Disruption Management-Based Coordinated Scheduling for Vessels and Ship Loaders in Bulk Ports

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Abstract:

For ensuring the orderly operation of the port, it is vital to coordinately schedule available ship loaders and vessels that plan to enter and exit the port when ship loaders are unable to work due to faults. Therefore, this paper studies the coordination between vessels and ship loaders scheduling problem affected by failed ship loaders (VSLPB), and proposes a novel disruption management-based method to address this problem. An innovative optimization model is developed to reduce the generalized cost with the constraints of disruption management strategies (DMS), aiming to minimize the impact of failed ship loaders on the coordinated scheduling and the bulk cargo handling efficiency. For solving the VSLPB, an effective two-stage row generation (TSRG) algorithm is developed. In the first stage, the disruption conditions in the model are released to find the available ship loaders and berths for vessels affected by the failure factors. In the second stage, the optimal strategy is sought among multiple DMS to minimize the objective function value. Using the proposed method in Huanghua Coal Port as a case study, the results show that our method can effectively solve the impact of ship loader failure on the efficiency of bulk cargo handling and the efficiency of vessels entering and leaving the port. These further highlights the importance of implementing DMS, and show that the proposed method can provide an efficient and reliable solution for port production and operation to deal with disruption problems. Furthermore, the proposed method in this paper can help improve the ability of the port to resist uncertain factors, thus improving the ability of the entire supply chain to resist risks.

Key words: Bulk Port; Disruption Management; Vessel Traffic Scheduling; Coordinated Scheduling; Ship Loader Failure; Row Generation

1. Introduction

The worldwide dry bulk shipping industry is increasing, and the Baltic exchange dry index (BDI) hit a 12-year high of 5,650 points in early October 2021; in 2021, the average value of the BDI was 2,943 points, up 176.1 percent in the corresponding period. Moreover, the worldwide dry bulk cargo market's transportation capacity reached 945 million deadweight tonnage (DWT) at the end of 2021, up around 3.6 percent [1]. With this background, the throughput of bulk ports increases, which puts forward new requirements and challenges for the efficiency of bulk vessels scheduling at bulk ports. To solve this, terminal operators around the world are committed to improving efficiency by updating equipment and enhancing management levels. However, the efficiency of vessels entering and leaving the port is still constrained by various reasons and has not considerably improved. As a result, a significant mismatch between the efficiency of ship loaders and the efficiency of vessels entering and leaving the port appears, which eventuates in an increased waiting time of vessels at the port and subsequentially affects the efficiency of the port. Ship loaders are the equipment that connects terminals and vessels directly, and ship loader allocation is essential to vessel traffic scheduling in decreasing the waiting time of vessels. Thus, coordinating and optimizing ship loader and vessel traffic organization to generate the initial scheme is an awkward problem [2].

However, as one of the crucial ways to improve the efficiency of vessels entering and leaving the port, vessel traffic scheduling is easily affected by the ship loader, especially the ship loader failures during the scheduling process. Moreover, when executing the initial scheme, operations in modern coal terminals are frequently interrupted [3], resulting in the initial scheme being inapplicable. In practice, the terminal's adjustment configuration for the plan is based mainly on the unique scenario and prior operational experience, lacking systematic adjustment goals. As a result, the whole system will be severely disrupted, which could lead to issues like service quality degradation, decreased efficiency, cost increases, etc. In summary, it is necessary to coordinate ship loader allocation and vessel inbound and outbound process, and study how to adjust the initial scheme to realize vessels' effective entry and exit when ship loaders failures are taken into account in a bulk cargo port. Therefore, this paper studies the combined optimization problem of available ship loaders and vessels entering and leaving the port under the influence of fault factors. The coordination between vessels and ship loaders is equivalent to the coordination between the scheduling process of vessels entry and exit the port and the allocation process of ship loaders. One of the key issues in determining the entry and exit process of vessels is to allocate berths. When assigning berths to a vessel, choosing different berths will result in different entry and exit processes, as well as different feasible ship loaders. Therefore, vessels and ship loaders are connected and coordinated by berth allocation process. This problem allocates appropriate time and berths for vessels entering and leaving the port, and arranges available ship loaders for them to minimize the impact of loader failure on cargo handling efficiency and ship delay.

The new contributions of this paper are stated as follows: (1) development of a novel mixed integer linear program (MILP) model based on disruption management strategies to minimize the generalized cost and solve the VSLPB, in which this paper, for the first time, tackles the practical challenge of scheduling the vessels and ship loaders considering the disruptive factors. (2) exploitation of the disruption management strategies and the method of soft and hard constraints to prepare for designing a solving algorithm. These approaches could take advantage of reducing the model size and simplifying the problem. Furthermore, it develops an efficient TSRG algorithm to solve the problem optimally. (3) demonstration of the good interpretability of the proposed method and provide a case study with deep insights. Our solution can allocate available ship loaders for inbound and outbound vessels under the influence of fault factors and can minimize the impact of failed ship loaders on cargo handling efficiency and vessel delay.

In the rest of the paper, a literature review is presented in Section 2. Section 3 describes the studied problem in detail and provides a novel mathematical formulation. The new formulation enables the development of an efficient TSRG algorithm approach for its solution, which is enhanced by a disruption management strategy and column generation (Section 4). Computational studies are conducted in Section 5 to evaluate the performance of the proposed TSRG based approach. Finally, the research results are summarized in the conclusions in Section 6.

2. Literature review

It is evident from the current literature that little coordinated research on vessel traffic scheduling concerning the disruptive effect of ship loader failures, despite the increasing number of relevant incidents that occurred in practice. Within the context of water transportation, the most relevant references are focusing on berth plan recovery (BPR) and liner ship schedule recovery (LSSR). However, both BRP and LSSR overlook the incorporation of cargo loading failures as a disruptive factor in the vessel scheduling optimization and coordination, which is evident to be an unavoidable problem to be addressed in urgency to ensure the success of the VSLPB. From an applied research perspective, it strikes the new coordination of vessel scheduling and port operations in the dry bulk area beyond the dominated container sector. Obviously, given the difference between container and bulk shipping, the existing methods in container shipping cannot be applicable to the bulk sector without new developments. In the following subsections, we focus on three aspects of vessel traffic scheduling, disruption factors, and disruption management applied to water transportation.

2.1 Vessel traffic scheduling

Vessel traffic scheduling optimization is primarily concerned with the orders of vessels passing through the channel, safely and effectively. Most existing research on vessel traffic scheduling was based on deterministic conditions and did not refer to disruption factors. Previous studies have been conducted to carry out relevant research based on different channel types, Zhang et al. [4,5] studied the integration problem of vessel scheduling and berth allocation in a one-way channel. They first studied the problem in a fixed planning period for a discrete berth bulk cargo port with a single harbor basin, then studied the problem in a multi-harbor basin. Zhang et al. [6] studied the optimization model and algorithm of vessel traffic scheduling in a restricted two-way channel in Huanghua Port, taking the channel as the main object. Li et al. [7] investigated the traffic scheduling problem of vessels entering and leaving restricted channels in a multi-harbor basin and generated an optimal traffic scheduling scheme for each vessel to ensure the safety and efficiency of vessel navigation. Within this context, the state-of-the-art is the studies on the coordination and optimization of vessel traffic scheduling and terminal equipment. For instance, Li et al. [8] studied loading plans and equipment cooperation problems to get an allocation scheme.

In addition, many other scholars have researched vessel traffic scheduling, considering different elements involved in the port production process. Jia et al. [9,10] considered the characteristics of different channel types and took the vessel entering and leaving port process as the critical factor to study the traffic scheduling problem under the combination of vessel and berth. Niu et al. [11] studied the coordination problem of anchorage allocation and vessel traffic scheduling in Shanghai Yangshan deep-water port. Abou Kasm et al. [12] studied the mathematical model of the vessel scheduling problem with tug and pilotage constraints and channel restrictions; then, they designed an exact solution method based on constraint separation. Liu et al. [13] studied the seaport berth and channel planning problem, aiming to minimize the expected total weighted completion times of ships. Chen et al. [14] how to optimize slot capacity allocation within a container liner alliance under the slot exchange mode in the containerized maritime logistics industry.

However, there is no evidence showing the existence of any optimization research on ship loaders coordinating with vessels, and the primary method of the present research on vessel traffic scheduling optimization focused on deterministic conditions concerning no disruption factors. Obviously, they could not reflect and fit the high research demand in today's bulk shipping industry.

