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A Collaborative Berth Planning Approach for Disruption Recovery

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ABSTRACT Traditionally, terminal operators create an initial berthing plan before the arrival of incoming vessels. This plan involves decisions on when and where to load or discharge containers for the calling vessels. However, disruptive unforeseen events (i.e., arrival delays, equipment breakdowns, tides, or extreme weather) interfere with the implementation of this initial plan. For terminals, berths and quay cranes are both crucial resources, and their capacity limits the efficiency of port operations. Thus, one way to minimize the adverse effects caused by disruption is to ally different terminals to share berthing resources. In some challenging situations, terminal operators also need to consider the extensive transshipment connections between feeder and mother vessels. Therefore, in this work, we investigate a collaborative variant of the berth allocation recovery problem which focuses on the collaboration among terminals and transshipment connections between vessels. We propose a mixed-integer programming model to (re)-optimize the initial berth and quay crane allocation plan and develop a Squeaky Wheel Optimization metaheuristic to find near-optimal solutions for large-scale instances. The results from the performed computational experiments, considering multiple scenarios with disruptive events, show consistent improvements of up to 40% for the suggested collaborative strategy (in terms of costs for the terminal operators).

INDEX TERMS Collaborative berth planning, disruption recovery, mixed-integer program, metaheuristic.

I. INTRODUCTION

INTERNATIONAL maritime trade has been greatly increasing over the last decades, and the global container port throughput reached its peak, 811.2 million Twenty-foot Equivalent Units (TEU) in 2019 [1]. These large volumes require efficient and robust quay-side operations for the calling vessels. Providing a quick and reliable berthing plan while minimizing costs and congestion is important for both shipping lines and terminal operators. Because changing the configuration of terminals (e.g., extending the quay) needs a rather expensive investment, improving the efficiency of available berths and quay cranes is essential for terminals to remain competitive. The berthing plan determines when and where to load or discharge containers for the calling vessels as well as the number of quay cranes to be allocated. Generally, terminal operators form a weekly berthing plan before the calling of vessels. However, there are frequent disruptions (e.g., vessel arrival delay or extreme weather) hindering the execution of the initial plans. Thus, uncertainties cannot be ignored, and a well-functioning berthing plan should incorporate both efficiency and disruption recovery [2].

Current research deals with uncertainties from two main perspectives, namely proactive and reactive. Proactive strategies focus on anticipating the uncertainty and variability of the real-world scenarios before the disruption [2]–[4]. This scenario-based research is important in the long run, but terminal operators also need instant decision-making support [5]. Thus, this paper studies reactive strategies that aim to make quick and effective responses to disruptions. Reviewing the literature on reactive strategies, researchers tend to prioritize larger vessels in response to disturbances, but they mostly ignore the implied transshipment connections

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between vessels. Containers that are discharged from one vessel and then loaded on another vessel may delay the transshipment because of the uncoordinated berth planning. Moreover, during major disruptions, some calling vessels have to wait a long time until the berths and quay cranes are idle.

Collaboration has been identified as a win-win strategy for both collaborating terminals [6], especially when terminals confront major disruptions. This strategy reduces the waiting time of disrupted vessels by allying different terminals to share berthing resources, that is, allowing the calling vessels to transfer to other terminals. Vessel transfer between terminals may cause much inter-terminal and intra-terminal costs, but it can relieve the congestion caused by disruptions in the current terminal.

Cooperative decisions and collaboration among terminals have been considered in the berth planning problem in [7], [8]. To the best of our knowledge, studies on collaborative berth planning among terminals are limited, not to mention the disruption management model. In addition, the authors of [6] and [9] consider transshipment connections between feeder and mother vessels under deterministic assumptions. However, research has not yet investigated disruptions for the berthing plan from this more realistic perspective, that is, considering transshipment connections and the collaboration among terminals together.

In this article, we develop a collaborative berth planning model for terminals in response to disruptions. The Berth Allocation Problem (BAP) is an NP-hard problem, and commercial solvers cannot find optimal solutions in an acceptable time for large-scale instances of the problem. Therefore, we propose Squeaky Wheel Optimization (SWO)-based metaheuristic and conduct computational experiments that demonstrate that the new collaborative approach can yield cost savings of up to 40% for disruption recovery. The main contributions of this study are as follows:

1) We propose a new reactive berth allocation and quay crane assignment problem from a more practical perspective, which considers transshipment connections between feeder and mother vessels. Furthermore, we incorporate the collaboration among terminals by allowing vessels to transfer to other terminals in response to major disruptions;
2) We establish a new Mixed Integer Non-Linear Programming (MINLP) model for the proposed problem, and then we linearize it;
3) We design a dedicated, efficient, and effective SWO-based metaheuristic to solve large-scale instances of the proposed mathematical model, which can obtain the near-optimal solutions within the limited time;
4) The reactive and collaborative berth planning method provides new insights on terminal operators to better respond to disruptions.

The remainder of this paper is organized as follows. Section II presents the related literature, and Section III explains the model formulation. Section IV develops the SWO-based heuristic, and Section V describes the conducted computational experiments. Section VI gives some managerial suggestions, and Section VII presents the conclusions, summing up the major findings and open challenges for future work.

II. RELATED WORK

Traditional berth planning for vessels to call at the container terminals requires making a sequence of decisions. This planning is generally viewed as three hierarchy problems: Berth Allocation Problem (BAP), Quay Crane Assignment Problem (QCAP), and Quay Crane Scheduling problem (QCSP). To support the decision-making process, researchers have developed various models and methods based on operation research techniques, especially the integration of the three problems, namely, the Berth Allocation and Quay Crane Assignment Problem (BACAP) and Berth Allocation and Quay Crane Scheduling Problem (BACSP). Readers may refer to [10]–[12] for comprehensive reviews. In bulk terminals, there are also similar decision-making problems, such as the integration of berth and ship-unloader allocation [13], and the coordination of rake schedule and stockyard operation [14]. The problem addressed in this paper can be referred to as the BACAP including when and where to conduct loading and unloading operations with how many quay cranes for each calling vessel. Relevant studies can be found firstly in [15]. The authors divide the scheduling method into the berth-scheduling phase and crane-assignment phase. In the berth-scheduling phase, the duration of berthing time is directly determined by the number of allocated quay cranes and the subgradient optimization technique is proposed to find a near-optimal solution. The result is applied as the input in the crane-assignment phase. Then some more practical considerations and algorithms have been incorporated in BACAP. In [16], the authors consider the different rates of quay cranes because their productivity can be reduced by the interference among quay cranes. Meta-heuristics of Tabu Search (TS) and Squeaky Wheel Optimization (SWO) are proposed to obtain near-optimal solutions. In [17], the authors loose the restriction on not allowing adjustment of quay cranes during the loading or unloading operation and increase the restrictions on the operation range of quay cranes. In [18], the authors propose a coupling BACAP to minimize not only the service time of vessels but also the number of quay crane shifts. In [19], the authors consider tide factors in berth allocation. In [20], the authors consider a longer planning horizon and propose the tactical BACAP. In [21], the authors especially consider that the demand for quay crane hours is increasing with the deviation from the desired berthing position. As for the heuristics, other than mentioned above, Adaptive Large Neighbourhood Search (ALNS) is proposed in [22]. In [23], the authors focus on the exact algorithm for BACAP. An exact Branch-and-Price (BP) as well as several accelerating schemes have been proposed and examined to outperform commercial solvers.

