Collaborative optimization for loading operation planning and vessel traffic scheduling in dry bulk ports

Abstract: While loading operation planning and vessel traffic scheduling are still deemed as two independent operations in practice, it has been realised that their collaborative optimization and coordination can improve port operation efficiency. It is because that two separate operations often result in vessels spending more waiting time when passing through channels and/or longer loading time at berth, and hence seriously affect the productivity and efficiency of ports. It is even worse in the case where multi-harbor basins share a restricted channel. Therefore, this paper aims to address the collaborative optimization of loading operation planning and vessel traffic scheduling (COLOPVTS) and to generate the optimal traffic scheduling scheme and loading operation plan for each vessel synchronously. Through analyzing the process of vessels entering and leaving dry bulk export ports, a multi-objective mathematical model of COLOPVTS is proposed. Due to the complexity of the model, a heuristic algorithm combining the Variable Neighborhood Search (VNS) and Non-dominated Sorting Genetic Algorithm II (NSGA-II) is applied to solve the model. Finally, the computational results on the practical data of Phase I and Phase II terminals in Huanghua coal port are analysed to verify the rationality and effectiveness of the proposed model and algorithm.

Keywords: Dry bulk port, Loading operation planning, Vessel traffic scheduling, Collaborative optimization, VNS, NSGA-II

1. Introduction

Dry bulk cargoes account for over 70% of global maritime logistics [1]. Dry bulk shipping market is expected to reach a market volume of 6,800.0 million tons by 2027 and expand at 5.10% compound annual growth rate (CAGR) during the forecast period [2]. The actual development of dry bulk ports has grown fast as maritime logistics is the cheapest transport way for dry bulk cargoes (e.g. coal, iron, and grain). Compared to the costly physical expansion of ports, it is more cost-effective to increase the efficiency of port operations to maximize port throughput. In the case of limited resources in dry bulk ports (such as berths, channels, and handling equipment), how to reasonably optimize these resources to improve port throughput has become the focus of port managers. For example, Huanghua coal port, as one of China's major dry bulk cargo ports, has exposed traffic throughput limit from its restricted channel, due to the features of its geographical location, the water depth and width of the channel. To ensure the navigational safety of vessels, vessels with deep draught requirements need to pass through the channel at certain tidal time windows. Moreover, vessels need to be allocated a reasonable navigation mode (i.e. one-way/two-way navigation mode) to pass through the channel with limited width. Many dry bulk ports have a similar environment, when multi-harbor basins sharing a restricted channel. Some illustrative examples are Newcastle port in Australia, Hamburg port in Germany, and Houston port in the United States of America. Although the navigational conditions of these ports are different, the theoretical generalization by adjusting the one-way or two-way related parameters to fit other ports is general.

Through the analysis of the aforementioned dry bulk cargo ports, the generic dry bulk port model in this paper is described in Fig. 1. Empty vessels sail from the anchorages to the berths through a restricted channel. After the vessels are moored, the required cargoes are reclaimed from the stockyard by reclaimers, then transferred to the shipside by conveyor belt systems, and finally loaded by ship loaders. The departure of loaded vessels are via the restricted channel to the channel entrance. Specifically, the process of vessels visiting the port can be divided into three stages, as shown in Fig. 2. First, according to the demand of empty vessels at the anchorage, the berth, reclaimer, and ship loader are reasonably allocated for the vessels. This stage is to make a loading plan for each vessel to quickly load cargoes from the stockyard to the vessels. It is necessary to consider the allocation of eligible berths with berthing capacity for the vessels with different demands and allocate efficient reclaimers/ship loaders for the vessels which have a large demand. More than one reclaimers/ship loaders on the same rail track need to consider operational constraints (i.e. non-crossing and non-collision). Secondly, the empty vessels arrive at the assigned berths through the restricted channel in a reasonable navigation mode and a certain order. Then, the assigned reclaimers and ship loaders are able to carry out loading operations on these vessels. Thirdly, after the loading of the vessels is completed, they leave the port through the same channel in a reasonable navigation mode and a certain order. However, due to the limited water depth in the restricted channel, loaded vessels with deep draught requirements need to wait for the appropriate tidal time windows to leave the port. The second and third stages are to make a vessel traffic scheduling scheme to ensure navigation safety for all vessels. In these two stages, it should be noted that each vessel is assigned a reasonable navigation mode based on navigation rules. It is necessary to consider traffic conflicts in the process of vessels navigation, such as overtaking, crossing and head-on situations. As can be seen from the above, the three stages are a complex decision-making process because the loading operation planning and vessel traffic scheduling are heavily linked.

Therefore, a potential problem may occur in the process of vessels traffic scheduling once a load operation plan is predetermined. Although the given load operation plan may be a preferable scheme related to vessels' demand, it is possibly not a desirable one from the perspective of optimizing the vessel traffic scheduling scheme. As a result, it is easy to increase the waiting time of empty and loaded vessels passing through the channel and even cause the loaded vessel misses the tidal time window, the waiting time will be longer. For instance, in Huanghua coal port, the average vessels' waiting time for the channel is approximately 3 hours, accounting for 21.72% of the loading operation time. Among them, the Supramax bulk carrier visits the port the most often, approxiamtely 1,850 times a year, where its rent is $30,000 per day [3]. Thus, the financial loss caused by waiting for the channel is considerable, as well as resource waste and operational plan delays. Therefore, the collaborative optimization for loading operation planning and vessel traffic scheduling in dry bulk ports has become a critical problem to further improve port throughput.

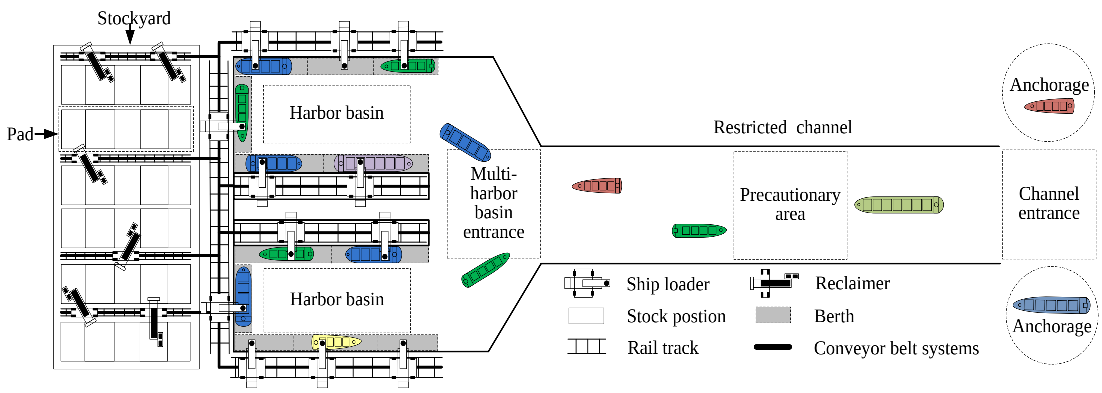

Fig.1. Overall structure of a dry bulk export port with multi-harbor basins sharing the same restricted channel.

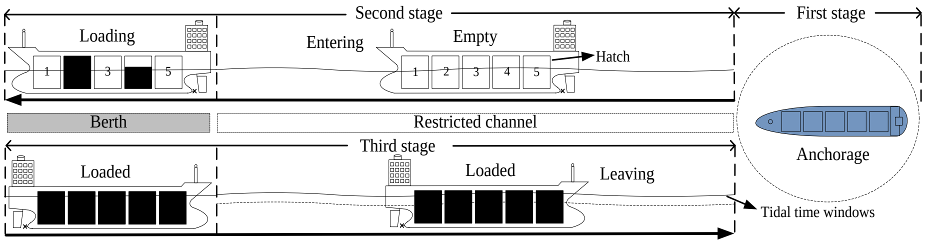

Fig.2. A schematic view of three stages taking place at the port area.

To address this issue, port managers usually adopt these strategies: (1) expanding investment, such as channel widening, increasing the number of berths and loading equipment [4]; (2) optimizing the loading operation planning [5]; and (3) scheduling vessel traffic scheme [6]. The first strategy does not provide a solution for all ports, particularly those involving fast-changing market demands in a short period. The advantages of the second and third strategies include that they can quickly adapt to the market demand. However, if these two problems are solved separately, it will bring new problems when a large number of vessels are presented. In practice, these two operations are currently still solved separately based on manual operations with spreadsheets. It is feasible for simple cases but unacceptable for complicated ones in which a large number of vessels arrive simultaneously or at a similar time. Manual operations will result in vessels spending more unnecessary waiting time through the channel or longer loading operation time at the berth. It is a very common problem encountered nearly in all dry bulk ports for their exported cargoes. With the increasing traffic of dry bulk carriers, the problem becomes more emerging and needs to be tackled with urgency. Extensive literature reviews have revealed that there are very few optimization tools that can be used for an effective solution to the problem. Therefore, this paper studies the collaborative optimization of the loading operation planning and vessel traffic scheduling (COLOPVTS) for dry bulk export ports.

The rest of the paper is structured as follows. Section 2 describes the related works for the COLOPVTS and emphasizes our contribution. Section 3 formulates the problem with a multi-objective mathematical model. Section 4 details the proposed algorithm for the problem-solving. Numerical experiments are conducted in Section 5. Finally, conclusions are made in Section 6.