2.2 Disruption management

Researchers have conducted many methods to lessen the impact of disruptions, among which disruption management is deemed to be a leading position. Disruption management performs local optimization and adjustment of the initial scheme based on the state after the disruption factor has ended, resulting in an adjusted scheme that reduces the influence of disruption factors on the scheduling system [15]. Disruption management has been successfully applied to production job shops coping with disruptions in production and scheme execution. In the study of production scheme recovery problems, Baykasoglu and Karaslan [16] proposed a new disruption management approach, which includes a disruption management model and a multi-objective optimization algorithm that can effectively reduce the deviation. Li et al. [17] proposed a value function metric for the disruption problem in uncertain job shop scheduling problems to reduce carbon emissions in the manufacturing process. Ning and Wang [18] proposed the measurement method of value function based on prospect theory and the disruption management strategy of user's psychological perception and established a multi-objective optimization model for job-shop scheduling management through multi-objective programming. Fischer et al. [19] presented different strategies for handling disruptions in fleet deployment in roll-on roll-off liner shipping, which basically consists of assigning a fleet of vessels to predefined voyages at minimum cost. Ke et al. [20] proposed a framework based on optimization and regression analysis for recovery from random disruptions of rail intermodal terminals. At the same time, in light of the idea of gradual optimization for the target to obtain the job-shop scheduling adjustment scheme with minimum disturbance. Sun et al. [21] proposed an improved multi-objectives method to solve the dynamic job-shop scheduling problem based on disruption management, and a quantum genetic algorithm for adaptively adjusting the rotation angle. Malik and Sarkar [22] developed a mathematical model of a multi-item production-inventory system to maximize the total profit within a single disruption-recovery time window. Sang et al. [23] proposed a new disruption management method, that includes the disruption management model and the many-objective optimization algorithm.

In light of the above, the most similar sector to bulking shipping is job shop scheduling, in terms of both theories and applications of disruption management, and hence the relevant papers have been thoroughly reviewed for a cross reference purposes.

2.3 Disruption management applied to water transportation

Holistic research on waterway transportation and disruption management mainly focused on berth plan recovery and liner ship schedule recovery. Cheraghchi et al. [24] concerned with speeding up strategy in vessel schedule recovery problems, modeled S-VSRP as a multi-objective optimization problem and resorted to several multi-objective evolutionary algorithms to approximate the optimal Pareto set, which provides vessel route-based speed profiles. Han et al. [25] applied the dynamic disruption management method to collaboratively plan the resources of container terminals in a cyclical environment, considering the uncertainty of vessel arrival time and market demand. Abioye et al. [26] presented a novel mixed-integer nonlinear mathematical model for the green vessel schedule recovery problem, which considered two recovery strategies, including vessel sailing speed adjustment and port skipping. The objective was aiming to minimize the total profit loss, endured by a given liner shipping company due to disruptions in the planned operations. Then, Abioye et al. [27] formulated a novel mathematical model for the vessel schedule recovery problem in liner shipping, aiming to minimize the total profit loss, suffered by the liner shipping company due to disruption occurrences at a given liner shipping route. van der Steeg et al. [28] proposed a rolling window strategy to deal with the disruption factors coping with the early or late arrival of vessels or disruptions requiring longer loading and unloading times, and a real-time disruption management decision model was proposed. De et al. [29] addressed the environmental concerns related to fuel consumption and carbon emission within shipping operations and simultaneously presents strategies for countering disruption within the maritime transportation domain. Elmi et al. [30] offered a thorough review of the current liner shipping research primarily focusing on two major themes: uncertainties in liner shipping operations; and ship schedule recovery in response to disruptive events. They provided representative mathematical models that could be used further in future research efforts dealing with liner shipping and ship schedule recovery uncertainties. Chen et al. [31] studied the co-deployment of liner alliance fleets under the vessel pool operation with uncertain demand. Then, Chen et al. [32] studied the fleet scheduling problem of container liner alliance members in the slot exchange mode, with sulfur emission restrictions taken into consideration.

From the above analysis, disruption management research in the shipping field primarily focused on container liner shipping, with less research on bulk cargo transportation. However, there are some distinctions between bulk cargo ports and container ports. For example, the loading and unloading equipment in a bulk cargo port often moves continually, while the one in the container port moves between bays, which is often seen as a separate activity. As a result, research is required based on the peculiarities of bulk cargo ports.

To sum up, relatively few articles have studied the problem of disruption management in vessel traffic scheduling. Most of the existing theories in the field of disruption management focus on the recovery of production plans; studies on disruption management in waterway transportation concentrate on container ships. However, the above studies did not involve the coordinated optimization of vessel traffic scheduling and ship loaders, nor did they concern the disruption factors with the coordinated optimization problem. Therefore, the existing models and algorithms could not be used to address the research problem described below, and it is necessary to explore new models and algorithms according to their unique characteristics.

3. Problem description and mathematical formulation

3.1 Problem description

To realize the adjustment of vessels' arrival and departure times and redistribution of ship loaders within a limited range, this paper proposes disruption management strategies by dividing the operation status of vessels, affected by ship loader failures, into different stages based on actual situations. Fig. 1 shows all the possible divided stages.

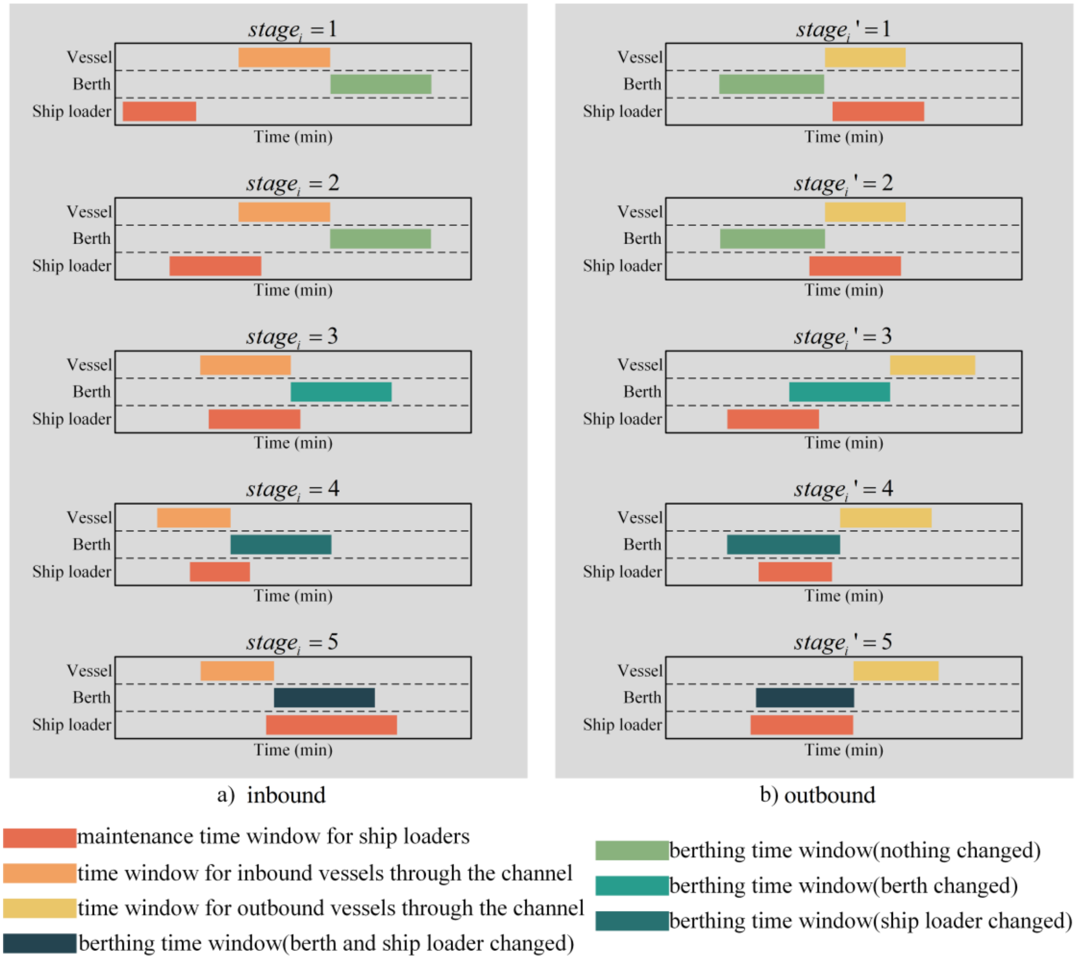


Fig. 1. The Divided Stages.