The research above is based on deterministic information of calling vessels, while many uncertainties exist in reality. In [24], the authors analyze the key factors associated with the efficiency of seaside logistics based on the case of the Indian shipping logistics sector. Their work contributes to getting researchers connected with the practical scenarios. Compared with the extensive literature on berth planning under normal conditions, the studies on responding to disruptions (e.g., uncertain vessel arrival time and quay crane breakdown) are limited. These topics related to the robustness and resilience of maritime logistics systems, however, are now generating considerable recent interest. In response to disruptions, there are two mainstream approaches: proactive and reactive. Some proactive concepts and models have been designed for robust planning to disturbances. In [25], the authors insert time buffers between vessels allocated to the same berthing position to obtain more adjustment flexibility under disruption. In [26], the authors extend the time buffer to vessel-specific buffer times to chase for a higher robustness performance. In [27], the authors propose a robust initial berth plan which incorporates not only anticipation of the uncertainty of arrival time and handling time but also possible recovery cost under practical disruption scenarios. The concept is further applied in [28] which considers both uncertain vessel arrival times and quay crane handling rates. In [4], the authors develop a bi-objective model by minimizing the average and the total service time simultaneously. In [29], the authors firstly propose an initial plan which especially considers quay crane productivity and formulate a robust optimization model with price constraints to deal with the uncertainty of quay crane handling time. For container terminals, a higher degree of robustness generally means a higher possibility of underused berth or quay crane resources. Thus, some studies directly relevant to this paper study the reactive approaches, which means making recovery decisions once the disturbances occurred. Its focus is to mitigate the adverse effects brought by disruptions. In [5], the authors formulate quay crane rescheduling model and berthing position reallocation model according to the degree of disruptions. In [30], the authors consider the early dispatch service under disruptions for some vessels that require early departure and the corresponding profits can be seen as the compensation for recovery cost. In [31], the authors propose a recovery berth plan based on the scheme of updating arrival and handling time in real time. In [32], the authors also regard the baseline schedule as a reference and propose a Mixed-Integer Programming (MIP) to minimize the cost incurred by the deviation from the baseline. In [9], the authors additionally consider the transshipment connection between feeder and mother vessels during the recovery process and try to avoid the delay of transshipment flows caused by disruptions.

Berths and quay cranes are both precious resources in container terminals and the configuration cannot be changed in short-term horizons. Thus, under major disruptions, the responding strategy has to sacrifice the turnaround time of vessels because of the limitation of resource capacity. To overcome this, some models of collaborative planning by increasing the collaboration among multi-user terminals have been proposed. In [7], the authors develop a joint berth scheduling through cooperation between adjacent terminals when an unexpected shutdown happened in a terminal. A decentralized mechanism is proposed based on the flexible scheme of transfer payment adjustment. In [8], the authors propose a new mathematical model for BACAP in a multi-user terminal in which the transfer of vessels to other terminals is allowed through collaboration among them. In [33], the authors propose a collaborative berth planning based on strong collaboration between port terminals and shipping lines from the perspective of the shipping network. For all sailing legs between the nodes in the network, the speed of each vessel can be optimized to reduce total fuel consumption.

Although the concept of collaboration has been applied in liner shipping studies, most of them view the berth allocation at a strategic or tactical management level. There is limited amount of research considering collaborative berth planning from the operational level in response to disruptions. As is shown in Table 1, this paper addresses the reactive BACAP that incorporates the transshipment connections between vessels and collaboration among terminals by allowing vessels to transfer to other terminals. Delay of vessel arrival time and handling time, quay crane breakdown, and unexpected shutdown of the terminal are considered in scenario analysis to testify our model and metaheuristic.

III. PROBLEM DEFINITION

In this section, we first present the reactive BACAP allowing vessels to transfer to other terminals in the context of major disruptions, in which the transshipment connections between feeder and mother vessels are simultaneously considered. Next, we introduce the MINLP model for generating a recovery plan with the minimized cost of deviation from the original one. Assumptions that are in line with the practice needed in our study are listed as follows.

1) The operation process for each vessel is conducted without interruption, which means quay cranes are not allowed to move to other vessels when they are at work.
2) The number of quay cranes that work on the same vessel simultaneously is restricted by a minimum number and the maximum number. The minimum number is based on the agreement between terminal operators and vessel companies, and the maximum number is limited by technical operation requirements.
3) This paper is based on the setting of multi-user terminals. Dedicated terminals are not considered in the proposed problem because the resources cannot be shared for the dedicated terminals that belong to one exact shipping company.

A. PROBLEM DESCRIPTION

Consider the scenario where the disruptions (e.g., vessel arrival delay, quay crane breakdown, and so on) make the initial berthing plan into trouble, affecting the loading or

TABLE 1. Related work for robustness and resilience of the berth and quay crane planning subject to major disruptions.

Reference	Handling Scheme		Considered Disruption			Special Consideration		Uncertainty Representation		Method			Berth Type		Research Problem		
	P	R	UA	UH	QB	TR	CP	SS	PD	M	RO	SP	D	C	BA	BACAP	BACSP
1		*	*					*		*				*		*	*
2	*	*	*	*				*	*			*		*	*		
3	*		*	*				*		*				*	*		
4	*		*	*				*		*			*		*		
5		*	*	*			*	*		*				*		*	
6		*			*		*	*		*				*			*
7	*		*	*				*				*	*		*		
8		*	*	*					*	*			*		*		
9	*		*	*			*	*		*			*			*	
10		*	*	*	*			*		*			*			*	
11	*		*						*			*		*	*		
12	*	*	*	*				*			*			*	*		
13	*	*	*	*				*	*			*		*		*	
14		*					*	*		*				*			*
15		*	*			*		*		*				*		*	
This study		*	*	*	*	*	*	*		*				*		*	

P: proactive; R: reactive;
UA: uncertainty of arrival time; UH: uncertainty of handling time; QB: quay crane breakdown;
TR: transshipment between feeder and mother vessels; CP: collaborative planning;
SS: scenario simulation; PD: probability distribution;
MIP: mixed integer programming; RO: robustness optimization; SO: stochastic programming;
D: discrete; C: continuous;
BA: berth allocation problem; BACAP: berth allocation and quay crane assignment problem; BACSP: berth allocation and quay crane scheduling problem

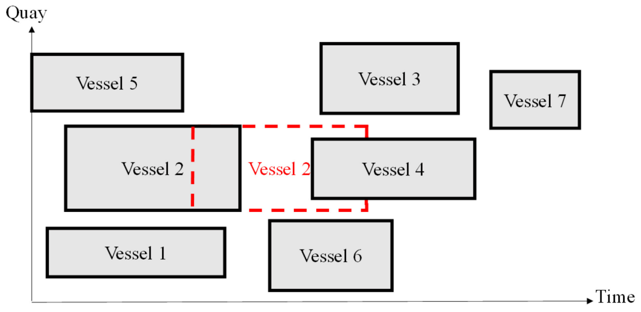


FIGURE 1. Initial berthing plan under the disruption.