2. Literature review

At present, the COLOPVTS in dry bulk export ports has received very little attention. In the last two decades, loading operation planning and vessel traffic scheduling are largely studied separately and significant contributions have been made at each local level. From the aspect of loading operation planning, the majority of existing research focuses on investigating different operational problems, including berth allocation, ship loader allocation, reclaimer allocation, and the hybrid of these problems. In terms of vessel traffic scheduling, most researchers investigate the optimal traffic scheduling scheme in different channels through a variety of optimization methods. Finally, our work is compared with the relevant literature of the COLOPVTS.

2.1 Loading operation planning

Over the last few decades, three different berth layouts have been considered in berth allocation optimization: discrete [7], continuous [8], and hybrid [9]. Barros et al. [10] proposed stock capacity constraints of loading cargoes to allocate discrete berths. Wang et al. [11] studied a discrete berth allocation problem in ports considering container transshipment and port operation. Zhen [12] proposed that a continuous berth allocation can be approximated by a discrete berth allocation. They assumed that the berths were very small and one ship could occupy several adjacent berths. Ernst et al. [13] discussed the allocation of continuous berths affected by tides. Kavoosi et al. [14] considered the available equipment, equipment efficiency and yard space, established a discrete berth scheduling model and proposed an evolutionary algorithm to solve the model. Umang et al. [15] considered the distance between cargo locations and berths to allocate hybrid berths in bulk ports. These studies assumed that the berthing capacity of each berth is the same. In fact, the berthing capacity of berths at a dry bulk export port could be very different. However, the berthing capacity of each berth must meet the demand weight of each vessel visiting it. Therefore, it is necessary to set a discrete berth layout of a dry bulk export port for further investigation.

The ship loader allocation problem is similar to the quay crane allocation one in nature, because they work similarly by traveling on rail track to load. Fu et al. [16] established a model considering the safety distance between quay cranes to obtain the task sequence of quay cranes for vessels. Nguyen et al. [17] developed a quay crane allocation system based on task priority to reduce the traveling time of quay cranes. Chang et al. [18] studied the quay crane allocation under a dynamic strategy. Zhang et al. [19] considered the non-crossing constraint of quay cranes. The objective was to minimize the completion time of a vessel. Different from the quay crane allocation, ship loaders need to move frequently to load cargoes in accordance with the vessels' loading sequence. Thus, a ship loader usually serves only one vessel at the bulk cargo export port.

A reclaimer travels back and forth along the rail track 55 times to complete the reclaiming operation from the stockpile [20]. In addition, a reclaimer can only reclaim the stockpile on both sides of the rail track. This fact results in interference restrictions on the movement of the reclaimers on the same track. Hence, compared with the stockyard allocation problem [21], the reclaimer allocation problem is different in that it takes more consideration of operation interference of multiple reclaimers on the same track. Angelelli et al. [20] developed a constant factor approximation algorithm to minimize the operation time according to the constraints of the reclaimer operation sequence. Kalinowski et al. [22] proved the NP-completeness of the reclaimer allocation problem and formulated it as a mixed-integer program. They proposed an exact branch-and-bound algorithm based on reference [20]. Huang et al. [23] considered the non-crossing constraint of multiple reclaimers on the same track and established a mathematical model with minimizing the operation and maintenance costs.

Previous studies have also demonstrated some hybrid models by combining two among three interconnected problems. For instance, Iris et al. [24] explored the integrated berth allocation and quay crane assignment problem. They extended the current state-of-the-art by proposing novel set partitioning models. Zhen et al. [25] proposed an integer programming model of berth allocation and quay crane assignment with considering tide cycles and navigation channel constraints. Then, Wang et al. [26] investigated berth allocation and quay crane assignment problems from the perspective of carbon emission taxation, then established a bi-objective optimization model to minimize the total operating cost of quay cranes and completion delay of tasks. Recently, He et al. [27] studied the berth allocation and quay crane assignment problem in terms of driver cost and operating efficiency. Furthermore, the integrated three problems were investigated, but with a smaller number in the literature. Unsal et al. [5] considered the berth allocation, non-crossing of reclaimers and operation time of ship loaders. They proposed a MIP model of dry bulk export terminals and designed a logic-based Benders decomposition algorithm to solve the model. De et al.

[28] took three coal export terminals in Newcastle port sharing one channel as an example, in which its layout, berthing time of vessels, loading equipment, and inbound/outbound sharing resources were considered. They presented a parallel genetic algorithm to improve the throughput of coal ports. However, they did not consider the impact of the traffic scheduling scheme on the loading operation planning. Given the increasing dry bulk traffic in port the question as to how to adjust the loading operation plan of each vessel appropriately according to their traffic scheduling scheme becomes the bottleneck that limits a ports efficiency.

2.2 Vessel traffic scheduling

Within the context of vessel traffic scheduling, many researchers focus on vessel traffic scheduling in one-way, two-way, and/or compound channels, while few in restricted channels. Jia et al. [29] considered the influence of tides and anchorage, by establishing a vessel traffic scheduling model in a one-way channel. They proposed a Lagrange relaxation heuristic algorithm to solve the model. Lala Ruiz et al. [30] studied a two-way channel scheduling problem in which the waiting time of vessels, along with their passing times, were minimized. A myriad factors comprising depth, capacity, and width of the passage were considered in this study. Furthermore, the draft limit of vessels and tidal impacts on water levels were included in the designed mathematical model of a two-way channel. Later, Meisel et al. [31] proposed a new optimization model for vessel traffic in a two-way channel, which included variable vessel speed, navigation mode and traffic conflicts. They considered the same/opposite safe distance to avoid traffic conflicts such as overtaking and a head-on situation. Zhang et al. [32] determined the vessel traffic conflicts in key areas by analyzing the complex traffic flow in a compound channel. They proposed a multi-objective model which mainly took into account the constraints of tidal time windows, navigation mode, overtaking, head-on and crossing situations. Until recently, the studies on the vessel traffic scheduling for a restricted channel emerge. Corry et al. [33] proposed an optimization model for a restricted channel to minimize the waiting time for vessels. They mainly considered avoiding a head-on situation and tidal constraints in the channel. On this basis, Li et al. [6] extracted the traffic conflicts in key areas by analyzing vessel traffic flow. Considering the navigation mode and tidal time window, a MIP model for vessel scheduling was proposed to optimize vessel sequence.

The relevant literature reveals that most of the existing studies aim at minimizing the waiting time of vessels. To ensure navigation safety of vessels, they establish the models for different channel types to obtain the optimal traffic scheduling through heuristic algorithms, involving navigation mode, tidal time window, and traffic conflict. However, few of them concern the impact of the loading operation plan on the vessel traffic scheduling. With the diversification of the demand for dry bulk cargo carriers, how to properly adjust a traffic scheduling scheme according to the loading operation plan is particularly important in practice and high value in science.

2.3 Our contribution to the literature

Although the two aspects of loading operation planning and vessel traffic scheduling have attracted great attention in recent decades, few studies focused on COLOPVTS. For container ports, Fatemi-Anaraki et al. [34] considered the problem of simultaneous berth allocation, quay crane assignment, and two-way channel scheduling for container ports, which is similar to a three-stage hybrid flow shop scheduling problem. The constraints of this problem are the availability of berth resources, the number of quay cranes, the influence of tides, and the width limitation of the two-way channel. They proposed three different mathematical methods to solve the problem. However, they did not take into account the actual limitations of port operations, such as berthing capacity of wharves and operational efficiency matching of handling equipment.

For dry bulk ports, Badu et al. [35] and Tang et al. [36] analyzed the unloading operation process of dry bulk import terminals to propose the collaborative optimization of inland resource plans (such as stockyards, trains, and equipment) and ship scheduling. They established a MILP mathematical model and developed a heuristic/exact algorithm to solve the model. However, they assumed that a channel of port meets the navigation needs of vessels at any time. They did not consider the actual situation of dry bulk ports, such as berthing capacity and different navigation modes constraints. In particular, they lacked the establishment of a relationship between vessel traffic scheduling and loading operation planning.

With this concern, simultaneously considering these two problems to achieve a traffic scheduling scheme and load operation plan is a theoretically challenging problem for port managers. Despite the fast development of the similar topic in other sectors (e.g. container ports), the optimization work concerning loading and vessel scheduling coordination in dry bulk ports is scanty. It does not match the growing demand on the dry bulking shipping practice. Furthermore, from a theoretical perspective, the established models for container ports reveal some serious constraints when being used within the dry bulking shipping context, due to its uniqueness in terms of berthing capacity of wharves, operational efficiency of handling equipments, and different navigation modes of ports. To address them, a new model of COLOPVTS for dry bulk export ports is proposed in this paper. This work presents an exploratory study within this context. Compared with the above literature, the contribution of this study lies in that:

(1) This is the first work that solves the COLOPVTS in dry bulk export ports. The interrelated constraints involved in the complex decision-making process are considered, such as berthing capacity restrictions, operational efficiency matching of ship loaders and reclaimers, vessels' loading sequence, non-crossing operation of ship loaders on a single rail track, non-collision operation of reclaimers on different rail tracks, different navigation modes, tidal time window, traffic conflicts, and so on

(2) A mathematical model of COLOPVTS is developed to simultaneously obtain a traffic scheduling scheme and loading operation plan for each vessel. The model aims to optimize terminal loading operations and vessel scheduling

(3) Experiments with randomly generated test sets based on practical data of a large representative coal port are adopted in this research.

In this study, the relationship between arrival/departure times and loading completion time of vessels at berth is first configured to formulate the minimum loading completion time constraint (see Section 3.3.3 for more details). It can combine the loading operation planning and vessel traffic scheduling problems together into a collaborative model with the purpose of minimizing the total waiting time and total loading completion time for all vessels.