Fig. 2 describes the specific disruption management strategies in various stages according to the direction of vessels, whether ship loaders can be repaired before the vessels inbound or outbound the port, whether the vessel berths at the initial berth, and whether uses the initial ship loader.

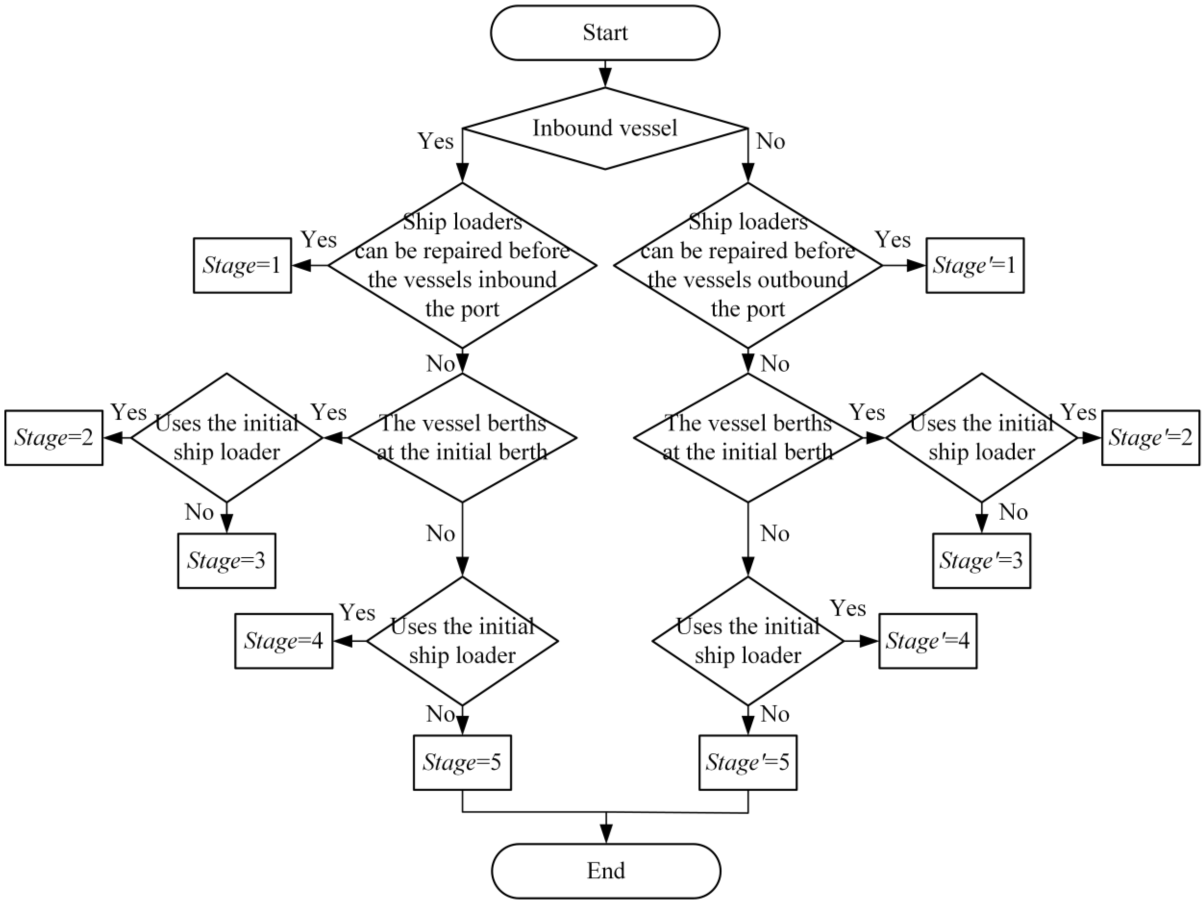


Fig. 2. Specific disruption management strategies in various stages.

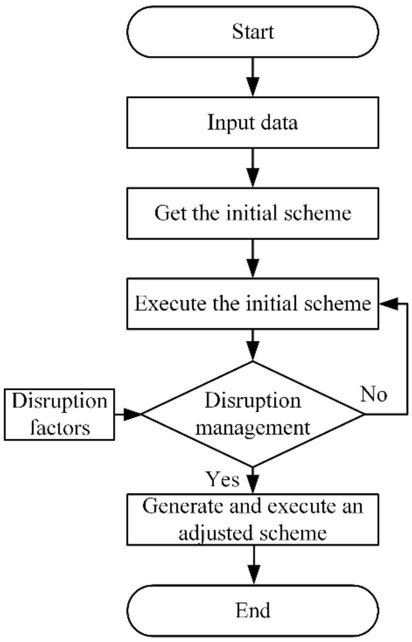


Fig. 3. Disruption Management Adjustment Strategy Flow Chart.

When executing the initial scheme, disruption factors prevent the initial scheme from having the optimal effect it should. It will be determined whether to manage the factors; if disruption management is not required, then the initial scheme is executed; if disruption management is required, a new scheme is generated and executed based on the disruption management strategies. Fig. 3 shows the flow chart of the disruption management adjustment strategy.

Since other operations in the port are arranged according to a vessel's arrival and departure scheme and loading operation scheme, the temporary adjustment of these two schemes will significantly increase the time and economic costs. The problem studied in this paper is how to adjust the initial scheme to generate a new scheme based on less adjustment and redistribution of resources. The new scheme should take into account the original optimization objectives while minimizing the effects caused by disruptions [15]. Therefore, it is essential to choose a proper objective function to measure the cost of the adjusted scheme.

To reflect the rationality of the new scheme and the difference between the new scheme and the initial scheme comprehensively, [33-37] are referred to use the generalized cost as the objective function, including the cost of implementing the new scheme and the penalty cost of adjusting the initial scheme. In addition, the hard constraints in the model have to be satisfied, while the soft constraints will be satisfied to the greatest possible extent. Given that the vessels studied in the one-way channel in this paper have the characteristics of entering and leaving the port in a group if the vessel-grouping constraints are met absolutely, it is easy to encounter the situation where the solution set is empty when solving VSLPB. Therefore, according to the related concepts of soft and hard constraints, the vessel-grouping constraints are set as soft constraints.

The assumptions of establishing the optimization model are defined as follows:

(1) The weather conditions and berth depth in the port meet the berthing requirements of each vessel.

(2) The maintenance time windows of ship loaders are known.

(3) The berthing plan has been generated before the vessels' inbound or outbound ports.

(4) The resources of pilots, tugs, and yard storage are sufficient.

(5) The decision time is short, so the influence of the decision point is ignored.

(6) The initial scheme existed before disruption management started.

3.2 Model formulation

This section introduces an innovative model formulation for coordinated re-optimizing vessel traffic scheduling and ship loaders allocation problem. We considered the disruption management strategies and the practical requirement of safety. The notations of the VSLPB model are presented as follows.

Sets and parameters	
Symbol	*Explanation*
I	set of vessels

J	set of berths
K	set of ship loaders
N	set of time intervals
R	set of time points
S	set of yards
m_1 / m_2 / m_3 / m_4 / m_5	coefficients of each influence factor in the objective function
M	a sufficiently large positive number
a_i	ready time of vessel $i, i \in I$
a_i'	adjusted ready time of vessel $i, i \in I$
l_i	length of vessel $i, i \in I$
L	length of channel
h	safe time interval of vessels in the same direction
h'	safe time interval of vessels in different directions
x_i	the earliest start time of vessel $i, i \in I$
x_i'	adjusted the earliest start time of vessel $i, i \in I$
y_i	the earliest end time of vessel $i, i \in I$
y_i'	adjusted end time of the vessel $i, i \in I$
$\overline{p_k}$	upper bound of the maintenance time window for ship loader $k, k \in K$
$\underline{p_k}$	lower bound of the maintenance time window for ship loader $k, k \in K$
v_i	speed of the vessel $i, i \in I$
$\overline{g_i}$	upper bound of tide riding time window of vessel $i, i \in I$
$\underline{g_i}$	lower bound of tide riding time window of vessel $i, i \in I$
q_{su}	the amount of cargo $u, u \in U$ stored in yard $s, s \in S$
q_{iu}	the amount of cargo $u, u \in U$ required by the vessel $i, i \in I$
q_{iu}'	the amount of cargo $u, u \in U$ that vessel $i, i \in I$ still needs to carry after the occurrence of the disruption
ω_k	operation efficiency of ship loader $k, k \in K$
t_{ijk}^1	start time of vessel $i, i \in I$ served by ship loader $k, k \in K$ at berth $j, j \in J$
$t_{ijk}^1{}'$	start time of vessel $i, i \in I$ served by ship loader $k, k \in K$ at berth $j, j \in J$ after berth shifting
t_{ijk}^2	end time of vessel $i, i \in I$ served by ship loader $k, k \in K$ at berth $j, j \in J$
$t_{ijk}^2{}'$	end time of vessel $i, i \in I$ served by ship loader $k, k \in K$ at berth $j, j \in J$ after berth shifting
t_{kj}	operation time of ship loader $k, k \in K$ at berth $j, j \in J$
t_{kj}'	operation time of ship loader $k, k \in K$ at berth $j, j \in J$ during the disruption management phase
$\overline{T_n}$	upper bound for vessel $i, i \in I$ inbound or outbound the port in the $n, n \in N$ subgroup
$\underline{T_n}$	lower bound for vessel $i, i \in I$ inbound or outbound the port in the $n, n \in N$ subgroup
W_i	the deviation time of total waiting time for vessel $i, i \in I$
O_i	the deviation time of total operation time for ship loader $k, k \in K$