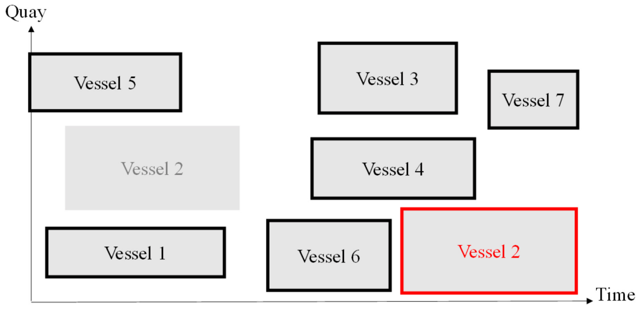


FIGURE 2. Reactive berthing plan without considering the transshipment connection.

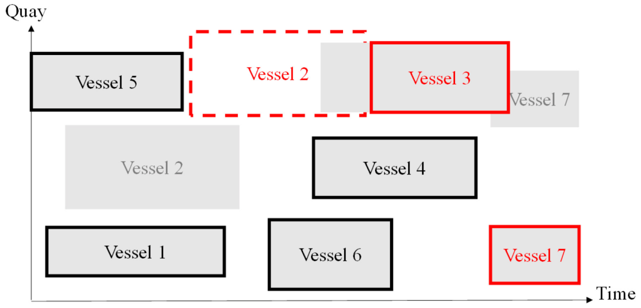


FIGURE 3. Reactive berthing plan considering the transshipment connection.

discharging operations of one or a few vessels. As illustrated in Fig. 1, the delay of the initial plan for Vessel 2 causes the plan for Vessel 4 invalid, and some adjustment for the initial plan is needed. For container terminals, rescheduling the berthing plan at a lower cost as well as reducing the disturbance to the whole system incurred by disruptions is important. Thus, the objective of the studied reactive berthing problem mainly considers minimizing the cost of space deviation and time deviation from the original plan.

For some instances where exist transshipment connections between vessels, the delay of operation for vessels has to be specially considered. As shown in Fig. 2, the transshipment from Vessel 2 to Vessel 7 cannot be fulfilled as planned, which causes unnecessary holding costs of the delayed containers. In Fig 3, the transshipment between Vessel 2 and Vessel 7 can be satisfied by adjusting vessel 3 and Vessel 7, which is at the cost of a higher deviation from the initial plan. Facing major disruptions, as shown in Fig 4, Vessel 2 is also allowed to transfer to other terminals to eliminate the disturbance to the current terminal. However, reassigning vessels to other terminals can incur the extra cost of inter-terminal and intra-terminal transportation.

As mentioned above, the post-disruption berthing plan needs sophisticated decision-making support. The challenge is how to make a trade-off between the deviation cost, the transshipment delay cost, and the transfer cost. Thus, the objective function in this paper consists of three parts. The first part presents the deviation cost of berthing

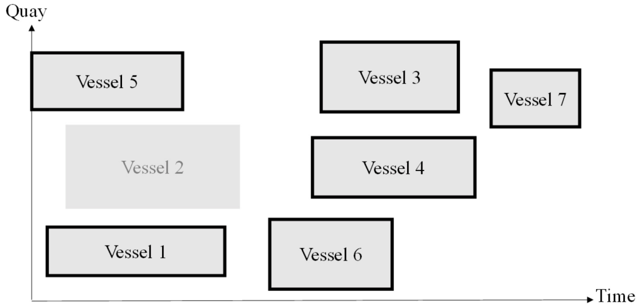


FIGURE 4. Reactive berthing plan by transferring Vessel 2 to the other terminal.

position and the tardiness of departure time. The second part considers the penalty cost of transshipment delay between vessels. The third part regards allowing vessels to transfer to other terminals. The number of quay cranes is also reassigned during the process simultaneously.

B. MODEL FORMULATION

Following the notation of the earlier paper [9], we define the notations for mathematical modelling in this paper:

Sets:

- V: Set of all vessels, $V = \{0, 1, \dots, |V|\}$;
- V_1: Set of mother vessels, $V_1 \subset V$;
- V_2: Set of feeder vessels, $V_2 \subset V$;
- T: Set of one-hour time periods, $T = \{0, 1, \dots, |T|\}$;
- I: Set of transshipment flows, $I = \{0, 1, \dots, |I|\}$;
- P: Set of complementary terminals, $P = \{0, 1, \dots, |P|\}$;

Parameters:

- c_0: Time cost of delay for each period;
- c_1: Unit cost of horizontal moving of containers;
- c_2: Penalty cost for missing of transshipment flow;
- c_3^p: Extra cost incurred by transferring a vessel to terminal $p \in P$;
- l_i: Length that vessel $i \in V$ will occupy;
- b_i: The berthing position of vessel $i \in V$ in the initial plan;
- d_{ij}: 20-ft equivalent units required to be operated from vessel $i \in V$to vessel $j \in V$;
- w_i: QC capacity demand by vessel $i \in V$ given as number of QC-hours;
- q_i^{min}: Minimum number of QCs needed to serve vessel $i \in V$;
- q_i^{max}: Technically maximum number of QCs allowed to serve vessel $i \in V$;
- MAX_p: Maximum number of vessels that can be transferred to terminal $p \in P$
- g_i: Total 20-ft equivalent units required to be loaded or discharged on vessel $i \in V$;
- Δ: The time interval of preparing for transshipment operation;
- AR_i: Actual arriving time of vessel $i \in V$;
- ST_i: Initial operation start time of vessel $i \in V$;
- CT_i: Initial operation completion time of vessel $i \in V$;
- Q: Total number of available QCs in the terminal;
- L: Length of the quay;

Decision variables:

- b'_i: Actual berthing position of vessel $i \in V$;
- $x_{ij} \in \{0, 1\}$: 1 if vessel$i \in V$ is berthed on the left of vessel $j \in V$ in the space dimension, and 0 otherwise, $i \neq j$;
- $y_{ij} \in \{0, 1\}$: 1 if vessel $j \in V$ is berthed after the operation of vessel $i \in V$ in the time dimension, and 0 otherwise, $i \neq j$;
- $\gamma_{it} \in \{0, 1\}$: 1 if at least one QC is assigned to vessel $i \in V$ at time $t \in T$, and 0 otherwise;
- $\lambda_{ij} \in \{0, 1\}$: 1 if transshipment flow from vessel $i \in V$ to vessel $j \in V$ is missed, and 0 otherwise, $i \neq j$;
- $k_{ip} \in \{0, 1\}$: 1 if vessel $i \in V$ is transferred to terminal $p \in P$, and 0 otherwise;
- $ST'_i \geq 0$: Actual operation starting time of vessel $i \in V$;
- $CT'_i \geq 0$: Actual operation completion time of vessel $i \in V$;
- $q_{it} \geq 0$: Number of QCs assigned to vessel $i \in V$ at time $t \in T$;

