

Article

Departure Vessel Scheduling Optimization Considering Traffic Restrictions in Turning Basin: A Case Study for Xuwen Terminal

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Abstract: As the largest modern passenger Roll-on Roll-off (RoRo) terminal around the world, the berthing operation of Xuwen terminal is occasionally suspended due to bad weather, such as strong wind or thick fog. During the suspension, the number of stranded passengers and vehicles increasingly accumulates. As soon as the weather permits, the growth exerts great pressure, especially on large-scale vessels leaving the port, whose inefficiency may cause a loss of access to the terminal for inbound ships and chaos for port management. The focus of this study is to improve the efficiency of departure scheduling by optimizing traffic rules in the harbor basin. A mathematical optimization model is formulated for minimizing the total scheduling time, and then an adaptive simulated annealing (ASA) algorithm is proposed to solve the model. A specific decoding rule is introduced, referring to the characteristics of the mentioned model. After employing the operation data of the Xuwen terminal, a numerical experiment showed that the proposed scheduling method outperformed the first-come, first-served (FCFS) strategy and an improved ant colony algorithm (ACA). Moreover, the constructed simulation model of the terminal manifested the validity of the optimal solution.

Keywords: passenger Roll-on Roll-off terminal; departure ship scheduling; turning basin



Citation: Jia, Q.; Li, R.; Li, J. Departure Vessel Scheduling Optimization Considering Traffic Restrictions in Turning Basin: A Case Study for Xuwen Terminal. *J. Mar. Sci. Eng.* **2023**, *11*, 1311. <https://doi.org/10.3390/jmse11071311>

Academic Editor: Mihalis Golias

Received: 16 May 2023

Revised: 18 June 2023

Accepted: 19 June 2023

Published: 27 June 2023



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1. Introduction

Passenger Roll-on Roll-off (RoRo) shipping is widely applied in the inland sea, strait, and coastal islands because of its quick turnover and low investment. With the gradual increase in economy and tourism, passenger RoRo terminals have been increasingly constructed [1]. As the largest modern passenger RoRo terminal worldwide, Xuwen terminal is located at the southernmost point of the Chinese mainland, the core of the golden path Qiongzhou Strait, connecting Hainan Island and Guangdong province. After the terminal began operation in 2020, the route from Xuwen terminal to Xinhai terminal was greatly shortened in distance to 12 n miles and in navigation time to less than one and a half hours from the mainland to Hainan Island, as shown in Figure 1. At present, Xuwen terminal is responsible for most sea-cross demands of passengers and vehicles. However, severe weather, e.g., heavy fog, typhoon, and so on, plays an important role in passenger RoRo shipping, the frequency of which is growing gradually in the context of global warming. When faced with severe weather, the operations of Xuwen terminal must be suspended so as not to harm life and property, which leaves thousands of stranded passengers and vehicles. On a reopening day when the weather returns to normal, the terminal is forced to undertake several times more transportation tasks than usual. A large number of ships are scheduled to carry waiting passengers and vehicles across the sea as soon as possible. Because the berths are almost completely occupied by outbound ships loading stranded

passengers and vehicles at the beginning of the reopening day, there are no vacant berths for arrival vessels. If the efficiency of evacuating outbound ships is poor enough, bottlenecks can occur in both land traffic and marine traffic. During the Spring Festival of 2023, there was a huge traffic jam in Xuwen terminal due to heavy fog, leading to great inconvenience and generating an adverse effect on the social reputation of the terminal. Therefore, there is an urgent need for an efficient departure ship scheduling plan during a reopening day to allow vessels to leave the terminal quickly.



Figure 1. Location of Xuwen terminal.

As is known, the existing research on passenger RoRo terminals mainly involves four categories: ship stowage [1,2], security assessment [3,4], layout planning [5], and capacity analysis [6,7]. Studies on passenger RoRo ship scheduling are rare. Apparently, most researchers focus on container ports, bulk cargo ports, and so on. In these ports, waterway traffic rules are always regarded as the primary object for optimizing vessel sequence. Zhang et al. [8] established a single-objective model and a simulated annealing and multiple population genetic algorithm (SAMPGA) to coordinate the channel and berth. Furthermore, a multi-objective mathematical formulation and a multi-objective genetic algorithm (MOGA) were proposed by Zhang et al. [9]. To minimize the weighted dwelling time of vessels, Liu et al. [10] came up with a mixed-integer linear programming (MILP) formulation. Liu et al. [11] applied fuzzy theory to optimize ship scheduling in a one-way waterway. This approach improved the adaptability of the scheduling system to uncertain external factors. Gan et al. [12] proposed an online ship sequencing and scheduling algorithm (OSS-SW) for managing ship sequences in restricted waterways. By integrating the sliding window scheme, the ship scheduling problem was divided into several subproblems, which were solved using the OSS method. Corry and Bierwirth [13] integrated the discrete berth allocation and restricted waterway scheduling with three-segment and five-segment transits, assuming the navigation route of ships as fixed. To minimize the total waiting time of all ships, Zhang et al. [14] studied inbound and outbound orders through a two-way channel affected by tides. The waterway ship scheduling problem (WSSP) was proposed by Lalla-Ruiz et al. [15] for the sake of assigning waterways to different vessels. Then, taking the WSSP as the multi-mode resource-constrained project scheduling problem, Hill et al. [16] reformulated a mathematical model. Jia et al. [17] managed channel traffic, simultaneously optimizing waterway and anchorage utilization by proposing a Lagrangian relaxation heuristic. Zhang et al. [18] paid attention to three key

conflict areas in a compound waterway and proposed a multi-objective scheduling model aimed at minimizing the waterway occupancy time and total waiting time for all ships.