0-1 Decision variables

Symbol	*Explanation*

B_{ij}	equals 1 if vessel $i,\ i\in I$ moors at berth $j,\ j\in J$ and 0, otherwise
B_{ij}'	equals 1 if vessel $i,\ i\in I$ moors at berth $j,\ j\in J$ after the occurrence of disruption and 0, otherwise
C_{ius}	equals 1 if cargo $u,\ u\in U$ required by vessel $i,\ i\in I$ stored in yard $s,\ s\in S$ and 0, otherwise
D_{ijs}	equals 1 if yard $s,\ s\in S$ is connected to berth $j,\ j\in J$ where vessel $i,\ i\in I$ berths and 1, otherwise
E_{in}	equals 1 if vessel $i,\ i\in I$ belongs to subgroup $n,\ n\in N$ and 0, otherwise
E_{in}'	equals 1 if vessel $i,\ i\in I$ belongs to subgroup $n,\ n\in N$ after the occurrence of disruption and 0, otherwise
F_{ijk}	equals 1 if ship loader $k,\ k\in K$ serves vessel $i,\ i\in I$ at berth $j,\ j\in J$ and 1, otherwise
F_{ijk}'	equals 1 if ship loader $k,\ k\in K$ serves vessel $i,\ i\in I$ at berth $j,\ j\in J$ after the occurrence of disruption and 1, otherwise
G_{kj}'	equals 1 if ship loader $k,\ k\in K$ can be moved and used for berth $j,\ j\in J$ after the occurrence of disruption and 0, otherwise
U_{ikr}	equals 1 if ship loader $k,\ k\in K$ serves vessel $i,\ i\in I$ at moment $r,\ r\in R$ and 0, otherwise
IO_i	equals 1 if vessel $i,\ i\in I$ is entering port and 0, otherwise

Based on the above assumptions and symbols, the mathematical model of coordinated scheduling for vessels and ship loaders considering disruption management is formulated as follows:

Objective function

$$\min\sum_{i,j,k}\left(W_i+O_i+m_1*\left|x_i^{'}-x_i\right|+m_2*B_{ij}'+\mathrm{m}_3*F_{ijk}'+\mathrm{m}_4*\mathrm{G}_{kj}'+\mathrm{m}_5*E_{in}'\right) \tag{1}$$

Hard constraints

$$x_i\ge a_i \tag{2}$$

$$\left(IO_i-IO_{i'}\right)\left(U_{ikr}*x_i-U_{i'k(r-1)}*x_{i'}\right)\ge h \tag{3}$$

$$\left[1-\left(IO_i-IO_{i'}\right)\right]\left(U_{ikr}*x_i-U_{i'k(r-1)}*x_{i'}\right)\ge h' \tag{4}$$

$$h=\max\left(l_i,l_{i'}\right)*\alpha_1\Big/v_{behind} \tag{5}$$

$$h'=l_{behind}*\alpha_2\Big/v_{before} \tag{6}$$

$$D_{ijs}*C_{ius}*B_{ij}*F_{ijk}=1 \tag{7}$$

$$\sum_i U_{ikr}\le 1 \tag{8}$$

$$F_{ijk}+F_{ijk}'=1,\ \ i,\ i\in I \tag{9}$$

$$\sum_i U_{ikr}*x_i+M*\left(1-\sum_i U_{ikr}\right)\ge\sum_i U_{ik(r-1)}*y_i \tag{10}$$

$$t_{ijk}^1+t_{kj}\le t_{ijk}^2 \tag{11}$$

$$\sum_{i,j,k} F_{ijk} \le k_{\max} \tag{12}$$

$$\sum_{i} q_{iu} \le \sum_{s} q_{su} * \left(1 - C_{ius}\right) \tag{13}$$

$$\underline{g_i} \le x_i \le \overline{g_i} \tag{14}$$

$$\underline{g_i} \le x_i + {L}/{v_i} \le \overline{g_i} \tag{15}$$

$$\underline{T_n} \le E_{in} * x_i \le \overline{T_n} \tag{16}$$

$$\underline{T_n} \le E_{in} * y_i \le \overline{T_n} \tag{17}$$

$$y_i \ge x_i + F_{ijk} * t_{kj} \tag{18}$$

$$\sum_{k \in K} U_{ikr} \left(\overline{p_k} - \underline{p_k}\right) = 0 \tag{19}$$

$$x_i ' \ge a_i ' \tag{20}$$

$$\left(1 - IO_i\right) x_i ' = \overline{p_k} + t_{ijk}^{1} ' + t_{kj} \tag{21}$$

$$t_{ijk}^{2} = \left(\overline{p_k} + t_{kj} '\right) * \left(1 - B_{ij} '\right) * F_{ijk} ' * \left(1 - G_{kj} '\right) \tag{22}$$

$$t_{ijk}^{2} ' = \left(t_{ijk}^{1} + \sum_{u} q_{iu} ' / \omega_k\right) * \left(1 - B_{ij} '\right) * F_{ijk} ' * G_{kj} ' \tag{23}$$

$$B_{ij} ' * A_{ij} = 1 \tag{24}$$

$$t_{ijk}^{2} ' = \left(t_{ijk}^{1} ' + \sum_{u} q_{iu} ' / \omega_k\right) * B_{ij} ' * F_{ijk} ' * G_{kj} ' \tag{25}$$

Soft constraints

$$\underline{T_n} \le \left(1 - E_{in}\right) * x_i ' \le \overline{T_n} \tag{26}$$

$$\underline{T_n} \le \left(1 - E_{in}\right) * y_i ' \le \overline{T_n} \tag{27}$$

The objective function (1) is the disruption measure function, it is chosen primarily depending on actual demands, but there is currently no general standard. As per the definition of generalized cost, we take it as a disruption measure function composed of seven terms. The generalized cost includes the vessels' total waiting time (W_i), the ship loaders' total operation time (O_i), the penalty for altering the vessel's inbound or outbound time ($m_1 * \left|x_i' - x_i\right|$), the penalty for shifting berth ($m_2 * B_{ij} '$), the penalty for altering ship loaders ($\mathrm{m}_3 * F_{ijk} '$), the penalty for moving ship loaders ($\mathrm{m}_4 * \mathrm{G}_{kj} '$), and the penalty for changing the groups of vessels ($\mathrm{m}_5 * E_{in} '$). Function (2) ensures that the vessels' start time cannot be earlier than the arrival time. Functions (3) to (6) state the safe distance between vessels measured by time. Function (7) ensures the correspondence between berths, vessels, cargos, and yards. Functions (8) to (12) state the time-space constraints of the ship loaders. Function (8) and (9) ensure one ship loader can merely service one vessel at a time, and one vessel can only be handled by one ship loader at a time. Function (10) and (11) ensure the feasible service time of ship loaders. Function (12) restricts the number of ship loaders serving simultaneously to no more than the total number. Function (13) states the weight constraint of the loaded cargo. Functions (14) and (15) ensure the tidal time window for the vessels. This paper studies a one-way channel, which means that vessels can only enter or leave the port simultaneously. Additionally, to limit the number of channel direction changes and ensure an orderly inbound and outbound process, vessels were usually grouped to pass the channel in a practical process, functions (16) and (17) state the grouping time constraint of the vessels. Function (18) calculates the end of vessels' inbound or outbound time. Functions (19) to (23) state the disruption management strategies, and the objective function values corresponding to different recovery strategies are calculated when ship loader fails. The recovery strategy with the smallest objective function value is selected. Function (19) states that the berth corresponding to the ship loader is unavailable during the maintenance time window. Function (20) ensures vessels' start time cannot be earlier than their adjusted arrival time. Function (21) calculates the earliest start time of the vessel outbound the port after adjustment. Function (22) calculates the initial ship loader operation ending when the vessel still berths at the initial berth and is served by the initial ship loader. Function (23) calculates the end time of the ship loader operation when the vessel still berths at the initial berth but is served by another ship loader. Function (24) ensures that when the vessel shift berth, the cargo required by the vessel can still be transported to this berth. Function (25) calculates the time when the vessel needs to be served by the ship loader on the corresponding berth after shifting berth. Therefore, functions (26) and (27) state the soft constraints, which mean that the disturbed vessel's adjusted arrival and departure time meet the initial group as much as possible.