Based on the above notations, the reactive model for collaborative berth planning problem is formulated as follows:

$$\begin{aligned} \min z = & \sum_{i \in V} c_1 g_i \left| b_i - b'_i \right| \\ & + \sum_{i \in V} c_0 \left(CT'_i - CT_i - M \cdot \sum_{p \in P} k_{ip} \right)^+ \\ & + \sum_{i \in V} \sum_{j \in V} c_2 d_{ij} \lambda_{ij} + \sum_{i \in V} \sum_{p \in P} c_3^p g_i k_{ip} \end{aligned} \tag{1}$$

Subject to:

$$c_1 g_i |b_i - b'_i| \leq M \cdot \left(1 - \sum_{p \in P} k_{ip} \right) \quad \forall i \in V \tag{2}$$

$$\sum_{p \in P} k_{ip} \leq 1 \quad \forall i \in V \tag{3}$$

$$\sum_{i \in V} k_{ip} \leq MAX_p \quad \forall p \in P \tag{4}$$

$$\sum_{t \in T} \gamma_{it} = CT'_i - ST'_i \quad \forall i \in V \tag{5}$$

$$AR_i \leq ST'_i < CT'_i \quad \forall i \in V \tag{6}$$

$$ST'_i \leq \gamma_{it} \cdot t + M(1 - \gamma_{it}) \quad \forall i \in V, t \in T \tag{7}$$

$$CT'_i \geq \gamma_{it} \cdot (t + 1) \quad \forall i \in V, t \in T \tag{8}$$

$$\sum_{t \in T} q_{it} \geq w_i \left(1 - \sum_{p \in P} k_{ip} \right) \quad \forall i \in V \tag{9}$$

$$\sum_{i \in V} q_{it} \leq Q \quad \forall t \in T \tag{10}$$

$$M \cdot (\gamma_{it} - 1) - q_{it} < 0 \quad \forall i \in V, t \in T \tag{11}$$

$$q_{it} \leq M \cdot \gamma_{it} \quad \forall i \in V, t \in T \tag{12}$$

$$q_{it} \geq 0 \quad \forall i \in V, t \in T \tag{13}$$

$$q_{it} \geq \gamma_{it} \cdot q_i^{min} \quad \forall i \in V, t \in T \tag{14}$$

$$q_{it} \leq q_i^{max} \quad \forall i \in V, t \in T \tag{15}$$

$$b'_i + l_i \leq b'_j + M \cdot (1 - x_{ij}) + M \cdot \sum_{p \in P} k_{ip} \quad \forall i \in V, j \in V, i \neq j \tag{16}$$

$$CT'_i \leq ST'_j + M \cdot (1 - y_{ij}) + M \cdot \sum_{p \in P} k_{ip} \quad \forall i \in V, j \in V, i \neq j \tag{17}$$

$$x_{ij} + x_{ji} + y_{ij} + y_{ji} \geq 1 - M \cdot \sum_{p \in P} k_{ip} \quad \forall i \in V, j \in V, i \neq j \tag{18}$$

$$M \cdot (\lambda_{ij} - 1) - \left(CT'_i + \Delta - ST'_j\right) < M \sum_{p \in P} k_{ip} \quad \forall i \in V, j \in V, i \neq j \tag{19}$$

$$M \cdot \lambda_{ij} - \left(CT'_i + \Delta - ST'_j\right) \geq -M \cdot \sum_{p \in P} k_{ip} \quad \forall i \in V, j \in V, i \neq j \tag{20}$$

$$\lambda_{ij} \leq M \cdot \left(1 - \sum_{p \in P} k_{ip}\right) \quad \forall i \in V, j \in V, i \neq j \tag{21}$$

$$0 \leq b'_i \leq L - l_i \quad \forall i \in V, j \in V \tag{22}$$

$$x_{ij} \in \{0, 1\} \quad \forall i \in V, j \in V \tag{23}$$

$$y_{ij} \in \{0, 1\} \quad \forall i \in V, j \in V \tag{24}$$

$$\lambda_{ij} \in \{0, 1\} \quad \forall i \in V, j \in V \tag{25}$$

$$\gamma_{ij} \in \{0, 1\} \quad \forall i \in V, j \in V \tag{26}$$

$$k_{ip} \in \{0, 1\} \quad \forall i \in V, j \in V \tag{27}$$

$$ST'_i \geq 0 \quad \forall i \in V \tag{28}$$

$$CT'_i \geq 0 \quad \forall i \in V \tag{29}$$

The objective function (1) is to minimize the total cost of the reactive berthing plan, including spatial deviation from the initial plan, tardiness of planned departure time, penalty of transshipment delay between correlated vessels, and extra cost incurred by reassigning vessels to collaborative terminals. Constraint (2) presents that the deviation cost and transshipment delay cost of Vessel i can be avoided by reassigning it to other terminals. Constraint (3) ensures that each Vessel i can be transferred to only one collaborative terminal at most. Constraint (4) restricts the number of vessels transferred to the same terminal p cannot exceed its large capacity. Constraints (5)-(8) restrict the completion time and the start time of Vessel i. Constraint (9) ensures that requirements for QC-hour of Vessel i after adjustment can be satisfied. Constraint (10) guarantees the number of QCs assigned to time t without beyond the total number of QCs. Constraints (11)-(14) restrict the relationship between variables q_{it} and γ_{it}. Constraints (15) restricts the maximum number of QCs that can be assigned to each Vessel i. Constraint (16) denotes the relationship between berthed vessels in the dimension of space. Similarly, constraint (17) states that relationship in the time dimension. Constraint (18) ensures that no overlapping exists in berthing time and berthing position. Constraints (19) and (20) are the definition of λ_{ij}. Constraints (22) states the berthing position limitation by the length of quay line. Constraints (23)-(29) specify the range of decision variables.