3. Problem formulation

This section first presents a general description for COLOPVTS in dry bulk export ports (see Fig.1) with a focus on the investigated coordination optimization problem. It is followed by the problem formulation of a mathematical model using mixed-integer linear programming (MILP).

3.1 Problem description

As shown in Fig.1, each product is stored as a rectangular pile (stock position) at a stockyard and each pad has several stock positions. Due to the limited capacity of each stock position, the same product may occupy more than one stock position (multiple stockpiles). Because of the different capacities of each berth, it is necessary to allocate appropriate berths according to the vessels' demand weight. In discrete berths, each berth is a discrete resource of a single vessel capacity.

When more than one ship loaders are on the same rail track, the non-cross constraint of ship loaders should be considered. A vessel has several hatches for loading products. In the loading process of the vessel, the loading sequence of a vessel should be considered to discharge ballast water smoothly. For example, the loading sequence of a vessel with five hatches is "2-4-3-1-5", namely, the sequence of ship loader traveling.

Moreover, there can be more than one reclaimer on each rail track, and these reclaimers cannot pass each other. When two stockpiles are overlapping in time and x-axis, these two reclaimers cannot reclaim simultaneously, because they need to cross each other. Similarly, when such two reclaimers are on both sides of the pad, and the two reclaimers simultaneously reclaim the same stockpile, they cannot reclaim simultaneously to avoid a collision. There should be an additional time of transporting the very last part of the stockpile to the vessel concerning the distance between the stockyard and the berth that the vessel is moored. It is assumed that this amount of time does not depend on the exact location of the related stockpile over the pad, as it is affected by the conveyor belt configuration (design) between the berth and the stockyard where the stockpiles of this vessel are located. Dry bulk carriers often demand one type of product, but their demand is much greater than the capacity of the stacking position and the same product has multiple stockpiles, so the reclaimers need to move frequently for reclaiming. Moreover, one reclaimer can only be connected to one ship loader because of the technological restrictions of the in-terminal transportation system (connection of conveyor belts and ship loaders). For this reason, each vessel is often loaded by a single reclaimer and a single ship loader (see Section 3.3.1).

According to the special characteristics of the restricted channel, from the perspective of time, the departure of the loaded vessels is constrained by the appropriate tidal time window due to their weights. If the loading operation plan is unreasonable, a late loading completion time may cause the vessel to miss the currently available tidal time window. From the perspective of space, vessels need to maintain a safe distance/time to enter and leave port. In such cases, traffic conflicts such as overtaking, crossing and head-on situations have to be avoided in different areas (see Section 3.3.2).

3.2 Assumptions of the model

To solve the problem described above, the following assumptions are set:

(1) Products will be stacked immediately once they arrive at the stockyard

(2) Each vessel requires one type of product and the loading sequence is known in advance

(3) Berths and ship loaders shall not be changed during the loading

(4) Each vessel will apply for departure immediately upon completion of loading

(5) Extreme weather conditions and equipment failures are not considered

3.3 Mathematical model

Using the symbols listed in Appendix A, a multi-objective mathematical model of COLOPVST is formulated as follows:

$$\min\ F_1 = \sum_i \left(A_i' - A_i\right) + \sum_i \left(E_i' - E_i\right) \tag{1}$$

$$\min\ F_2 = \sum_i \left(LJ_{ilrb} - SJ_{ilrb}\right) \tag{2}$$

Objective functions (1) and (2) minimizes the total waiting time and the total loading completion time of vessels, respectively.

3.3.1 Constraints - Loading operation planning

$$\sum_b \sum_j D_{bij} = 1 \quad \forall i \tag{3}$$

$$P_{bii'} + P_{bi'i} \le Q_{ib} \quad \forall b, i, i' : i \ne i' \tag{4}$$

$$P_{bii'} + P_{bi'i} \ge Q_{ib} + Q_{i'b} - 1 \quad \forall b, i, i' : i \ne i' \tag{5}$$

$$\sum_i Q_{ib} G_{bl} = 1 \quad \forall b, l \tag{6}$$

$$LT_{ijlc} = LS_{icc'} LV_l \left|\varphi^{c}_{ijlc} - \varphi^{c'}_{ijlc'}\right| + \left(1 - LS_{icc'}\right) LV_l \left|\varphi^{c}_{ijlc} - \varphi^{c'}_{i'j'lc'}\right| \quad \forall i, l, j, c, c' : c \ne c' \tag{7}$$

$$\begin{gathered} \alpha_{rr'k}\left(\theta^{w}_{irjfw} - \theta^{w'}_{i'r'j'f'w'}\right) + \left(1 - \alpha_{rr'k}\right)\left|RM_{irjfw} - RM_{i'r'j'f'w'}\right| > 0 \\ \forall k, i, i' : i \ne i', j, j' : j \ne j', r, r' : r \ne r', f, f', w, w' \end{gathered} \tag{8}$$

$$\begin{gathered} RT_{irj} = RS_{ijj'} RV_r \left|\theta^{w}_{irjfw} - \theta^{w'}_{irj'f'w'}\right| + \left(1 - RS_{ijj'}\right) RV_r \left|\theta^{w}_{irjfw} - \theta^{w'}_{i'rj'f'w'}\right| \\ \forall i, i' : i \ne i', j, j' : j \ne j', r, r' : r \ne r', f, f', w, w' \end{gathered} \tag{9}$$

$$\sum_l \sum_r \Omega_{ilr} = 1 \quad \forall i \tag{10}$$

$$\Omega_{ilr}\left(LF_l - RF_r\right) > 0 \quad \forall i, l, r \tag{11}$$

$$LP_{ii'lr} + LP_{i'ilr} \le \Omega_{ilr} \quad \forall l, r, i, i' : i \ne i' \tag{12}$$

$$LP_{ii'lr} + LP_{i'ilr} \ge \Omega_{ilr} + \Omega_{i'lr} - 1 \quad \forall i, l, r, i, i' : i \ne i' \tag{13}$$

$$\sum_l \sum_r \sum_b \beta_{ilrb} = 1 \quad \forall i \tag{14}$$

$$Q_{ib} + \Omega_{ilr} \le \beta_{ilrb} + 1 \quad \forall i, l, r, b \tag{15}$$

$$LJ_{ilrb} = \sum_j RJ_{irj} + \sum_j RT_{irj} + \sum_c LT_{ijlc} + Distance_b + \left(1 - \beta_{ilrb}\right) M \quad \forall i, j, b, l, r, c \tag{16}$$

The constraints associated with loading operation planning are presented by Eqs. (3) - (16). Specifically, the constraints of berth allocation are defined by Eqs. (3) - (5). Constraint Eq. (3) simply ensures that the capacity of each berth meets the weight of all tasks of each vessel. $P_{bii'}$ and Q_{ib} variables are put together by constraints Eqs. (4) and (5) to determine the berthing order of the vessels that are assigned to the same berth. If vessels i and i' are assigned to the same berth, then they must use that berth sequentially ($P_{bii'} + P_{bi'i} = 1$). If at least one of i' and i is not assigned to berth b, then corresponding $P_{bii'}$ variable takes the value of 0.

The constraints of ship loader allocation are defined by Eqs. (6) and (7). Constraint Eq. (6) ensures that when vessel i is assigned to berth b, the ship loader only serves the vessel i at the berth

b. That is to avoid ship loaders crossing each other on the same rail track. According to the loading sequence of vessel, the traveling time of the ship loader is calculated by constraint Eq. (7).

The constraints of reclaimer allocation are described by Eqs. (8) and (9). Constraint Eq. (8) ensures that reclaimers on the same rail track avoid crossing each other, and reclaimers on different rail tracks avoid reclaiming the same stockpile simultaneously. According to the vessel's task sequence, the traveling time of the reclaimer is calculated by constraint Eq. (9).

Constraints Eqs. (10)-(16) are used to link the constraints of the berth allocation, the ship loader allocation, and the reclaimer allocation. Constraint Eq. (10) states that each vessel requires one ship loader and one reclaimer. Constraint Eq. (11) ensures that operational efficiency of the allocated ship loader and reclaimer match. $LP_{ii'lr}$ and $LP_{i'ilr}$ variables are put together by constraints Eqs. (12) and (13) to determine the order of vessels on the same ship loader and the same reclaimer, similar to those of the berth allocation. Constraints Eqs. (14) and (15) determine the berth, the ship loader and the reclaimer are assigned for each vessel. These constraints together enforce β_{ilrb} to take the value of 1 if vessel i is assigned to berth b ($Q_{ib}=1$), ship loader l ($G_{bl}=1$) and reclaimer r ($\Omega_{ilr}=1$). By constraints Eq. (16), the loading completion time of the vessels is calculated by taking the completion time of reclaiming each stockpile, the traveling time of the reclaimer, the traveling time of the ship loader and the distance between the berth and the stockyard into account.