The existing research and applications of soft constraints are primarily reflected in intelligent optimization algorithms [38-43]. Most of these studies use the method of punishing fitness and adding punishment measures to reduce individual fitness for violating hard and soft constraints in the individual genetic algorithms. To simplify the model and ensure the effectiveness of the model solution, we add the soft constraints into the objective function based on an interior point penalty function method. The simplified model is stated as follows.

Objective function

$$\Phi(x,\mu) = \min \sum_{i,j,k} \left(W_i + O_i + m_1 * \left| x_i' - x_i \right| + m_2 * B_{ij}' + \mathrm{m}_3 * F_{ijk}' + \mathrm{m}_4 * \mathrm{G}_{kj}' + \mathrm{m}_5 * E_{in}' \right) + \mu C^{-1}(x) \tag{28}$$

Functions (2) ~ (25) are constraints. Moreover, function (28) states the simplified soft constraint $C(x)$ defined in function (29).

$$C(x) = \overline{T}_n - (1 - E_{in}) * y_i' \tag{29}$$

4. A TSRG algorithm

The solution objective of the algorithm is to obtain the adjusted scheme at a fast speed when disruption factors occur. According to the established mathematical model above, the number of constraints involved in this paper is enormous. Since the problem of the vessel traffic scheduling process considering disruption factors is complex, it is difficult to solve the model directly using commercial solving software. Among all the constraints, only a small number of the constraints play a decisive role. The above propositions inspire the consideration of a method to reduce the model size. The row generation method has advantages in solving problems with multiple constraints. Each interference management strategy is independent of the others, and when solving the constraints corresponding to one interference management strategy, it does not have an impact on other interference management strategies. Accordingly, using the row generation method for solving is suitable. Therefore, an algorithm based on the row generation method is employed to reduce the number of constraints. By delaying the generation of optimal solutions, we reduce the number of constraints to speed up the solution.

To solve the problem effectively, a new TSRG algorithm based on the row generation algorithm and the disruption management strategies in section 3 is designed. The main idea of TSRG is to relax some constraints of the model formulated in section 3 to obtain a master problem, construct the corresponding sub-problem after solving the master problem, then add the corresponding constraints until finding the optimal solution. First, all constraints of the disruption management strategy are relieved, and all available berths and ship loaders are obtained. Then, based on all the berths and ship loaders obtained, different objective function values corresponding to the various disruption management strategies are calculated. Suppose the decision variable corresponding to the optimal objective function value satisfies the constraint of the integer variable simultaneously. In that case, the objective function value is the optimal solution, and the corresponding disruption management strategy is the optimal adjustment strategy selected. Suppose the decision variable corresponding to the obtained objective function value does not meet the integer constraint. In that case, it is necessary to add an integer constraint on this basis to continue solving the issue and repeating this process until the optimal solution meeting the conditions is obtained.

Fig. 4 shows the specific flow of the TSRG algorithm. The first stage of the TSRG algorithm is to get the available berths and ship loaders when vessels berth at the adjusted time. In this stage, we relaxed the integer variables in the model into continuous variables, took function (28) as the objective function and functions (2) to (19) as the initial constraints, then treated them as the master problem. The second stage is to get the minimum objective value and corresponding strategy. In the second stage, we took function (28) as the objective function and add functions (20) to (25) for further solutions. We have adopted some heuristic strategies to accelerate the solving process. Firstly, the feasible berths and ship loaders obtained in the first stage are grouped: all solutions of the same berths are grouped and arranged in ascending order. In this case, the ascending order is for the corresponding changes of each disruption management strategy, while the strategy with a larger sequence number refers to the solution with a change in the ship loaders. In addition, the greedy criterion is used to prioritize the search for solutions with small changes, i.e. those with higher sequence numbers. Then, using a rolling search strategy, the intersection of available berth time windows, available ship loader time windows, formation time windows, and unoccupied time windows between two adjacent vessels is searched first. If no solution satisfies the intersection time window, the complement of formation time windows is searched. At the same time, a rolling search strategy is used during the search process, ensuring the unoccupied time windows between adjacent vessels are searched one by one. Last but not least, taboo strategies are used to label the found optimal solutions and avoid repeated searches in the subsequent search process.

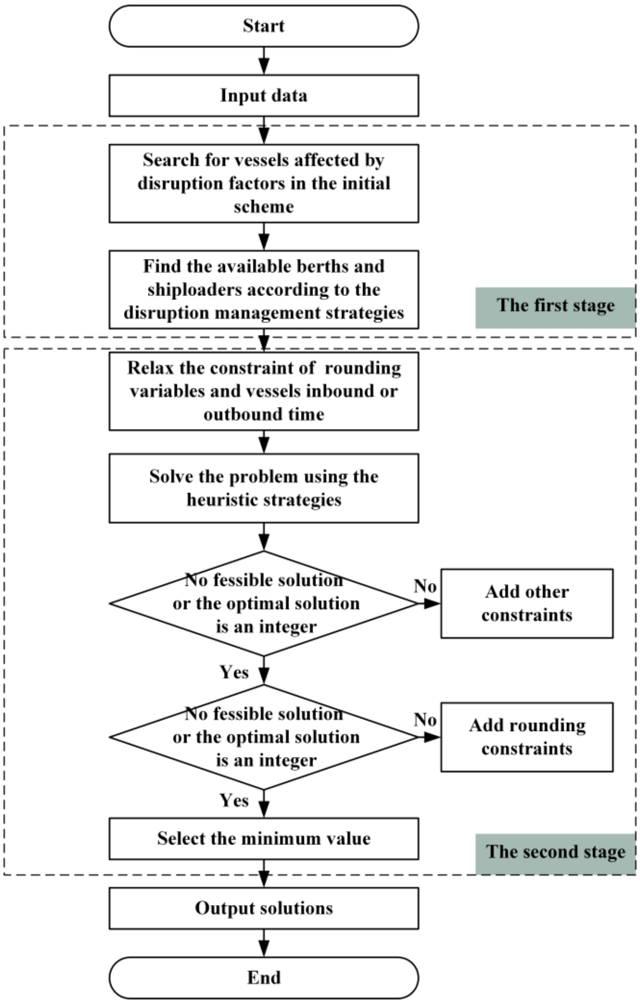
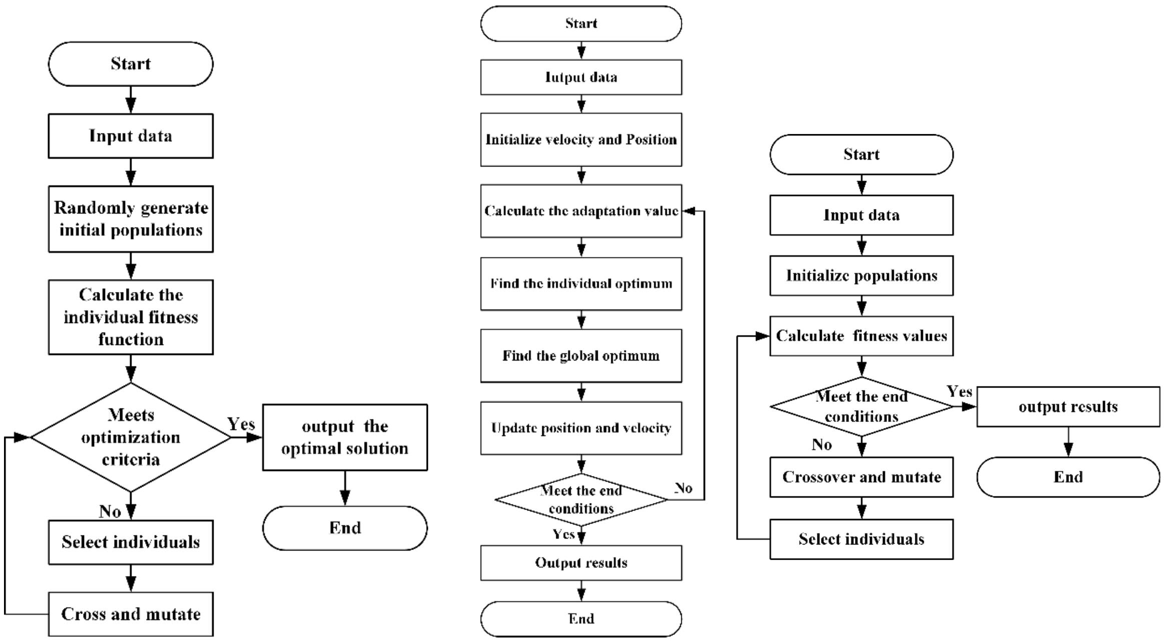