The terms of calculating deviation of the berthing position and tardiness of the departure time in the objective function (1) and constraint (2) are nonlinear. Thus, they need to be linearized by defining an additional decision variable $\theta_i = |b_i - b'_i|$ and $\xi_i = (CT'_i - CT_i)^+$. The related additional constraints are defined as follows:

$$\theta_i \geq b'_i - b_i - M \cdot \sum_{p \in P} k_{ip} \quad \forall i \in V \tag{30}$$

$$\theta_i \geq b_i - b'_i - M \cdot \sum_{p \in P} k_{ip} \quad \forall i \in V \tag{31}$$

$$\xi_i \geq CT'_i - CT_i - M \sum_{p \in P} k_{ip} \quad \forall i \in V, p \in P \tag{32}$$

$$\theta_i \leq M \cdot \left(1 - \sum_{p \in P} k_{ip}\right) \quad \forall i \in V \tag{33}$$

$$\xi_i \geq 0 \quad \forall i \in V \tag{34}$$

$$\theta_i \geq 0 \quad \forall i \in V \tag{35}$$

Therefore, the reactive model for collaborative berthing plan problem can be reformulated as a mixed integer linear program as follows:

$$\begin{aligned} \min \quad z = & \sum_{i \in V} c_1 g_i \theta_i + \sum_{i \in V} c_0 \cdot \xi_i \\ & + \sum_{i \in V} \sum_{j \in V} c_2 \lambda_{ij} d_{ij} + \sum_{i \in V} \sum_{p \in P} c_3^p g_i k_{ip} \\ \text{Subject to} \quad & \text{Constraints (3)–(35).} \end{aligned} \tag{36}$$

IV. SOLUTION APPROACH

The BAP has been recognized as an NP-hard problem. Compared with BAP, the proposed reactive berthing plan problem extends to consider vessel transfer between terminals and vessel-to-vessel transshipment as well as quay crane assignment, which should also be an NP-hard problem. Exact solutions are only achievable for small-scale instances and may not be practical for solving large-scale problems. SWO has demonstrated effective performance in solving related problems (as described in Section II) whose objective function consists of multiple individual elements. In this work, the objective function represents the total cost for rescheduling the berthing plan after disruptions, which can be decomposed into the cost of each vessel during the rescheduling process. Therefore, the SWO-based heuristic method is developed.

A. SWO-BASED HEURISTIC FRAMEWORK

The idea of the SWO-based heuristic approach is to search solutions through two-phase (construction phase and priority phase) in two spaces: priority space and solution space, as

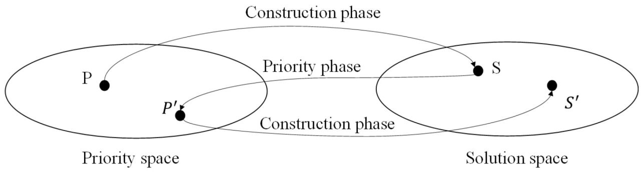


FIGURE 5. **Principle of the SWO Algorithm.**

Algorithm 1: General Framework of the SWO-Based Heuristic

```
Input: baseline parameters
initialization;
while the termination criteria is not met do
    construction phase: obtain feasible solution
        $(b'_i, CT'_i, k_{ip})$
    calculate the individual cost $z^i$
        $c_1 g_i |b_i - b'_i| + c_0^i (CT'_i - CT_i)^+ + c_2 \sum_{j \in V} d_{ij} \lambda_{ij}$
    priority phase: generate a new order $inseq'$ return:
    the minimal cost of all vessels.
end
```

shown in Fig. 5. In the studied problem, a point in the priority space denotes an order of vessels for resource allocation and a homologous point in the solution space represents the potential solutions. The construction phase is to find a set of feasible solutions under the given processing order for vessels, and then update the point in the priority space by priority phase, in which the order of vessels is reassigned according to the cost of each vessel. The principle is the vessels with higher costs are assigned a higher priority. SWO schemes to explore better solutions via a coherent shift in the priority space and solution space iteratively. The outline of the solution framework is presented in Algorithm 1.

B. CONSTRUCTION PHASE

The procedure in the construction phase is shown in Fig. 6. In Step (a) the iteration number is counted. In Step (b) and (c) the berthing position of Vessel i is set as the baseline and the berthing time is set to the actual arrival time. If the available number of quay cranes is larger than q_i^{min}, in Step (d) the number of quay cranes is allocated to Vessel i to handle the vessel as fast as possible until Constraint (9) holds. If the available number of quay cranes is less than q_i^{min} before satisfying Constraint (9), the quay crane assignment stopped. Postponing the berthing time in Step (e) and the quay crane assignment is then reallocated by returning to Step (d), which incurs a longer waiting time for Vessel i after arrival but guarantees no deviation of the berthing position. Certainly, the waiting time should not be too long so if it exceeds the limitation, a new berthing position is generated in Step (f) and return to Step (c). Because the large deviation of the berthing position from the original one means the great cost of horizontal moving of containers, the new berthing position is restricted in $[b_i - l_i b_i + l_i]$. After the quay crane assignment of Vessel i is finished, the completion time for Vessel i can be fixed and one vessel has been arranged already. Then check whether the vessel overlaps with other vessels in the space-time diagram. If there is no overlapping, compare the cost of rescheduling Vessel i with transferring Vessel i to other terminals, choose one with less cost in Step (g). Arrange next Vessel i' until all the vessels have been inserted. Otherwise, the arrangement of Vessel i will be processed again from the new generation of berthing positions. Once the berthing position and quay crane assignment for all vessels are determined, the total cost can be calculated according to function (1). Then return to Step (a) to start the next iteration until the maximum iteration times. Finally, the construction phase returns the best-found solutions under the current given order of vessel.

C. PRIORITY PHASE

The point of the priority phase is to find a neighborhood sequence for the given order of vessels. The basic idea is swapping the sequence of two vessels if the higher priority vessel makes less contribution regarding overall cost than the lower priority one: choose two Vessels i and j from the last iteration, compare the objective value z^i and z^j. If Vessel i is inserted before Vessel j and $z^j \geq z^i$, then these two Vessels i and j should be swapped and a new order is generated accordingly. An example is shown in Fig. 7. Generally, the concept of SWO is to figure out the 'bottle neck' elements which contribute a relatively large proportion to the objective value and then to give them higher priority during resource allocation to search for better solutions. Thus, after the priority phase, the vessel with the largest cost obtained in the construction phase should have the highest priority in the new order of vessels and so on.

V. COMPUTATIONAL STUDY

The SWO-based heuristic is running on a PC with 1.70 GHz CPU and 8 GB RAM under C++ environment. The mathematical model is solved by CPLEX12.8 and running time is reported in seconds. In this section, the instance generation and experimental parameters are introduced firstly. And then we design comprehensive computational experiments in order to assess the efficiency and effectiveness of the proposed mathematical model and the SWO-based heuristic.