3.3.2 Constraints - Vessel traffic scheduling

$$A_i' \geq A_i + M\left(1 - IO_i\right) \quad \forall i \tag{17}$$

$$T_{1i'} \geq T_{1i} + \delta_1 + M\left(3 - IO_i - IO_{i'} - Y_{ii'}\right) \quad \forall i, i' : i \neq i', v_i \geq v_{i'} \tag{18}$$

$$T_{1i'} \geq T_{1i} + \delta_2 + M\left(2 - X_i - Z_{ii'} - X_{i'}\right) \quad \forall i, i' : i \neq i' \tag{19}$$

$$T_{1i'} \geq T_{1i} + \delta_2 + M\left(3 - X_i - Z_{ii'} - X_{i'}\right) \quad \forall i, i' : i \neq i' \tag{20}$$

$$T_{1i'} \geq T_{1i} + \delta_2 + M\left(1 - X_i - Z_{ii'} - X_{i'}\right) \quad \forall i, i' : i \neq i' \tag{21}$$

$$T_{2i'} \geq T_{2i} + \delta_2 + M\left(1 - X_i - Z_{ii'} - X_{i'}\right) \quad \forall i, i' : i \neq i' \tag{22}$$

$$T_{3i'} \geq T_{3i} + \delta_1 + M\left(4 - IO_i - IO_{i'} - Y_{ii'} - H_{ii'}\right) \quad \forall i, i' : i \neq i', v_i \geq v_{i'} \tag{23}$$

$$T_{3i'} \geq T_{3i} + \delta_2 + M\left(2 - X_i - Z_{ii'} - X_{i'}\right) \quad \forall i, i' : i \neq i' \tag{24}$$

$$T_{3i'} \geq T_{3i} + \delta_2 + M\left(3 - X_i - Z_{ii'} - X_{i'}\right) \quad \forall i, i' : i \neq i' \tag{25}$$

$$T_{3i'} \geq T_{3i} + \delta_3 + M\left(1 - X_i - Z_{ii'} - X_{i'}\right) \quad \forall i, i' : i \neq i' \tag{26}$$

$$T_{4i'} \geq T_{4i} + \delta_1 + M\left(1 - IO_i - IO_{i'} - Y_{ii'} - H_{ii'}\right) \quad \forall i, i' : i \neq i', v_i \geq v_{i'} \tag{27}$$

$$T_{4i'} \geq T_{4i} + \delta_2 + M\left(1 - Z_{ii'} - H_{ii'}\right) \quad \forall i, i' : i \neq i' \tag{28}$$

$$S_i \geq T_{4i} + M\left(1 - IO_i\right) \quad \forall i \tag{29}$$

$$E_i' \geq E_i \quad \forall i \tag{30}$$

$$E_i' \geq T_i + M\left(1 - IO_i - \gamma_i\right) \quad \forall i \tag{31}$$

$$T_{1i} > E_i' \quad \forall i \tag{32}$$

$$T_i' \geq T_{1i} + M\left(1 - IO_i - \gamma_i\right) \quad \forall i \tag{33}$$

The constraints from Eqs. (17) - (33) are associated with the vessel traffic scheduling. Constraint Eq. (17) states that the start time of the vessel sailing will not start before the application time of the vessel for entering port. The constraints of the navigation mode and vessel traffic conflict are defined by Eqs. (18) - (28) [6].

Constraints Eqs. (18) - (21) ensure that vessels avoid traffic conflicts at the channel entrance, such as overtaking and a head-on situation. Constraint Eq. (18) states that incoming vessels from different anchorages do not overtake the others. Constraint Eq. (19) guarantees there is a safe time interval between the incoming and outgoing vessels in a head-on situation when the vessels are in different navigation modes. Similarly, constraints Eqs. (20) and (21) ensure that in a head-on situation, the vessels with the same navigation mode need to maintain a safe time interval. Constraint Eq. (22) ensures that vessels are in the mixed navigation mode, it is necessary to maintain a safe time interval between the vessels at precautionary area.

Constraints Eqs. (23) - (26) ensure that traffic conflicts between vessels at the multi-harbor basin entrance are avoided. Constraint Eq. (23) states that the outgoing vessels from different basins do not overtake the others. Constraint Eq. (24) guarantees incoming and outgoing vessels avoids in a head-on situation, similar to constraint Eq. (19). Constraint Eq. (25) states that there is a safe time interval between the incoming and outgoing vessels when the vessels are in the one-way navigation mode. Constraint Eq. (26) ensures that vessels are in the mixed navigation mode, it is necessary to maintain a safe time interval in a crossing situation.

Constraints Eqs. (27) and (28) state that vessels avoid traffic conflicts in the same harbor basin. Constraint Eq. (27) guarantees outgoing vessels do not overtake the others. Constraint Eq. (28) ensures that there is a safe time interval between the incoming and outgoing vessels in a head-on situation. Constraint Eq. (29) ensures that the arrival time of an incoming vessel to its berth is later than its arrival time to harbor basin. Constraint Eq. (30) ensures that an outgoing vessel cannot leave before its application. Constraints Eqs. (31) - (33) ensure that the sailing time of the outgoing vessel from berth to channel entrance is within an eligible tidal time window.

3.3.3 Constraints – To link the loading operation planning and vessel traffic scheduling

$$SJ_{ilrb} \geq S_i \quad \forall i,l,r,b \tag{34}$$

$$E_i' \geq E_i \geq SJ_{ilrb} + LJ_{ilrb} \quad \forall i,l,r,b \tag{35}$$

$$S_{i'} \geq E_i' - M\left(1 - P_{bii'}\right) \quad \forall b,i,i' : i \neq i' \tag{36}$$

$$SJ_{i'lrb} \geq SJ_{ilrb} + LJ_{ilrb} - M\left(1 - \beta_{i'lrb}\right) + \varepsilon_{i'} \quad \forall i,l,r,b,i,i' : i \neq i' \tag{37}$$

$$\varepsilon_{i'} = Max\left\{RT_{i'rj'}, LT_{i'j'lc'}\right\} \quad \forall l,r,j',c',i,i' : i \neq i' \tag{38}$$

$$\alpha_{rr'k}, \beta_{ilrb}, \gamma_i, \Omega_{ilr}, D_{bij}, LP_{ii'lr}, LS_{icc'}, H_{ii'}, IO_i, P_{bii'}, Q_{ib}, RS_{ijj'}, G_{bl}, X_i, Y_{ii'}, Z_{ii'} \in \{0,1\} \quad \forall j,l,r,b,c,f,w,i,i' : i \neq i'$$

$$A_i, A_i', S_i, E_i, E_i', T_{1i}, T_{2i}, T_{3i}, T_{4i}, T_i, T_i', \delta_1, \delta_2, \delta_3 \geq 0 \quad \forall i \tag{39}$$

$$RJ_{irj}, RT_{irj}, RV_r, LT_{ijlc}, LV_l, SJ_{ilrb}, LJ_{ilrb}, \theta_{irjfw}^{w}, \varphi_{ijlc}^{c}, \varepsilon_{i'}, distance_b \geq 0 \quad \forall j,l,r,b,c,f,w,i,i' : i \neq i'$$

Constraint Eq. (34) states that the start time of the vessel’s task will not begin before its arrival time. Constraint Eq. (35) guarantees the departure time of the vessel will not start before the completion time of the vessel's task. Constraint Eq. (36) ensures that vessels using the same berth are non-overlapping. Namely, if $P_{bii'}=1$, then vessel i' must moor behind vessel i. By constraint Eq. (37), vessels using the same berth, same ship loader, and same reclaimer cannot undertake the tasks simultaneously. That is, the start time of the next vessel's task needs to consider the start time of the current vessel's task, the completion time of all tasks of the current vessel, and the preparation time of the next vessel's task. Constraint Eq. (38) ensures that the preparation time of the next vessel's task is the maximum time required for the reclaimer/ship loader to travel. Lastly, constraint Eq. (39) determines the domains of variables.

4. Solution approach

Loading operation planning and vessel traffic scheduling are NP-hard problems [5,30], respectively. The collaborative optimization of these two problems is also an NP-hard problem as well as a complex combinatorial optimization problem. Due to many constraints of the proposed mathematical model of COLOPVTS, all exact approaches for even in its simplest form will most likely have running time that increases exponentially against the problem size. Moreover, the model of COLOPVTS is a multi-objective problem. NSGA-II is used as the main algorithm to solve such a problem [37]. The solutions of NSGA-II have good distribution uniformity. But there are a lot of repeated individuals in the solution, it easily falls into a local optimum [38]. The variable neighborhood search (VNS) algorithm is one of the most renowned regional search algorithms used in solving complex combinatorial optimization problems [39]. The main difference between this algorithm and other regional search algorithms is that it considers more than one neighborhood structure transformation to get out of the local convergence and find optimal solutions. Therefore, a heuristic algorithm combining NSGA-II and VNS is designed, called NSGA-II-VNS. The pseudo-code of the algorithm is shown in Algorithms 1 and 2.

