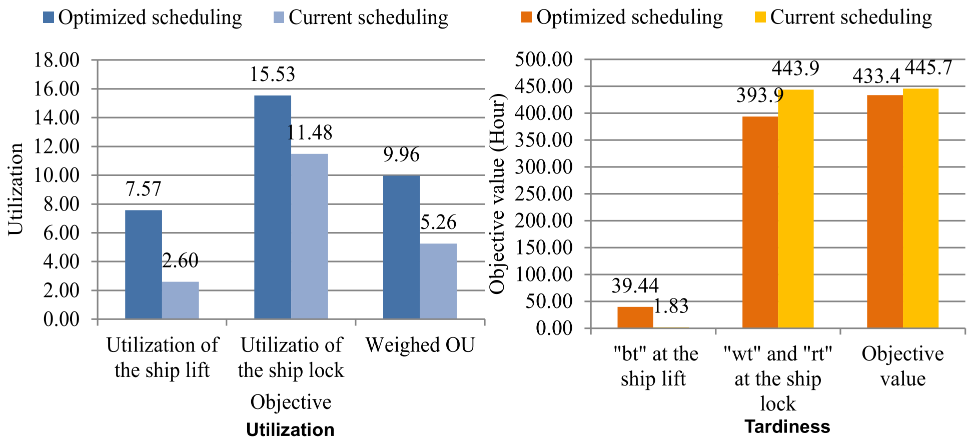


FIGURE 13. Comparison between the current navigation scheduling and the optimized navigation scheduling.

be placed in the lift chamber each time, and the requirement on the size of the vessel is strict. This results in a relatively stable AUR no matter which scheduling plan is implemented. However, compared with the current scheduling, more vessels are assigned to the ship lift in the optimal scheduling, which leads to a significant increase on the number of operations and the facility utilization. Due to the number of vessels assigned to the ship lift is increased by 192.7%, the total waiting time at the ship lift will be drastically increased in the optimal scheduling.

For the operations of the five-stage ship lock with the optimal scheduling, the number of vessels assigned, the number of operations and the utilization of the ship lock are increased by 19.1%, 15.9% and 35.3%, respectively. Thus, the improvement on the utilization of the ship lock is contributed by the increase on both the number of operations and the AUR of the ship lock. In the optimal scheduling, a larger number of smaller vessels are assigned to the ship lift. In the placement of vessels in lock chambers, these smaller vessels usually cause a low rate of utilization of the chamber space due to larger gaps between the vessels in the same group. Furthermore, the algorithm optimizes the vessel placement in lock chambers so that the AUR of the lock chamber is maximized. Considering the total tardiness of vessels in lockage, the optimal result suggests a reduction of 11.3% can be achieved. This compensates the increase on the total waiting time at the ship lift and leads to a reduction on the total tardiness for both passing facilities at the TGD.

VII. CONCLUSIONS

In recent years, traffic congestion at the TGD has become a big challenge due to the significant increase of waterway transportation on the Yangtze River. In this paper, a co-scheduling problem of ship lift and ship lock at the TGD is investigated. The problem is formulated as a mixed integer nonlinear program, which consists of two stages of problems. The first-stage problem maximizes the utilization of the two passing facilities, while the second-stage problem aims at minimizing the total tardiness of all vessels scheduled to pass the TGD within a given period. Furthermore, the model also considers the improvement on effectiveness, safety and fairness of the navigation scheduling by the introduction of the ship lift. The model is a complex optimization problem. A hybrid metaheuristics is developed to solve the first-stage problem in an effective and efficient manner, and the second-stage problem is solved by CPLEX. The proposed mathematical model and solution algorithm are validated through a set of numerical experiments and a case study. The computational results show the applicability of the proposed methods and the effectiveness on the improvement of the navigation scheduling at the TGD.

Among other insights, by adopting the optimal solution, the results suggest a significant improvement on the co-scheduling problem of the TGD may be achieved in the following aspects:

- The number of the vessels scheduled per day may be increased by 29.6%.
- The utilization of both ship lift and ship lock may be increased by 89.4%.
- The average tardiness and the waiting cost of the vessels in passing the TGD may be reduced by 25.0%.

For further improvement of the current research, two suggestions are made. First, the water level of the Three Gorges reservoir needs to fulfill the requirements for flood control and power generation in some periods. This may lead to a significant impact on the navigation scheduling. Thus, further research may be conducted to model and investigate the co-scheduling problem of ship lift and ship lock under different water level constraints at the TGD. Second, the optimization model may be extended to further incorporate with the consideration of stochastic events related to natural disasters and equipment failures.

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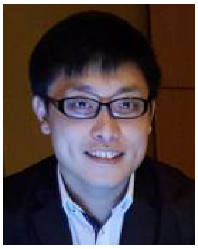

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