A. GENERATION OF INSTANCES

The detailed attributes of three-vessel types (Feeder, Medium, and Jumbo) are generated according to Table 2. In addition, the number of transshipment containers between feeder and mother vessel d_{ij} is generated in accordance with industry standards. The number of the collaborative terminals is distinct in different scenarios, but it is not more than 5. We restrict the number of collaborative terminals to no more than 3. The post-disruption BACAP planning horizon is one week

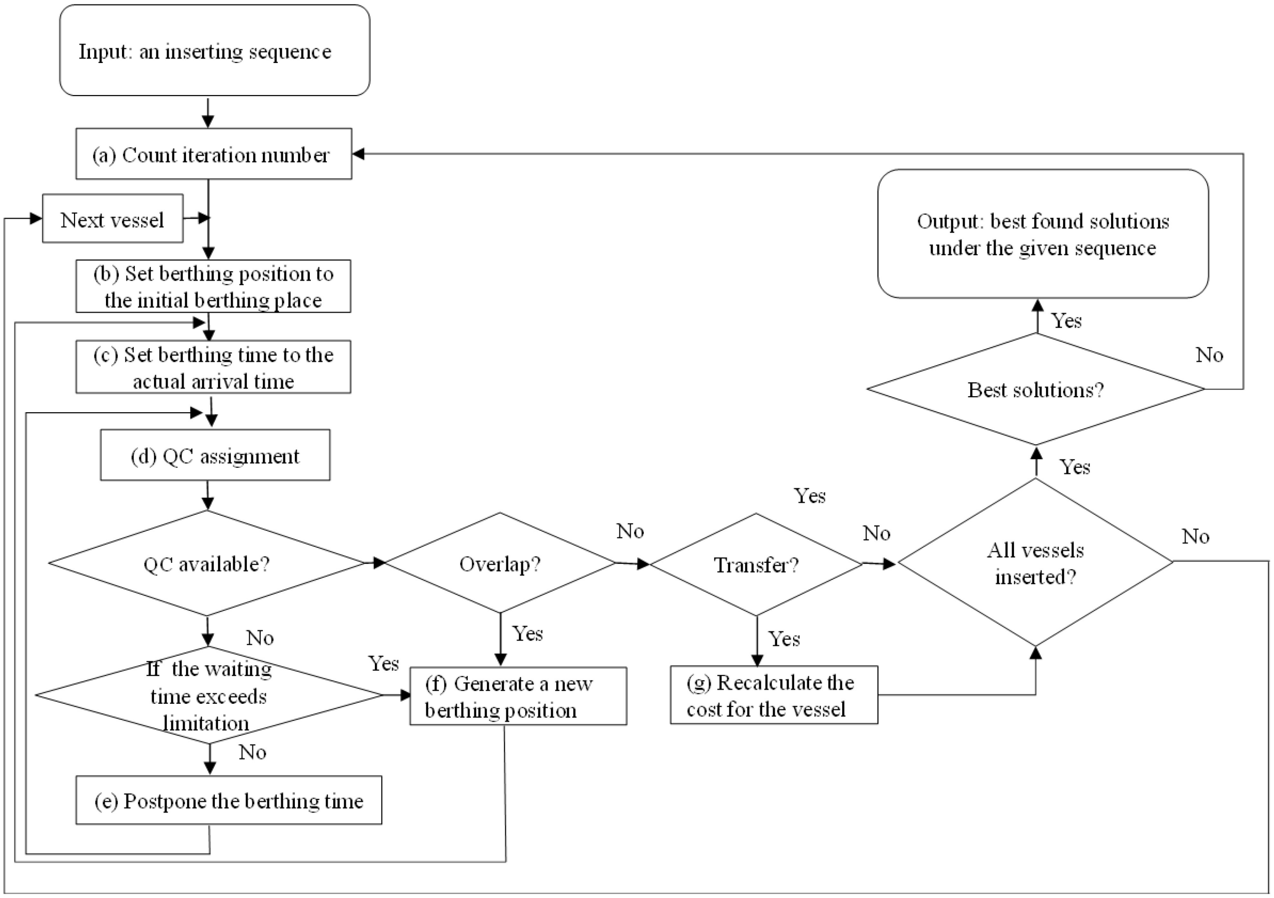


FIGURE 6. Construction phase.

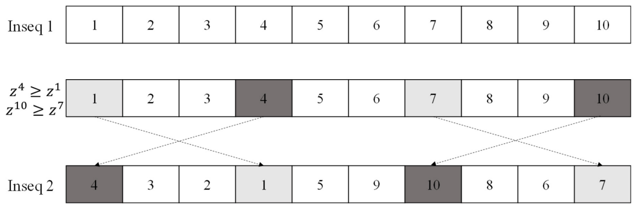


FIGURE 7. Priority phase.

TABLE 2. Vessel types and related attributes.

Types	l_i(m)	w_i(qc*hour)	q_i^{min}	q_i^{max}	TEU
Feeders	U[8,21]	U[4,15]	1	2	U[500,3500]
Mother-Medium	U[21,30]	U[15,36]	1	4	U[3500,5000]
Mother-Jumbo	U[30,40]	U[36,48]	3	6	U[5000,7500]

(168 h) and the length of the quay side is set as 3250m. The time interval for preparing for transshipment between vessels δ is 10. Other parameters related to the cost are set as In c1, 1 should be the subscript of c. The same with c2 and c0. The terminated iteration number of the SWO heuristic is 1000.

B. RESULTS ON SMALL-SCALE INSTANCES

Table 3 presents the total cost given by SWO-based heuristics and CPLEX (with the model proposed in Section III). The instances include 15 vessels, in which 5 mother vessels, 10 feeder vessels and the number of transshipment flow between feeder and mother vessels is 10. The proportion of vessels facing operation delays due to disruptions is 20%, 40% and 60% and their delay time is set as 5, 10, 15 respectively. For the results obtained by CPLEX, the objective value is denoted by z^{MIP} and the computational time is reported. For the SWO-based heuristic, we report the similar information and the total cost during the post-disruption rescheduling is denoted by z^{SWO}. The last column in the table represents the gap percentage between the MILP solution and SWO

TABLE 3. Results of SWO-based heuristic with CPLEX.

Delay Proportion	Instance Id	Delay hours	Cplex		Swo		Gap
			z^{MIP}	Time	z^{SWO}	Time	
20%	Data_I1	5	622.6	0.8	622.6	3.84	0%
	Data_I2	10	772.6	0.73	772.6	3.06	0%
	Data_I3	15	944.2	0.46	944.2	3.02	0%
40%	Data_I4	5	672.6	0.67	672.6	2.99	0%
	Data_I5	10	1309.34	0.96	1309.34	4.88	0%
	Data_I6	15	1559.34	0.69	1559.34	4.82	0%
60%	Data_I7	5	822.6	0.75	822.6	2.98	0%
	Data_I8	10	1609.34	0.75	1609.34	4.91	0%
	Data_I9	15	1122.6	0.57	1122.6	2.95	0%

TABLE 4. Instance parameters.

Instance	$\|V\|$	$\|V1\|$	$\|V2\|$	$\|I\|$
Set 1	15	5	10	10
Set 2	21	6	15	30
Set 3	28	8	20	40
Set 4	40	10	30	60

solution, which is calculated by:

$$\frac{|Z^{SWO} - Z^{MIP}|}{Z^{MIP}} \times 100\% \tag{37}$$

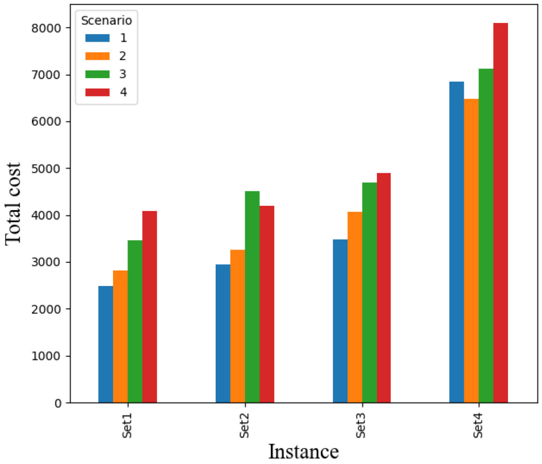
As shown in Table 3, the proposed SWO-based heuristic is able to obtain high quality solutions for the small-scale problem with 15 vessels and 10 transshipment flows between vessels.