Algorithm 1. Pseudo-code for NSGA-II-VNS

Input: $V, L, R, B, H, J, F, W, K, C, A_i, X_i, T_i, T_i', IO_i, \delta_1, \delta_2, \delta_3$

1: Initialize a chromosome p_1

2: Initialize the population $pop=\{p_1, p_2, ..., p_{NIND}\}$

3: $gen \leftarrow 1$

4: $pop_{gen} \leftarrow$repair (pop_{gen})

5: **while** ($gen < MAXGEN$) **do**

6: $F_1, F_2 \leftarrow$fitness evaluation (pop_{gen})

7: $p \leftarrow$fast non-dominated sorting (F_1, F_2)

8: $p \leftarrow$VNS (p, N_k, λ, σ)

9: $pop_{gen} \leftarrow$crowding-distance assignment (F_1, F_2)

10: $pop_{gen}' \leftarrow$selection (pop_{gen} , $GGAP$)

11: $pop_{gen}' \leftarrow$crossover (pop_{gen}' , PC)

12: $pop_{gen}' \leftarrow$mutation (pop_{gen}' , PM)

```
        pop_gen′ ←repair ( pop_gen′ )
        F1′ , F2′ ←fitness evaluation ( pop_gen′ )
        P′ ←fast non-dominated sorting ( F1′ , F2′ )
        pop_gen′ ←crowding-distance assignment ( F1′ , F2′ )
        pop_gen ←elite retention strategy ( pop_gen , pop_gen′ , P′ , P )
        gen ← gen+1
and while
if ( F1 < F1′ ) then
    P ← p
else
    if( F2 > F2′ ) then
        P ← p
    end if
end if
Output: P
```

4.1 Initialization and fitness

A chromosome consists of many gene positions, which includes two segments: traffic scheduling scheme and loading operation plan, as shown in Fig. 3. As each vessel needs to be scheduled to enter and leave port, it is therefore scheduled twice. Thus, the length of the traffic scheduling scheme is twice the number of vessels and consists of three layers: vessel number (NO), navigation direction (IO), and navigation mode (X). The length of the loading operation plan is the number of vessels, and it consists of three layers: berth number (B), ship loader number (L) and reclaimer number (R). A chromosome represents a solution, namely individual initialization. Population initialization is randomly generated by individual initialization. The fitness evaluation for each individual is calculated by the objective functions. The value of the fitness evaluation is small; the corresponding solution is optimal.

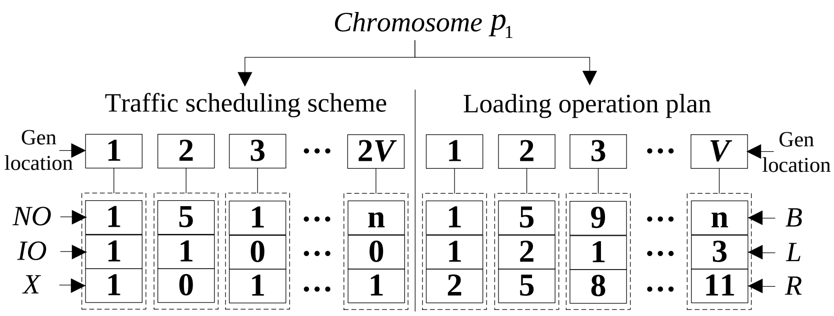

Fig.3. Chromosome encoding.

4.2 Selection, crossover, mutation and retention

In each iteration and for each solution, the rank and the crowding distance are calculated [40]. Specifically, the solutions are sorted using the rank and then the crowding distance in an order. Then according to the value of generation gap (GGAP), a certain proportion of chromosomes for crossover and mutation operation are selected by a roulette method. After the comparison through using different methods of crossover and mutation, and characteristics of chromosome encoding, a two-point crossover and mutation operation is adopted to effectively find optimal solution space. After this, the best individual of VNS is compared with the best individual offspring. The worst individual in offspring reproduction is replaced by the best individual, which is elite retention. The value of GGAP, cross parameter (PC), and mutation parameter (PM) are 0 to 1, 0.5 to 1, and 0 to 1, respectively.

4.3 Repairing operator

After the population initialization, VNS algorithm and mutation operation, an illegal chromosome is produced due to the encoding defects. There are two cases of illegal chromosomes. One case is the conflict of vessels' navigation mode. When incoming and outgoing vessels are in the different navigation modes through the channel, their navigation modes need to be adjusted according to the navigation rules. Another case is the conflict of vessels' loading operation plan: (1) berth allocation conflict, that is, the vessels in the same berth cannot overlap in time; (2) ship loader allocation conflict, that is, the ship loader cannot cross operation with others on the same rail track; (3) reclaimer allocation conflict, that is, the reclaimers shall avoid cross operation with others on the same rail track, and reclaimers on different rail tracks shall avoid the collision. Thus, a repair operator is designed to adjust the vessel's navigation mode or loading operation plan in the illegal chromosome to ensure that the solution is feasible.

4.4 Variable neighborhood search algorithm

There are two objective functions in this model. After fast non-dominated sorting, the two chromosomes corresponding to the optimal fitness values in the current solution are found and VNS on them performed respectively. The pseudo-code for VNS is described in algorithm 2. In the procedure of VNS, it is crucial to define effective neighborhood searches. According to the characteristics of COLOPVTS, three types of neighborhood structure are designed, and denoted by N_k ($k = 1,...,k_{\max}$). The detailed descriptions of these neighborhood structures are given as follows:

(1) $N_1(p)$ (Swap): For using this neighborhood strategy, firstly two genetic locations in the chromosome randomly are selected from a traffic scheduling scheme and then the locations of selected genes are exchanged. Similarly, the swap operation for a loading operation plan is repeated.

(2) $N_2(p)$ (Reversion): In this policy, besides conducting swap, the genes located in between the swapped gene locations are reversed, too.

(3) $N_3(p)$ (Insertion): In this case, firstly two genetic locations in the chromosome are randomly selected from a traffic scheduling scheme and then the gene in the back location is inserted into the gene ahead. Similarly, the insertion operation for a loading operation plan is repeated.

A single iteration of VNS is performed from lines from 3 to 22. The chromosomes are searched locally from three neighborhood structures in each iteration. If the fitness value of the new chromosome is better than the previous one, the most efficient solution is to save it in the list. If no new effective solution is found in the current neighborhood structure search, the number of the neighborhood structures with no improvement increases.

Algorithm 2. Pseudo-code for VNS

Initialize the set of neighborhood structure $N_k, k = 1, ..., k_{\max}$;
$\lambda \leftarrow 1, \sigma \leftarrow \varnothing, p$;
while ($\lambda < MAXGEN$) **do**
    $k \leftarrow 1$;
    while ($k < k_{\max}$) **do**
        $p_r \leftarrow$ pick a random solution p_r from the k^{th} neighborhood $N_k(p)$ of (p)
        $p'' \leftarrow$ local search (p_r)
        $p'' \leftarrow$ repair (p'')
        (F_1, F_2) , (F_1'', F_2'') $\leftarrow$fitness evaluation (p, p'')
        if ($F_1'' \le F_1$) **and** ($p'' \notin \delta$) **then**
            $p \leftarrow p''$
            $G \leftarrow p''$
        else
            if ($F_2'' < F_2$) **and** ($p'' \notin \delta$) **then**
                $p \leftarrow p''$
                $G \leftarrow p''$
            end if
        end if
        $k \leftarrow k + 1$
    and while
    $\lambda \leftarrow \lambda + 1$
and while
Return p

5. Computational experiments

In this section, a set of computational experiments based on the physical layout of Huanghua coal port in China are designed to verify the effectiveness of the proposed algorithm. The navigation rules of the port are as follows: (1) vessels with a length exceeding 225 m or a width exceeding 32.3 m are allowed to sail in one-way navigation mode; (2) two vessels with a width of fewer than 61 m are allowed to sail in mixed navigation mode; (3) one vessel should maintain a speed in the range of 8 to 10 knots.

Taking the Phase I and Phase II terminals of the port as an example, each terminal has a stockyard, six reclaimers, four ship loaders, and four berths in a harbor basin (as shown in Fig. 4). Each stockyard has six pads and each pad has eight stock positions. The storage capacity of the stock position for a product is limited to 30,000 tons. The distribution of product categories in each stockyard is shown in Fig. 4. The transfer speed of conveyor belt systems is 5 m/s, the average time for each reclaimer to travel at a stock position is 5 min, and the average time for each ship loader to travel at a hatch is 1.5 min. Data of berths, anchorages, ship loaders, and reclaimers are given in

Tables 2, 3, and 4, respectively.

The channel of the port is a typically restricted channel, which is shared by Phase I and Phase II terminals. Its physical layout is presented in Fig. 5. From buoy no.22 to buoy no.32 is a one-way segment with a distance of 4.66 nautical miles (nm). A two-way segment is 3.38 nm from buoy no.32 to buoy no.46. Buoy no.32 is a precautionary area and buoy no.40 is an avoiding encountering area. Among them, buoy no.40 is 3.38 nm from no.32 and 2.74 nm from no.46. Due to the spatial constraint of these harbor basins, vessels should avoid a head-on situation. The mathematical model of COLOPVTS for Phase I and Phase II terminals is established in Appendix B. All computational experiments are executed on a computer with 3.5 GHz Processor and 64GB RAM. CPLEX 12.6 with the default configuration is used and the time limit is set as one hour.

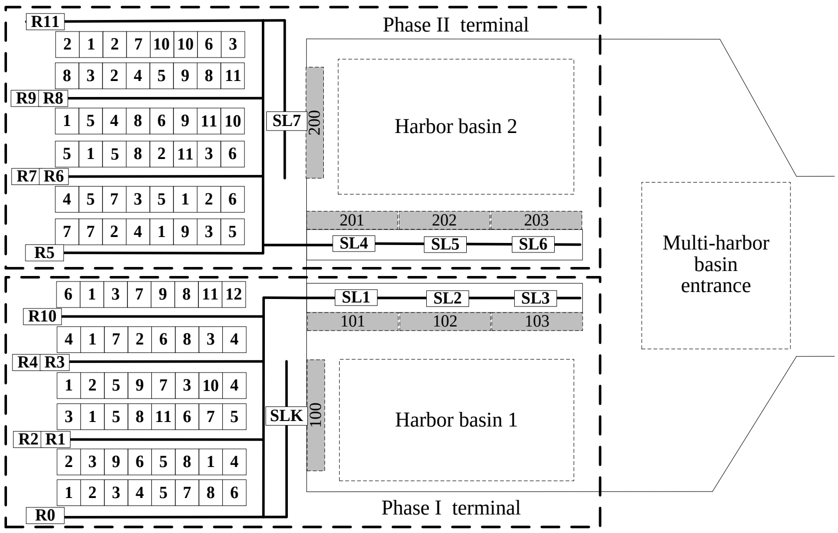

Fig. 4. Physical layout of Phase I and Phase II terminals of Huanghua coal port.