Fig. 4. Flow Chart of TSRG.

To obtain the solution efficiency and accuracy of the TSRG algorithm, we used the genetic algorithm (GA), particle swarm optimization algorithm (PSO), and differential evolution algorithm (DE) to solve the same problem. Fig. 5 presents the basic flow chart of the three aforementioned intelligent optimization algorithms.



(a) Flow chart of GA. **(b)** Flow chart of PSO. **(c)** Flow chart of DE.

Fig. 5. Basic Flow Chart of Each Algorithm.

5. Computational experiments and results

To verify the effectiveness of the proposed TSRG algorithm proposed, we conducted experiments based on the data from the Huanghua Coal Port. The illusion of Huanghua Coal Port is sketched in Fig. 6.

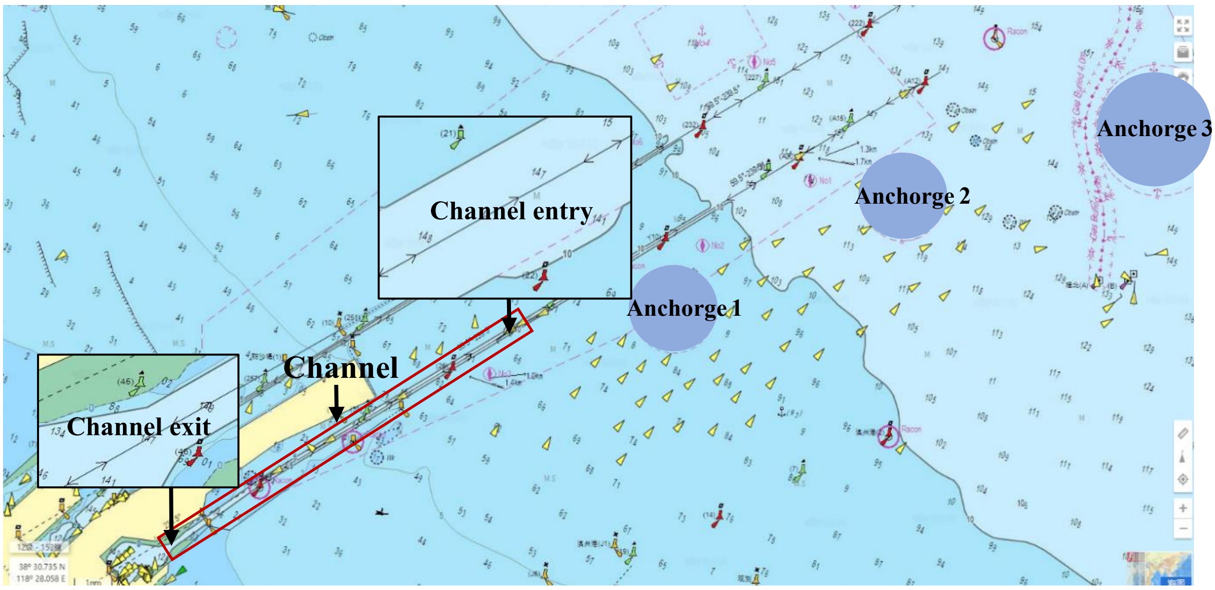


Fig. 6. Illusion of Huanghua Coal Port.

Generally, in the Huanghua Coal Port, the inbound vessels enter the channel at buoy no.22, and buoy no.46 is the joint of the harbor basins and the channel. Therefore, the buoy no.22 and no.46 are defined as channel entry and exit, respectively. The incoming vessels successively pass through the channel entrance and exit from the anchorage, finally arriving at the berth. The outcoming vessels navigate through the channel from the berth and finally depart at the channel entry.

Then, we studied the impact of different time windows of ship loader maintenance and different numbers of failed ship loaders based on the initial scheme of 25 vessels, which is supported by historical data. The initial scheme was shown in Table 1, and Table 2 shows the specific ship loaders' failure data.

All the computational experiments were performed on a computer with Intel Core i7-7500U 2.70 GHz CPU and 8GB RAM. The TSRG algorithm was solved using CPLEX 12.6.3, and each intelligent optimization algorithm was executed in Matlab with the R2016a version. Table 3 displays the specific values of each parameter for the three algorithms.

Table 1

Initial scheme of 25 vessels.

vessel number	in or out	tidal time window (min)	inbound moment (min)	outbound moment (min)	time of leaving the channel (min)	berth	ship loader *	the operation time window of ship loader (min)
1	out	—	—	0	92	#2	SL2	[0,0]
3	out	—	—	80	183	#3	SL3	[0,0]
4	out	—	—	114	222	#8	SL8	[0,57]
5	out	—	—	163	259	#10	SL10	[0,128]
7	out	—	—	206	286	#17	SL13	[0,151]
8	out	—	—	258	330	#7	SL7	[0,206]
9	out	[200,500]	—	286	349	#9	SL9	[0,252]
2	in	—	389	—	471	#1	SL1	[513,902]
11	in	—	413	—	492	#13	SL9	[570,867]
6	in	[400,700]	430	—	516	#8	SL8	[640,851]
12	in	—	459	—	536	#10	SL10	[884,1 183]
13	in	—	483	—	581	#2	SL2	[861,1 052]
15	in	—	523	—	605	#4	SL4	[800,1 056]
17	in	—	570	—	669	#17	SL13	[822,1 156]
10	in	—	591	—	698	#3	SL3	[861,1 253]
16	out	[720,820]	—	740	812	#4	SL4	[230,662]
18	out	—	—	775	876	#16	SL12	[232,651]
14	out	—	—	796	900	#5	SL5	[354,707]
19	out	—	—	822	929	#6	SL6	[344,768]
20	out	—	—	880	988	#14	SL10	[350,834]
22	out	—	—	960	1 068	#11	SL11	[530,920]
23	in	—	1 095	—	1 198	#7	SL7	[1 261,1 437]
21	in	[1 080,1 280]	1 116	—	1 227	#9	SL9	[1 255,1 461]
24	in	—	1 142	—	1 249	#6	SL6	[1 281,1 633]
25	in	—	1 266	—	1 408	#1	SL1	[1 428,2 041]

* the number of ship loaders is from SL1 to SL13

Table 2

Ship loader failure data.

experiment number	failed ship loader	the time window of ship loader maintenance (min)	experiment number	failed ship loader	the time window of ship loader maintenance (min)
1	SL5	[500,600]	8	SL8	[800,900]
2	SL5	[500,700]	9	SL8	[800,1 000]
3	SL5	[600,700]	10	SL8	[600,700]
4	SL5	[600,800]	11	SL8	[600,800]
5	SL5	[600,900]	12	SL5,SL8	[600,700],[800,900]
6	SL5	[600,1 000]	13	SL5,SL11	[600,700],[600,700]
7	SL5	[600,1 100]	14	SL8,SL13	[800,900],[800,900]

Table 3

Parameters of GA, PSO, and DE.

algorithm	parameter	value
GA	generation gap	0.9
	maximum generations	200
	crossover probability	0.7
	variation probability	0.002
PSO	iterations	200
	particle swarm	100
	maximum archive	200
	initial inertia weight	0.9
	particle size	3
	the first velocity update parameter	1.5
	the second velocity update parameter	2
	maximum velocity	0.2
	minimum velocity	-0.2
	divided raster	50*50
DE	iterations	200
	population	50
	scaling factor	0.2
	crossover probability	0.9

5.1 Rational verification of the adjusted scheme

The experiment is conducted based on the known initial scheme with 25 vessels, including the vessel arrival and departure scheme and loading operation scheme. The initial scheme is shown in Table 1. According to the actual production of Huanghua Port, 0:00 is recorded as moment 0 every day, and the moment is accumulated over time. The time intervals of vessels' inbound and outbound groups in a day are [0,360] min, [361,720] min, [721,1 080] min, and [1 081,1 440] min in order, and the navigation direction of vessel-grouping changes every 6 hours.