C. IMPROVEMENT FROM ALLOWING VESSELS TRANSFER TO COLLABORATIVE TERMINALS

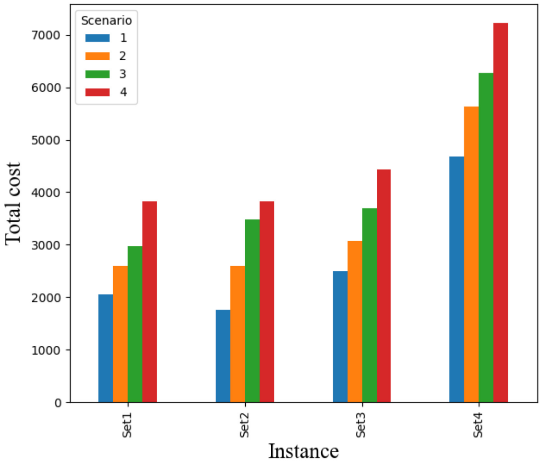
We also conduct some experiments to testify the effectiveness by allowing vessels to transfer to collaborative terminals when disruptions happened. As shown in Table 4, we generate four instance sets with different number of vessels and it varies between 15, 21, 28, and 40, for example, there are 28 vessels in Set 3, in which 8 mother vessels, 20 feeder vessels, and 20 transshipment connections occur. Four disruption scenarios are generated. In scenario 1, 30% of vessels are delayed to be operated because of vessel arrival delay and quay crane breakdown. The proportion is 35%, 40% and 50% in scenario 2, scenario 3 and scenario 4 respectively. Set1-01 means the instance Set 1 under Scenario 1. The results obtained by the SWO-heuristic with and without considering collaboration between terminals are presented in Table 5 and Fig. 8. The percentage of cost savings of four sets in four scenarios are obviously shown in Fig. 9. During the post-disruption rescheduling process for berthing plan, allowing vessels to transfer to other terminals can help to save 40% of the total cost at most. Thus, it is concluded that considering vessels transfer between terminals via collaboration is meaningful in response to disruptions.

D. PARAMETER SENSITIVITY ANALYSIS

The unit cost of horizontal moving of containers c_1 and penalty cost for delaying transshipment flow c_2 affect the final results. Hence, we analyze the two parameters to show their influence on the objective function. In Fig. 10(a), c_1 is set from 0.01 to 0.08, c_2 is kept at 0.1. It is shown that c_1 has a slight impact on objective function in Set 1-3 while a relatively significant influence in Set 4. These results show that larger container terminals are more sensitive to the price for horizontal container moving. In Fig. 10(b), c_1 is set as 0.01 while c_2 varies from 0.2 to 0.8. The results show that c_2 has a larger impact on the objective function than c_1. For container terminal operators, they can estimate the corresponding recovery cost according to the different penalties of transshipment delay, so as to make reasonable decisions on disruption recovery.



(a) Without collaboration



(b) With collaboration

FIGURE 8. Total cost with collaboration and without collaboration.

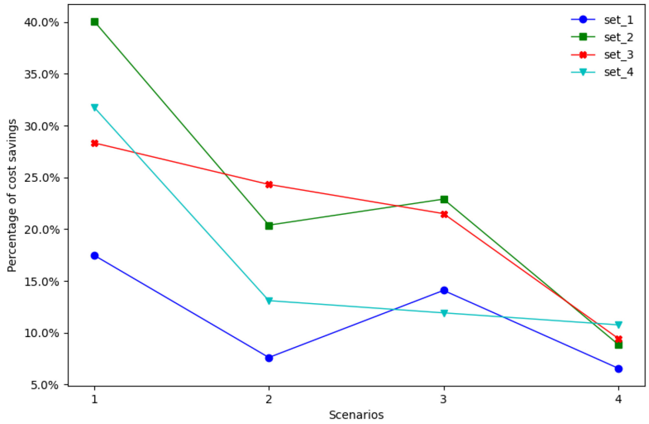


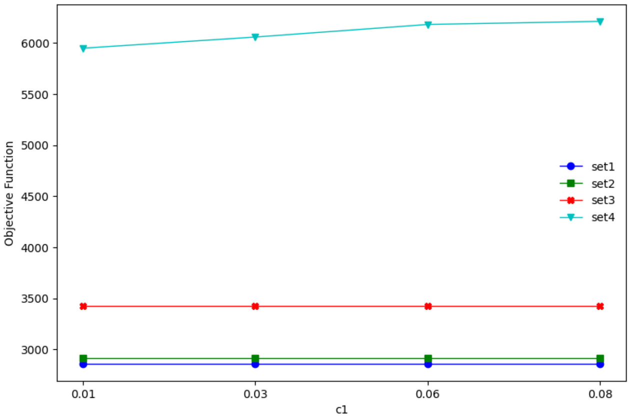
FIGURE 9. Percentage of cost savings in four scenarios by considering collaboration.

E. MEASURING THE COST OF RESILIENCE

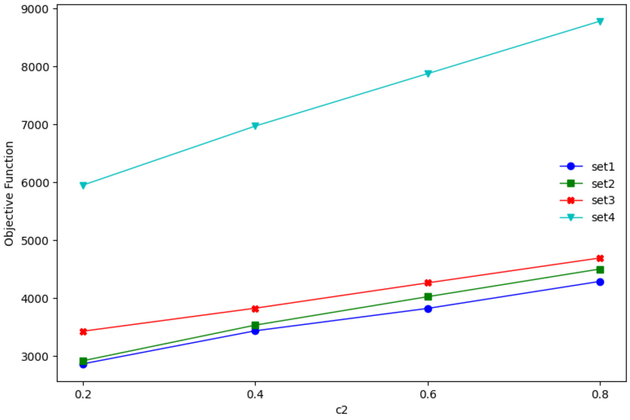
The recovery cost with collaboration is lower than without collaboration, which means the terminal operators pay less in response to disruptions by considering collaboration. To

TABLE 5. Results of SWO-heuristic with and without considering collaboration between terminals.