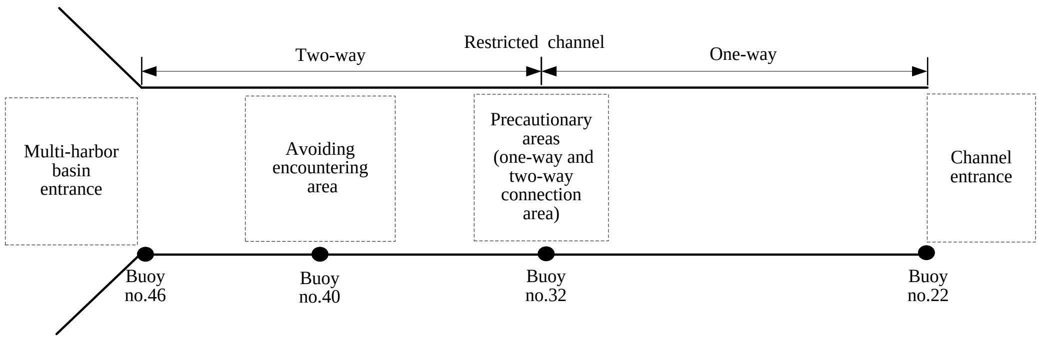

Fig. 5. Physical layout of the channel of Huanghua coal port.

Table 2. Data of berths.

H	B	B_ID	Berthing capacity	Distance from Phase I stockyard (m)	Distance from buoy no.46 (nm)	H	B	B_ID	Berthing capacity	Distance from Phase II stockyard (m)	Distance from buoy no.46 (nm)
1	100	1	20000	450	1.26	2	200	5	50000	450	1.32
1	101	2	35000	450	1.2	2	201	6	50000	450	1.22
1	102	3	70000	750	1.06	2	202	7	50000	750	1.08
1	103	4	70000	1000	0.9	2	203	8	100000	1000	0.9

Table 3. Data of anchorages

Anchorages	Distance from buoy no.22 (nm)
1	4.4
2	11
3	17.8

Table 4. Data of reclaimers and ship loaders.

R	R_ID	Stockyard	Operational efficiency of R	L	L_ID	B_ID	Operational efficiency of L
R0	1	I	3000t/h	SLK	1	1	6000t/h
R1	2	I	6000t/h	SL1	2	2	6000t/h
R2	3	I	3000t/h	SL2	3	3	6000t/h
R3	4	I	6000t/h	SL3	4	4	6000t/h
R4	5	I	3000t/h	SL4	5	6	6000t/h
R10	6	I	6000t/h	SL5	6	7	6000t/h
R5	7	II	6000t/h	SL6	7	8	6000t/h
R6	8	II	6000t/h	SL7	8	5	6000t/h
R7	9	II	3000t/h	-	-	-	-
R8	10	II	6000t/h	-	-	-	-
R9	11	II	3000t/h	-	-	-	-
R11	12	II	6000t/h	-	-	-	-

Table 5. Data of vessels.

NO	Demand weight(t)	Product category	Length (m)	Number of hatches	Breadth (m)	Anchorage	Speed (kn)	Application time	Tidal time window
1	69650	4	199	6	32	1	10	1:20	-
2	34500	3	149	4	21	2	8	2:41	-
3	82500	5	250	7	43	1	9	3:52	[20:00,22:00]
4	13000	1	159	4	23	1	9	4:48	-
5	45900	2	225	5	32	2	12	4:54	-
6	55900	6	185	5	32	1	10	5:34	-
7	29000	5	149	4	21	2	8	6:55	-
8	45900	7	199	5	32	3	10	7:37	-
9	47900	8	186	5	30	1	7	8:00	-
10	15000	1	165	4	25	1	8	10:48	-
11	35000	3	179	4	28	2	10	12:38	-
12	35000	10	190	4	32	2	11	13:00	-

5.1 12 Vessel experiment

From the operational data provided by Huanghua coal port, the data of 12 vessels is shown in Table 5. The numbers of hatches on these vessels are four, five, six and seven, respectively. The loading sequence of four, five, six, and seven hatches is “1-3-2-4”, “2-4-3-1-5”, “2-4-3-5-1-6”, and “2-4-6-5-3-1-7”, respectively. After repeated calculation of the experiment, the appropriate parameters of the algorithm are set as follows: $MAXGEN$ =300, $NIND$=200, $GGAP$ =0.8, PC =0.8, PM =0.05, k =3, and σ =100. Moreover, δ_1, δ_2, and δ_3 are set as 10 min respectively. 8 Pareto-optimal chromosomes are obtained, as shown in Fig. 6. The optimal solution for the minimum value of F_1 and the minimum value of F_2 are 3.7 h and 88.9 h, respectively. Among them, there are two optimal results: first is that the minimum value of F_1 is 3.7 h and the value of F_2 is 94.17 h; second is that the minimum value of F_2 is 88.9 h and the value of F_1 is 8.2 h.

The research findings can benefit port managers from different perspectives. Specifically, the first result is conducive to improving the environmental benefits of the port. By minimizing the waiting time of vessels, the total turnaround time of the ships in port is reduced. On the one hand this helps save energy and reduce exhaust emissions and on the other, addresses port congestion issue that the shipping industry is facing and waiting for effective solutions today. The second result is conducive to improving the economic benefits of the port. By minimizing the total loading completion time of vessels, the utilization rate of handling equipment is increased, thereby improving the operational efficiency and economic benefits of the port.

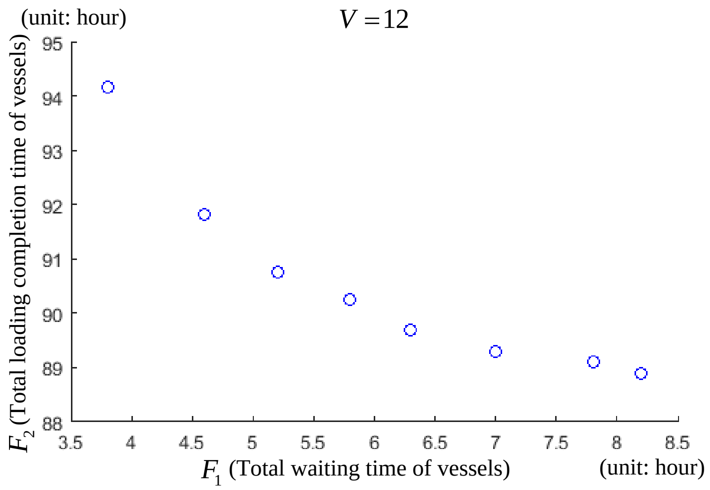

Fig. 6. Pareto-optimal front of the experiment with 12 vessels.

Generally, to protect the port environment, port managers usually choose the first result as the auxiliary decision of dry bulk export port operations. Therefore, the chromosome of 12 vessels with minimum value of F_1 is used as an example, as shown in Table 6. The information in this chromosome is decoded to obtain the arrival/departure timetable and the loading operation time of 12 vessels are obtained and shown in Tables 7 and 8. In addition, Fig.7 illustrates the detailed traffic scheduling scheme and loading operation plan of 12 vessels.

Table 6. Chromosome of 12 vessels with minimum value of F_1.

Traffic scheduling scheme											
111	211	311	411	611	511	911	810	400	200	710	1010
100	1110	500	1210	701	601	1001	901	801	301	1101	1201
Loading operation plan											
334	222	878	111	5812	446	222	657	7610	111	334	5812

Table 7. Timetable for 12 vessels entering and leaving port (unit: min).

NO	A_i	A_i'	T_{1i}	T_{2i}	T_{40i}	T_{3i}	T_{4i}	S_i	E_i	E_i'	T_{4i}	T_{3i}	T_{40i}	T_{2i}	T_{1i}	Waiting time
1	80	80	107	135	156	173	180	180	935	935	935	942	959	980	1008	0
2	161	161	244	279	305	326	335	335	694	694	694	703	724	750	785	0
3	232	232	265	300	326	347	354	354	1215	1215	1215	1222	1243	1269	1304	0
4	288	288	321	356	382	403	413	413	682	682	682	692	713	739	774	0
5	294	294	377	412	438	459	469	469	953	953	953	963	984	1010	1045	0
6	334	334	367	402	428	449	456	456	1052	1052	1052	1058	1075	1096	1124	0
7	415	539	622	657	683	704	713	713	1012	1012	1012	1021	1042	1068	1093	124
8	457	457	591	626	652	673	683	683	1162	1162	1162	1172	1193	1219	1254	0
9	480	480	513	548	574	595	604	604	1114	1114	1114	1123	1144	1170	1205	0
10	648	648	681	716	742	763	773	773	1082	1082	1082	1092	1112	1138	1173	0
11	758	810	877	905	926	943	950	950	1315	1315	1315	1322	1339	1360	1388	52
12	780	826	893	921	942	959	967	967	1331	1331	1331	1339	1356	1377	1405	46

Table 8. Loading operation time for 12 vessels (unit: min).