Taking experiment 12 in Table 2 as an example, we study which disruption management strategy should be adopted to adjust the initial scheme when SL5 and SL8 are under repair at [600,700] min and [800,900] min, respectively. The adjusted scheme of 25 vessels is solved by the TSRG algorithm, as shown in Table 4, which includes the adjusted vessel arrival and departure scheme and adjusted loading operation scheme. Comparing Table 1 with Table 4, it can be found that the damage SL5 affects vessel 14, and the damage SL8 affects vessel 6. The disruption management strategy adopted by vessel 6 is: wait at the initial berth and use the initial ship loader, that is, $stage_6 = 2$. The corresponding operation time window for SL5 changed from [640,851] min to [640,799] min∪ [901,953] min. Meanwhile, vessel 14 adopts the same strategy as vessel 6 but has a different direction from vessel 6, which means $stage_{14}' = 2$. The corresponding operation time window for SL8 changed from [354,707] min to [354,599] min∪ [701,809] min.

Table 4

Adjusted scheme of 25 vessels.

vessel number	in or out	tidal time window (min)	inbound moment (min)	outbound moment (min)	time of leaving the channel (min)	berth	ship loader	the operation time window of ship loader (min)
1	out	—	—	0	92	#2	SL2	[0,0]
3	out	—	—	80	183	#3	SL3	[0,0]
4	out	—	—	114	222	#8	SL8	[0, 57]
5	out	—	—	163	259	#10	SL10	[0,128]
7	out	—	—	206	286	#17	SL13	[0,151]
8	out	—	—	258	330	#7	SL7	[0,206]
9	out	[200,500]	—	286	349	#9	SL9	[0,252]
2	in	—	389	—	471	#1	SL1	[513,902]
11	in	—	413	—	492	#13	SL9	[570,867]
6	in	[400,700]	430	—	516	#8	SL8	[640,799]∪[901,953]
12	in	—	459	—	536	#10	SL10	[884,1 183]
13	in	—	483	—	581	#2	SL2	[861,1 052]
15	in	—	523	—	605	#4	SL4	[800,1 056]
17	in	—	570	—	669	#17	SL13	[822,1 156]
10	in	—	591	—	698	#3	SL3	[861,1 253]
16	out	[720,820]	—	740	812	#4	SL4	[230,662]
18	out	—	—	775	876	#16	SL12	[232,651]
19	out	—	—	822	929	#6	SL6	[344,768]
20	out	—	—	880	988	#14	SL10	[350,834]
14	out	—	—	906	1 010	#5	SL5	[354,599]∪[701,809]
22	out	—	—	960	1 068	#11	SL11	[530,920]
23	in	—	1 095	—	1 198	#7	SL7	[1 261,1 437]
21	in	[1 080,1 280]	1 116	—	1 227	#9	SL9	[1 255,1 461]
24	in	—	1 142	—	1 249	#6	SL6	[1 281,1 633]
25	in	—	1 266	—	1 408	#1	SL1	[1 428,2 041]

Fig. 7 and Fig. 8 show the adjusted berthing time and ship loaders' operation time, which can clearly reflect the berthing time of vessels and working time. Table 4, Fig. 7, and Fig. 8 show no conflict between vessels, berths, or ship loaders, so the rationale of the adjusted scheme is verified with 25 vessels.

Berth safety assurance verification. According to the berth operation time chart shown in Fig. 7, taking berth 17 as an example, it has two operation time windows, [0,151] min and [799,1 133] min. There is no overlap between the two yellow bars, which means no conflict between all berths, and the safety of each berth is ensured. It verifies that the safety of the rest berths is ensured.

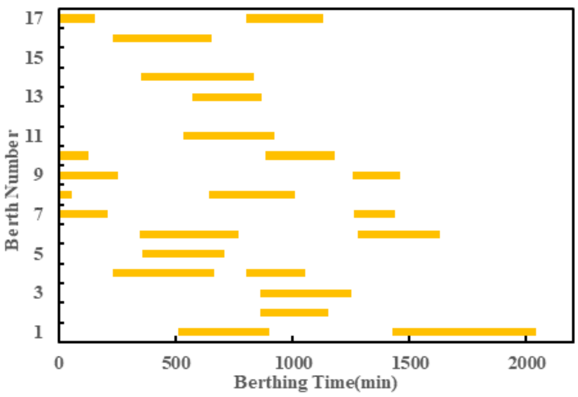


Fig. 7. Adjusted berthing time.

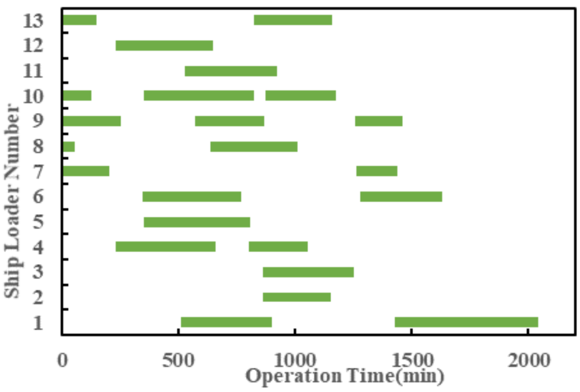


Fig. 8. Adjusted ship loaders' operation time.

Ship loaders allocation verification. According to the ship loaders' operation time shown in Fig. 8, taking ship loader 1 (SL1) as an example, it has two operation time windows, [513,902] min, and [1 428,2 041] min. Because there is no overlap between the two green bars, there will be no conflicts between the ship loader 1, thereby ensuring its safety. The rest of the ship loaders are confirmed to be safe.

Tide riding time verification. Table 4 shows that vessel 6, vessel 9, vessel 16, and vessel 21 need to take the tide to enter or leave the port. Vessel 6 is an inbound vessel with its tide riding time window at [400,700] min and the adjusted inbound time at [430,516] min. The tide riding time window is still satisfied, and the safety of traveling through the channel is ensured. Vessel 9 is an outbound vessel with the adjusted outbound time of vessel 9 at [286,349] min, which is falling in its tide riding time window [200,500] min. It proves that its safety in traveling through the channel is ensured. It is verified that all vessels' tide riding time windows are satisfied.

Vessel-grouping verification. In the adjusted scheme shown in Table 4, the first outbound vessel-grouping number is {1,3,4,5,7,8,9}. The first vessel in this group starts to leave the port at 0 min, and the last vessel ends up leaving the port at 349 min. This group of vessels leave the port at [0,360] min (the first time interval). The first inbound vessel group number is {2,11,6,12,13,15,17,10}. The first vessel in this group starts to enter the port at 389 min, and the last vessel enters at 698 min. This group of vessels enters the port at [361,720] min (the second time interval). It is verified that the time intervals of other vessel groups are also ensured.

In summary, the above results show that the adjusted scheme solved by the proposed TSRG algorithm can effectively ensure the safe coordinated optimization of vessels and ship loaders when ship loaders failed. Therefore, the method for solving VSLPB in this paper can obtain the valid adjusted scheme.

5.2 Algorithm performance analysis

To verify the performance of the TSRG algorithm, we conduct each group of experiments 50 times, and the average results of each experimental value are shown in Table 5. The average runtime of each algorithm is shown in Fig. 9.