Instance ID	Without collaboration		With collaboration		Improvement (3)
	Total cost(1)	Time	Total cost(2)	Time	
Set1-01	2490.80	3.00	2055.76	11.12	17.47%
Set1-02	2810.80	2.83	2597.26	5.91	7.60%
Set1-03	3450.80	2.99	2964.90	11.74	14.08%
Set1-04	4090.80	4.86	3822.28	7.76	6.56%
Average	-	-	-	-	11.43%
Set2-01	2935.80	3.43	1759.35	13.11	40.07%
Set2-02	3255.80	3.67	2592.28	10.62	20.38%
Set2-03	4513.40	3.56	3480.48	14.07	22.89%
Set2-04	4193.40	3.75	3821.80	10.59	8.86%
Average	-	-	-	-	23.05%
Set3-01	3485.80	5.92	2498.51	19.07	28.32%
Set3-02	4061.80	6.10	3074.51	19.44	24.31%
Set3-03	4701.80	6.10	3691.23	19.49	21.49%
Set3-04	4893.80	7.16	4431.96	20.37	9.44%
Average	-	-	-	-	20.89%
Set4-01	6850.68	8.98	4674.82	32.43	31.76%
Set4-02	6474.27	8.59	5626.80	29.90	13.09%
Set4-03	7114.27	8.55	6266.80	29.85	11.91%
Set4-04	8097.70	8.57	7226.80	30.27	10.75%
Average	-	-	-	-	16.88%



(a) Impact of parameter c_1



(b) Impact of parameter c_2

FIGURE 10. Impact of parameter c_1 and c_2 on the objective function.

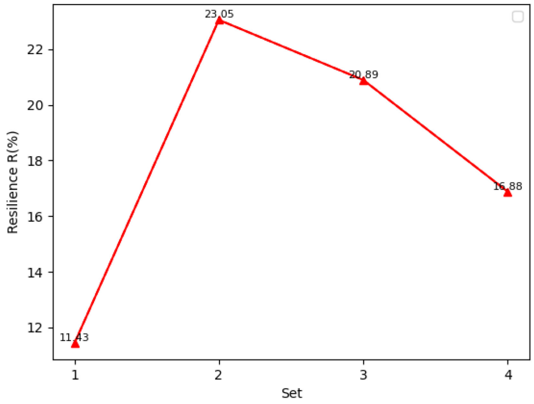


FIGURE 11. Different R under different instance set.

some extent, cost savings can be used to measure resilience. Thus, we applied the metrics proposed by [34]:

$$R = \frac{\sum_u^d C_u(t) - \sum_u^d \sum_m C_u^m(t) - \sum_m C_m(t)}{\sum_u^d C_u(t)} \tag{38}$$

Here, $\sum_u^d C_u(t)$ is the summation of recovery cost at time t under disruption d without any resilience mechanism and $\sum_u^d \sum_m C_u^m(t)$ represents the corresponding sum of recovery costs with resilience mechanism m. $\sum_u^d \sum_m C_u^m(t)$ is the cost associated with the investment of mechanism m. R values from 0 to 1. $R = 1$ implies perfect resilience while $R = 0$ implies less resilience to disruption. In this paper, we can simplify (38) into the following formulation:

$$R = \frac{\sum_u^d C_u(t) - \sum_u^d C_u^{wc}(t)}{\sum_u^d C_u(t)} \tag{39}$$

In our case, the mechanism is considering collaboration among terminals and the investment associated with the mechanism (extra cost incurred by transferring a vessel to terminal) has been calculated into the recovery cost $\sum_u^d C_u^{wc}(t)$. Fig.11 shows different R under different instances from Set1 to Set4.

VI. DISCUSSION

In this paper, we propose a collaborative berth planning approach to decide when and where the calling vessels should be berthed and which quay cranes should be assigned after disruptions occurred. With computational experiments considering four disturbance scenarios and we obtain several managerial insights for terminal operators and policy implications for handling disruptions at ports:

1) Our experiments show that the average cost savings brought by collaboration among terminals are in the range of 11.43%-23.5%. Therefore, terminal operators should consider establishing some forms of collaboration to allow integrated berthing plans to minimize disruptions and reduce recovery costs. For instance, in some disruption cases where the number of berths or quay cranes fails to satisfy the calling vessels, some vessels could be transferred to other terminals.

Of course, the extra cost caused by transferring vessels depends on the agreement with the collaborative terminals and there is a trade-off between service level and service cost for the disrupted terminals.

2) The percentage of cost savings in scenario 1 where the delayed proportion is 30% is greatly higher than in scenario 4 that is 50% disturbance. The results are reasonable because it is difficult to recover the berthing plan when the terminal gets into faces disruption. But in most cases, for instance, when the disturbance percentage is less than 50%, it is important to take measures at the operational level to prevent the terminal from getting congested. Otherwise, terminal operators need to resort to some tactical measures (e.g., speeding up vessels or changing the calling ports).
3) The proposed SWO-based metaheuristic is able to provide effective decision support for terminal operators within 60 seconds, which is meaningful in practice because compared to predicting the occurrence of disturbances, a rapid post-disruption recovery plan is more needed.
4) In the proposed approach, the operation time for each vessel is affected by the number of allocated quay cranes to reflect the systematic nature of the berth planning problem. Thus, terminal operators should employ an integrated mathematical model to make decisions, for instance, the integrated berth allocation and quay crane scheduling.
5) Traditional rules for disruption recovery such as First-Come-Fist-Service and Large-Vessel-First cannot work well in practice, especially in container transshipment terminals. The delayed containers that should be transshipped between feeder and mother vessels in this period not only occupy the resources of terminals but also incur extra costs. Thus, terminals operators should take into consideration the transshipment connections when rescheduling the original berthing plan to avoid the implied cost.

VII. CONCLUSION

The research trend on berth planning has shifted from deterministic models to models with uncertainty considerations reflecting the increasing importance of disruptive event in real-world. In [5] and [28], for instance, the authors propose two disruption recovery models in response to disruptions according to different scenarios. However, these studies mostly assume that each terminal makes its own independent plans, that is, the berthing plan of incoming vessels can only be adjusted within the current terminal when the disruption happens. In this work, we propose a collaborative berth planning approach for disruption recovery that explicitly considers collaboration between the terminals, allowing vessels to transfer to other terminals and transshipment connection between vessels. For the proposed MINLP model, the commercial solver, CPLEX, is used to find the optimal solutions and an SWO-based heuristic is presented for treating problems of larger size. Numerical experiments show that the SWO-based metaheuristic can obtain solutions (near)-optimal solutions for small-scale problems, and it provides solutions within the time requirements when the instance size grows. These results add to the research on berth planning recovery problem, confirming the effectiveness and efficiency of the proposed model and metaheuristic. Most importantly, the experimental comparisons show that the collaboration between terminals helps to save up to 40% of the total recovery cost. Therefore, our findings indicate that allying terminals to share berthing resources is a potential solution in response to disruptions. To the best of our knowledge, this is the first work to consider the transshipment connections between vessels as well as the collaboration between terminals for a in berth planning recovery problems. Our results show a significant potential for establishing and exploring forms of collaboration between terminal operators to achieve a higher-level performance on efficiency and reliability. This work does not consider negotiation between the collaborating terminals, however, to some extent, the recovery cost savings by collaboration depends on the negotiated payment between terminals. Thus, future work should incorporate negotiation mechanisms in the suggested approach.

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