NO	Reclaimer operation time	Reclaimer traveling time	Ship loader traveling time	Transfer time from stockyards to berths	Loading completion time
1	696.5	35	21	2.5	755
2	345	5	7.5	1.5	359
3	825	10	22.5	3.5	861
4	260	0	7.5	1.5	269
5	459	10	13.5	1.5	484
6	559	20	13.5	3.5	596
7	290	0	7.5	1.5	299
8	459	5	13.5	1.5	479
9	479	15	13.5	2.5	510
10	300	0	7.5	1.5	309
11	350	5	7.5	2.5	365
12	350	5	7.5	1.5	364

5.2 Verification of model rationality

To verify the rationality of the proposed model in Section 3, the chromosome of the minimum value of F_1 in Section 5.1 is selected for analysis. In Fig. 7, the loading operation plan and traffic scheduling scheme of each vessel corresponding to this chromosome become clear.

In terms of loading operation planning, each vessel is reasonably allocated to a berth, a ship loader, and a reclaimer. Among them, vessel no.1 and no.11 are allocated to berth 102; vessel no.2 and no.7 are allocated to berth 101; vessel no.4 and no.10 are allocated to berth 100; vessel no.5 and no.12 are allocated to berth 200. Due to the larger demand of vessel no.3, it is allocated to berth 203. Each vessel occupies the berth for a non-overlapping period of time. In addition, there is the non-crossing operation of ship loaders assigned to each vessel. Since all ship loaders have the same operation efficiency, matching high-efficiency reclaimers can effectively shorten the loading completion time of vessels with larger demand. Vessel no.1, no.2, no.3, no.4, no.5, no.6, no.7, no.8, no.9, no.10, no.11, and no.12 are assigned to reclaimer R3, R1, R6, R0, R11, R10, R1, R5, R8, R0, R3, and R11 respectively. However, there are no crossing and collision operations between reclaimers. Moreover, the interval time between vessel no.1 and no.11 at berth 102 is enough for the reclaimer R3 to travel to the stockpile of vessel no.11 and the ship loader SL2 to travel to the hatch 1 of vessel no.11. Similarly, the interval time of vessel no.2 and no.7 at berth 101, the interval time of vessel no.4 and no.10 at berth 100, and the interval time of vessel no.5 and no.12 at berth 200 meet the time of reclaimers R1, R0 and R11 traveling to the corresponding stockpile and the time of the ship loader SL1, SLK and SL7 traveling to the corresponding hatch, respectively.

In terms of vessel traffic scheduling, each vessel is assigned a reasonable navigation mode that complies with navigation regulations. No outgoing vessels are passing through the channel between 0 h and 10 h, and the incoming vessels are arranged in a one-way navigation mode. Similarly, the outgoing vessels are arranged in a one-way navigation mode, as there are no incoming vessels within 17 h to 24 h. The relative intensive time of vessels in a mixed navigation mode is from 10 h to 17 h. All vessels sail in one direction between buoy no.22 and no.32. Between buoy no.32 and no.46 is a dense area where incoming and outgoing vessels encounter. The results reveal that they do not conflict in buoy no.32, no.40, and no.46. Likewise, the time interval between vessel no.5 and no.12 is 14 min. According to the calculation, when vessel no.5 leaves harbor basin 2, vessel no.12 arrives at harbor basin 2, and there is no traffic conflict between the two vessels near buoy no.46. In other words, according to the detailed interval time of each vessel in Table 7, there are no vessel traffic conflicts in buoy no.22, no.32, no.40, no.46, and each harbor basin. In addition, the time of vessel no.3 passing through the channel is within the tidal time window [20:00, 22:00]. Through the detailed analysis of the loading operation plan and vessel traffic scheduling scheme, it is verified that the proposed model can better reflect the reality of the two investigated loading operation planning and vessel traffic scheduling problems in a collaborative manner.

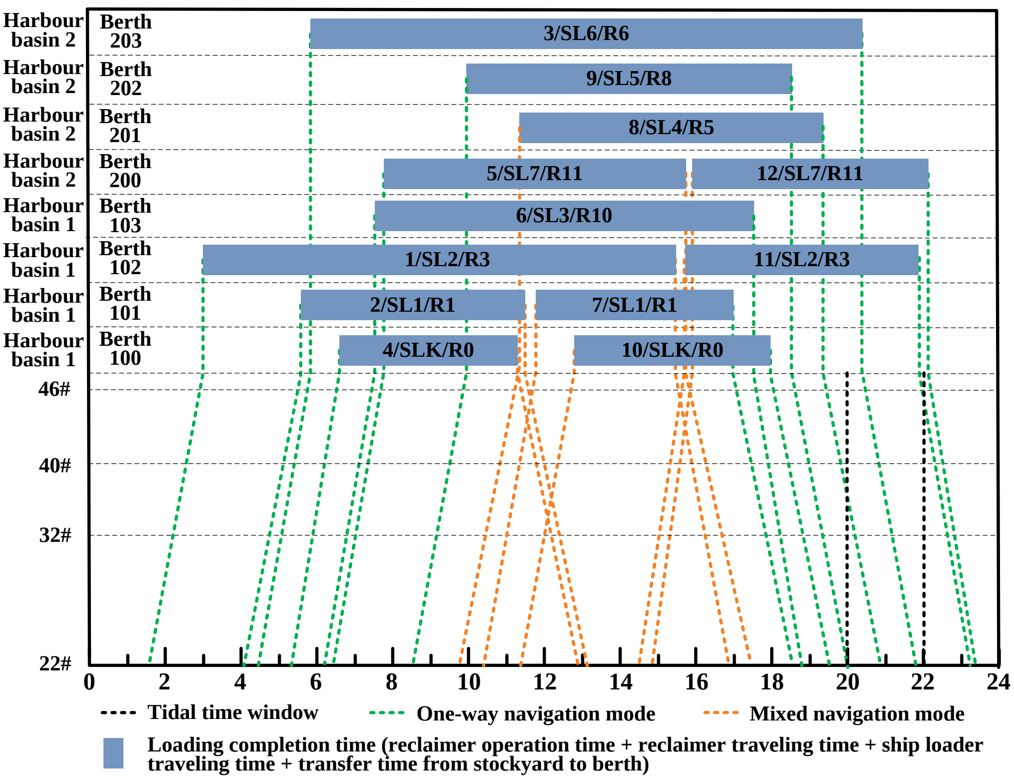

Fig.7. A detailed traffic scheduling scheme and loading operation plan of 12 vessels.

5.3 Comparison with NSGA-II-VNS, NSGA-II, FCFS, and CPLEX solver

To test the performance of NSGA-II-VNS, there are three methods selected for experimental comparison, including FCFS, NSGA-II, and CPLEX solver. First Come First Served (FCFS) is a practical principle in most ports. In practice, due to the fluctuation of coal market demand, the number of vessels calling at the port over a period of time varies considerably. This comparison experiment considers small- (i.e. V =5, 10) medium- (i.e. V =15, 20, 25) and large-scale instances (i.e. V =30, 35, 40) of numbers of vessels. The relevant parameter settings are consistent with those described in Section 5.1. Ten test scenarios are randomly generated for each number of vessels, as shown in Table 9.

From Table 9, it is demonstrated n that the optimal result of the NSGA-II-TS is better than the other three methods for all test instances. Overall, the FCFS has a short computational time, but the results of the FCFS are not optimal. When V =5, the number of berths, ship loaders, and reclaimers can far meet the demand of the number of vessels. So, the results of the four methods are the same results in all 10 instances. When V =10, 15, 20, the computational time of the CPLEX solver is longer and the results are not optimal. Since the increasing number of vessels significantly raises the complexity of decision variables and constraints, the computational time of solving these models will grow dramatically with the increase of the number of vessels for the CPLEX solver. Especially in V =25, 30, 35, 40, the CPLEX solver performance is the worst, some instances cannot get results in a limited time. In contrast, the NSGA-II-VNS successfully finds the optimal solutions for all instances. Although the computational time of the NSGA-II-VNS is slightly longer than the NSGA-II, the advantages of using the NSGA-II-VNS become increasingly significant as the number of vessels increases. This is more attractive for port managers because it can effectively shorten the loading operation time and waiting time of vessels and improve port efficiency, especially in the peak period of coal market demand.

Table 9. Comparison of FCFS, NSGA-II-VNS, NSGA-II and CPLEX solver associated with different numbers of vessels.