Table 5

Experimental results.

experiment number	objective function value (min)				GAP* (%)
	TSRG	GA	PSO	DE	
1	10 178	11 114	11 674	11 766	15.6
2	10 290	11 360	11 792	11 700	14.6
3	10 176	10 746	11 417	11 509	13.1
4	10 383	11 504	11 889	11 743	14.5
5	16 902	18 609	19 150	19 302	14.2
6	17 757	19 621	20 119	20 421	15.0
7	18 266	20 147	20 860	21 024	15.1
8	10 307	11 327	11 698	11 884	15.3
9	12 540	13 970	14 271	14 459	15.3
10	7 289	8 076	8 186	8 302	13.9
11	7 389	8 431	8 431	8 431	14.1
12	15 244	16 677	17 317	17 531	15.0
13	20 076	22 003	22 907	23 107	15.1
14	13 647	14 875	15 530	15 749	15.4

* GAP=[(the maximum result of GA、PSO、DE)-(the result of TSRG)]/ (the result of TSRG)*100%

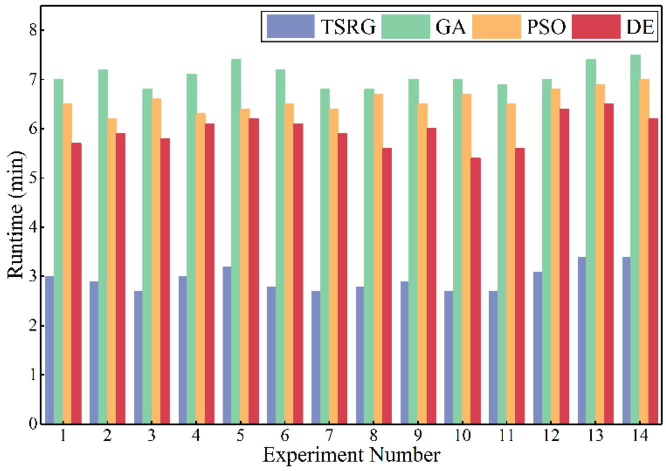


Fig. 9. Runtime of each algorithm.

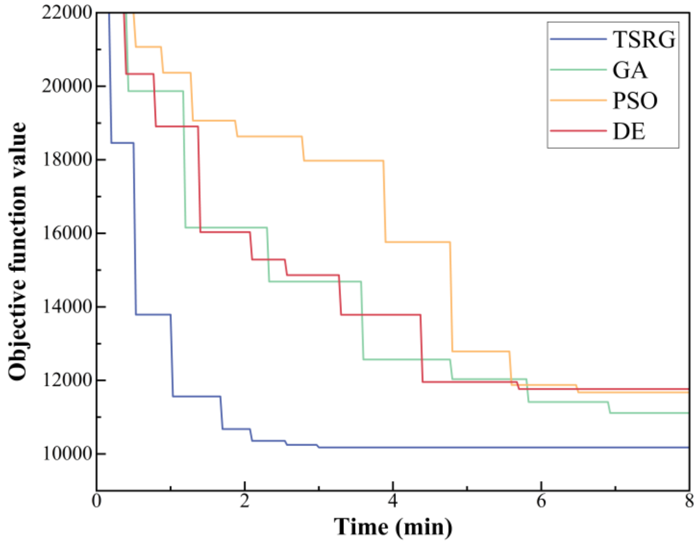


Fig. 10. Convergence speed of each algorithm.

According to the experimental results in Table 5, Columns 'TSRG' 'GA' 'PSO' and 'DE' are the solution results of each algorithm, respectively, the results show that the proposed TSRG algorithm out-performs the other algorithms in terms of solution results, and can solve all the instances to an optimal level. Column 'GAP' shows the difference in the solution results between the TSRG algorithm and other algorithms. This column's values fluctuate between 13.1% and 15.6%, which indicates that the TSRG algorithm's performance is stable. From the running time of each algorithm in Fig. 9, it can be seen that the TSRG algorithm designed in this paper has the shortest solution time with an average value of 3.0 min. To verify the convergence speed of each algorithm, we take experiment 1 in Table 5 as the example depicts the convergence speed of each algorithm in Fig. 10, which shows the convergence speed of the TSRG algorithm is superior to traditional algorithms.

To sum up, these above solutions indicate that the TSRG algorithm is suitable for the problem and the model established in this paper, and better fits the related disruption management techniques at various stages and enables quick revision of the initial plan.

5.3 Algorithm sensitivity analysis

In this section, we study differences caused by the impact of different disruption scenes. Sensitivity analysis is performed on the experiments.

The sensitivity analysis data is shown in Table 6, where the first set of experiments is used to verify the sensitivity of the start time when the ship loaders failure occurs. The second set is used to verify the sensitivity of the time length of a failure to the ship loader acting on the outbound vessels. The third set is used to verify the sensitivity of ship loaders at different stages. The fourth set is used to verify the sensitivity of the time length in a failure to the ship loaders acting on the inbound vessels. The fifth set is used to verify the sensitivity of the number of failed ship loaders. The sixth set is used to verify the sensitivity of the number of affected inbound and outbound vessels.

Comparing the results of sensitivity analysis data in Table 6, it reveals that in the six experimental cases, the influence of the vessels' directions inbound and outbound of the port on the initial schemes is the smallest. However, the failure duration of ship loaders at different stages of inbound and outbound vessels significantly influences the objective function. Accordingly, it is necessary to make targeted adjustment strategies according to the time and number of ship loader failures, to generate an adjustment scheme with the minimum generalized cost when disruptive factors occur.

Table 6
Sensitivity analysis data.

number of experimental groups	number of experiments	objective function value (min)	number of controlled experiments	results(min)	GAP* (%)
NO.1	1	10 359	3	10 176	1.8
	2	10 290	4	10 383	0.9
NO.2	3	10 176	5	16 902	66.1
	3	10 176	6	17 757	74.5
	3	10 176	7	18 266	79.5
NO.3	8	10 307	9	12 540	21.7
	10	7 289	11	7 398	1.5
NO.4	8	10 307	10	7 289	41.4
	9	12 540	11	7 398	69.5
NO.5	12	15 244	3	10 176	49.8
	12	15 244	8	10 307	47.9
NO.6	13	20 076	12	15 244	31.7
	14	13 647	12	15 244	11.7
	14	13 647	13	20 076	39.7

* GAP=|(the result of controlled experiments)-(the result of experiments)| / (the minimum result between experiments and controlled experiments)*100%

6. Conclusions and further research

This paper studied disruption management in vessel traffic scheduling in bulk cargo ports to solve the problem of ship loader failures in bulk ports. It constructed a disruption management model based on the disruption management theory. In addition, a new TSRG algorithm was designed according to the characteristics of the problem and the model. The experimental and sensitive analyses were conducted, and the results showed that the proposed method is effective and helpful in generating adjusted schemes.

The results of multiple experiments showed the fitness of the TSRG algorithm to the solution of the optimization model, which provided a new idea for the design of algorithms to solve problems of the same kind. Through sensitivity analysis experiments it was found that ship loaders' failure times at different stages had the most significant influence, meaning that it is necessary to purposefully adjust the initial scheme according to the specific stages in the actual operation process. In this paper, we proposed a TSRG algorithm. In the first stage, we did not consider disruption management strategies and rounding constraints to solve to obtain a feasible adjustment scheme quickly. In the second stage, we add disruption management constraints and rounding constraints to find the optimal adjustment scheme. Therefore, considering the distinctive properties of the TSRG algorithm, the framework of this algorithm can be applied to other similar problems, especially in adjusting the initial plan after being affected by disruption factors. These main findings provide useful insights for generating adjusted production schemes in the factor of unexpected disruptions in production operations.

On the basis of directing the safe entry and leave of vessels, these discoveries and findings can support the VTS center and increase the port's operational efficiency. In this study, we have proposed a framework, for solving the VSLPB, including the optimization model and the TSRG algorithm. The model proposed in this paper for dealing with VSLPB can be applied to different types of ports and other types of disruption factors after simple changes to the constraints of operation modes and disruption management strategies. In addition, the TSRG algorithm framework can also be extended to other types of ports and handle other types of disruption factors. However, it still requires some detailed modifications to meet different solving objectives for specific problems. Our method thus can be widely applied in many ports that seek an efficient and helpful way to handle disruption factors. Additionally, it helps the port increase its competitiveness while making a significant contribution to enhancing the port's capability for emergency response.

The limitation of this study lies in the fact that the VSLPB is addressed within one cycle. Moreover, this paper only investigates the impact of failed ship loaders, which is one of the uncertain factors in the port production process. Thus, future studies could consider the extensions model and solution method of this study. In this case, a study on the optimization vessel traffic scheduling problem of multiple plan cycles considering other uncertain factors is of good research value. Moreover, researching a new solution algorithm to improve its speed and effect on the new problem remains highly valuable in the future investigation in the associated direction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal

relationships that could have appeared to influence the work reported in this paper.

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