Vessel	FCFS			NSGA-II-VNS			NSGA-II			CPLEX solver			Comparisons	
V	F_1(h)	F_2(h)	*Time*(s)	F_1(h)	F_2(h)	*Time*(s)	F_1(h)	F_2(h)	*Time*(s)	F_1(h)	F_2(h)	*Time*(s)	*Gap_1(%)	*Gap_2(%)
5	1.75	35.25	2.4	1.75	35.25	4.8	1.75	35.25	4.5	1.75	35.25	3.7	0	0
10	7.4	81.4	3.5	3.8	75.3	50.4	4.1	76.5	47.1	5.3	79.3	401.2	48.65	7.49
15	12.3	124	4.6	6.4	112.8	93.5	7.1	115.4	90.2	9.2	120.4	1479.6	47.97	9.03
20	20.1	187.6	5.7	9.6	164.2	137.2	10.7	168.3	135.6	16.5	182.8	2964.3	52.24	12.47
25	22.4	219.1	6.8	14.2	198.7	189.7	16.5	201.1	184.3	-	-	3600	-	-
30	35.2	267.5	7.4	18.3	237.6	240.6	19.6	242.8	237.6	-	-	3600	-	-
35	56.3	345.3	8.1	23.5	280.3	287.3	28.7	286.2	281.4	-	-	3600	-	-
40	83.8	426.7	9.3	36.7	328.5	359.5	43.4	335.7	346.5	-	-	3600	-	-

* $Gap_1 = (F_{1\max} - F_{1\min}) / F_{1\max} \times 100\%$; $Gap_2 = (F_{2\max} - F_{2\min}) / F_{2\max} \times 100\%$

6. Conclusion

This work addresses a collaborative optimization problem for loading operation planning and vessel traffic scheduling in dry bulk export ports, where vessels have to pass a restricted channel with shared multi-harbor basins. To quickly load cargoes from stockyards to vessels and ensure the navigation safety of vessels, the problem of COLOPVTS is formulated as a multi-objective optimization problem. In terms of loading operation planning, the operational problems of berth allocation, ship loader allocation and reclaimer allocation are considered, including the berthing capacity and a realistic stockyard structure. The stockyard structure consists of pads and rail tracks, multiple loading tasks for vessels, multiple reclaimers and ship loaders on a single rail track. Such elements require the consideration of the vessels' loading sequence, the operational efficiency matching of reclaimers and ship loaders, the non-crossing constraint of reclaimers and ship loaders, and reclaimers on different rail tracks to simultaneously avoid reclaiming the same stockpile. In terms of vessel traffic scheduling, the main constraints of a restricted channel with shared multi-harbor basins are investigated, involving: the tidal time window, different navigation modes, the spatial constraint of multi-harbor basins, and traffic conflicts in different areas. Then a new COLOPVTS model is proposed with a MILP model to minimize the total waiting time of vessels and minimize the total loading completion time of vessels. Considering the characteristics of this problem, the NSGA-II-VNS is developed to generate the optimal traffic scheduling scheme and loading operation plan. Finally, the Phase I and Phase II terminals in a representative coal port and their comprehensive physical layouts and navigation rules are used and analysed as a real case study. The rationality of the model is verified by the 12 vessel experiment. Furthermore, the effectiveness and advantages of the NSGA-II-VNS are verified by extensive experiments for different scale instances.

It is worth mentioning that our proposed model is an initial model of COLOPVTS for dry bulk export ports. The factors such as topping-off time (final cargo adjustments for required maximum draught), ballast water discharge rate and handling equipment failure in the complex decision-making process of dry bulk export ports have effect on the coordination optimization, however their impact is relatively insignificant. The main constraints/influential factors in this process are considered based on their importance (effect on the overall timing), based on the practical operation observations. The important concerned factors are berthing capacity restrictions, vessels' loading sequence, non-crossing operation of ship loaders on a single rail track, non-collision operation of reclaimers on different rail tracks, different navigation modes, tidal time window, and traffic conflicts. For port managers, this approach provides opportunities to serve more vessels per unit time. Especially in the peak period of coal market demand, more benefits can be expected by port managers. Without loss of generality, it is also valid for handling operations in ports with other types of channels. Further research could follow the following directions:

(1) The impacts of factors such as topping-off time, ballast water discharge rate and handling equipment failure on the COLOPVTS can be deeply analyzed. These factors can be considered in the model constraints to further improve the proposed model

(2) Besides the loading completion time and waiting time, more objective functions can be explicitly analyzed and taken into consideration in further studies because the problem of interest is typically related to a multi-objective decision-making process

(3) An accurate solution method can be developed to speed up the searching process as the CPLEX solver has a relatively low time efficiency in solving medium- and large-scale problems

Appendix A. Definitions of symbols in the proposed model

Symbol	Description
Sets	
V	vessels
H	harbors

B	berths
L	ship loaders
R	reclaimers
J	tasks of a vessel (stockpiles)
F	pads at the stockyard
W	stock positions located on a single pad
K	rail tracks
C	hatches of a vessel

Indices

i	vessel
h	harbor
b	berth
l	ship loader
r	reclaimer
j	task of a vessel (stockpile)
f	pad
w	stock position
k	rail track
c	hatch

Parameters

M	a sufficiently large positive number
I_{ij}	weight of task j of vessel i in tonnage
LV_l	speed at which ship loader l travels at a hatch
RV_r	speed at which reclaimer r travels at a stock position
φ_{ijlc}^{c}	operating position of ship loader l on the rail track when ship loader l is assigned to undertake task j of vessel i in the hatch c
RM_{irjfw}	reclaimer r is assigned to undertake task j of vessel i in the stock position w of pad f, that is, reclaiming operation of reclaimer r
θ_{irjfw}^{w}	operating position of reclaimer r on the rail track during reclaiming operation of reclaimer r
A_i	application time of incoming vessel i at the anchorage
A_i'	start time when incoming vessel i is weighing anchor
δ_1	vessels avoid overtaking (in time units)
δ_2	vessels avoid in a head-on situation (in time units)
δ_3	vessels avoid in a crossing situation (in time units)

S_i	arrival time of vessel i to its berth
E_i	application time of outgoing vessel i at berth
E_i'	departure time when outgoing vessel i is cast off
T_i	start time of tidal time window when vessel i needs to leave by high tide
T_i'	end time of tidal time window when vessel i needs to leave by high tide
SJ_{ilrb}	start time of all tasks of vessel i is assigned to berth b, reclaimer r and ship loader l
LJ_{ilrb}	completion time of all tasks of vessel i is assigned to berth b, reclaimer r and ship loader l
RF_r	operational efficiency of reclaimer r
LF_l	operational efficiency of ship loader l
RJ_{ir}	completion time of reclaimer r to reclaim task j of vessel i, namely $RJ_{irj} = \frac{I_{ij}}{RF_{ri}}$
LT_{ijlc}	traveling time of ship loader l to perform task j of vessel i in the hatch c
RT_{irj}	traveling time of reclaimer r to perform task j of vessel i
$\varepsilon_{i'}$	preparation time of the next vessel's task
$Distance_b$	distance between berth b and stockyard (in time units)
T_{1i}	arrival time of vessel i at channel entrance
T_{2i}	arrival time of vessel i at precautionary area
T_{3i}	arrival time of vessel i at multi-harbor basin entrance
T_{4i}	arrival time of vessel i at harbor basin, namely arrival time of vessel i at the berth or leaving time of vessel i at the berth

Decision variables

D_{bij}	1 if berthing capacity of berth b meets the weight of all tasks of vessel i; 0 otherwise.
IO_i	1 if vessel i enters port; 0 if vessel i leaves port.
X_i	1 if vessel i sails in one-way navigation mode; 0 if vessel i sails in mixed (i.e. one-way and two-way) navigation mode.
$Y_{ii'}$	1 if vessel i sails ahead of i', and the two vessels are in the same direction; 0 otherwise.
$Z_{ii'}$	1 if vessel i is entering and vessel i' is leaving; 0 otherwise

$H_{ii'}$	1 if berths of vessel i and vessel i' are in different harbor basins; 0 otherwise.
$P_{bii'}$	1 if vessel i is moored to berth b, before vessel i'; 0 otherwise.
Q_{ib}	1 if vessel i is assigned to berth b; 0 otherwise.
$LS_{icc'}$	1 if the loading sequence of vessel i is hatch c' before hatch c; 0 otherwise.
$RS_{ijj'}$	1 if the task sequence of vessel i is task j' before task j; 0 otherwise.
$LP_{ii'lr}$	1 if vessel i' is assigned to reclaimer r and ship loader l, before vessel i; 0 otherwise.
Ω_{ilr}	1 if vessel i is assigned to reclaimer r and ship loader l; 0 otherwise.
G_{bl}	1 if berth b is served by a ship loader l; 0 otherwise.
β_{ilrb}	1 if vessel i is assigned to berth b, reclaimer r and ship loader l; 0 otherwise. In other words, $\beta_{ilrb}=Q_{ib}G_{bl}\Omega_{ilr}$
$\alpha_{rr'k}$	1 if reclaimer r and reclaimer r' are on the same rail track, and r is in right of r'; 0 otherwise.
γ_i	1 if vessel i takes tides to leave port; 0 otherwise.

Appendix B. A multi-objective mathematical model of COLOPVTS for Phase I and Phase II terminals in Huanghua coal port

s.t. (1)-(39)

$$T_{40i'} \geq T_{40i} + \delta_2 + M\left(1 - X_i - Z_{ii'} - X_{i'}\right) \quad \forall i, i' : i \neq i' \tag{40}$$

$$X_i = \begin{cases} 1, \, length_i > 225 \; or \; Breadth_i > 32.3 \; or \; Breadth_i + Breadth_{i'} > 61 \\ 0, \, otherwise \end{cases} \quad \forall i, i' : i \neq i' \tag{41}$$

$$v_i = \begin{Bmatrix} 8, v_i < 8 \\ v_i, 8 \leq v_i \leq 10 \\ 10, v_i > 10 \end{Bmatrix} \quad \forall i \in V \tag{42}$$

Constraint Eq. (40) states that vessels avoid encountering at buoy no.40. There is a safe time interval between the incoming and outgoing vessels. Constraints Eq. (41) and (42) are the constraints of navigation rules.

Additional parameters

Symbol	Description
T_{40i}	arrival time of vessel i at avoiding encountering area
v_i	speed of vessel i
$length_i$	length of vessel i
$Breadth_i$	breadth of vessel i

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