In addition to the waterway, other seaside operation resources have also received some attention, e.g., berth allocation [19,20], ship lock scheduling [21,22], quay crane scheduling [23,24], and so on. Roughly speaking, these resources are closely related to ships entering and leaving a port, where the turning basin is also a necessary water area. Each inbound or outbound ship must turn around within the turning basin, which has not obtained much attention. In container ports, limited maneuvering space for vessels leads to only one ship being able to turn around in the turning basin at a time. Even so, the multi-harbor layout of ports could mitigate the impact on overall scheduling efficiency. But for a port with one harbor designed to serve several vessels with good maneuverability turning around simultaneously, shown in Figure 2, the turning basin scheduling method greatly slows down operations. This paper presents a mathematical model coordinating fairway and turning basin to determine the sequence of outbound passenger RoRo vessels.

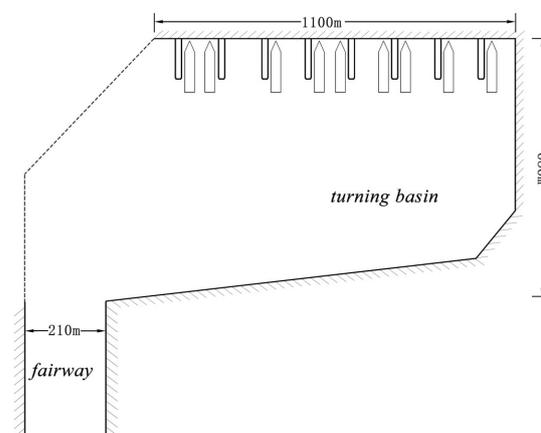


Figure 2. Schematic layout of Xuwen terminal.

Current algorithms proposed for the waterway, berth, quay crane, and so on are inapplicable to the scheduling optimization of the turning basin. An adaptive simulated annealing algorithm (ASA) is designed for the proposed mathematical model. The simulated annealing algorithm (SA) was given by Kirkpatrick et al. [25], Černý [26] as an extension algorithm of Metropolis et al. [27]. Some studies of port operation adopted the algorithm as the solution method. Kim and Moon [28] introduced a berth-scheduling model using SA. Concerning the navigation co-scheduling of three gorges, Zhang et al. [29] developed a mixed-integer nonlinear programming model as well as a hybrid of SA and a local search algorithm. Xu et al. [30] proposed a MILP model for the berth scheduling problem considering traffic limitations of channels, including one-way traffic, two-way traffic, and hybrid traffic. To solve these problems, a problem-specific hybrid simulated annealing algorithm was presented, which has demonstrated good computational performance and obtained near-optimal solutions. Therefore, SA was used as the research method due to its effectiveness in solving these problems.

The main contributions of the paper are summarized as follows: (1) Xuwen terminal has an urgent demand to evacuate outbound ships on the reopening day. Most studies of ship schedules are about the container and bulk cargo ports, etc., neglecting optimization of the turning basin. This paper promotes an effective departure scheduling scheme on a reopening day for Xuwen terminal based on improved traffic rules of the harbor basin. (2) Integrating the safety domain of vessels and continuity of navigation is taken to model the problem mathematically. Then, a mathematical formulation is provided with the objective of minimizing the total scheduling time. (3) An ASA is developed to solve the mentioned formulation. In the algorithm, the fitness function is the objective of the

model, and a problem-specific decoding rule is proposed to turn a vessel sequence into the scheduling time of each ship.

This paper is structured as follows. In Section 2, the departure vessel scheduling problem in the Xuwen terminal is recommended. A mathematical formulation is described in Section 3, and an ASA algorithm is illustrated in Section 4, followed by experiment and simulation in Section 5. Finally, some conclusions are provided in Section 6.

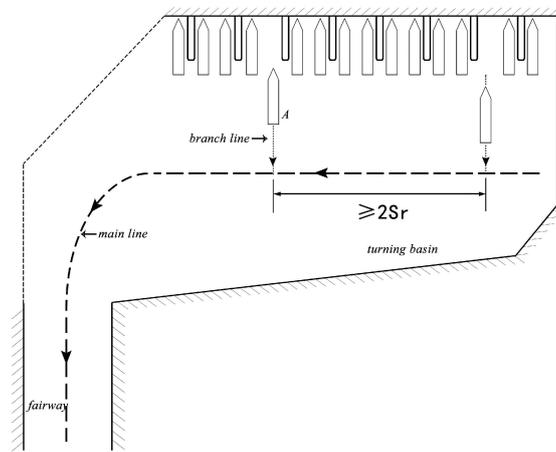
2. Problem Description

At Xuwen terminal, land-supporting facilities are relatively abundant and advanced. The comprehensive passenger reception building and passenger boarding bridge are able to efficiently, safely, and comfortably serve passengers. The waiting area for cross-sea vehicles before the security check is large enough to meet demands. The seaside layout of the Xuwen terminal is shown in Figure 2. The terminal fairway is narrow and unable to accommodate two-way navigation. There are eight jetties in the terminal basin, each with two berths distributed on either side of the jetty, for a total of 16 berths. An extra berth for dangerous cargo vessels is not within the scope of optimization in this paper. The harbor basin is restricted by the breakwater, the length of which prevents more than two ships from turning around at the same time and the width of which also prevents two vessels from overtaking, meeting, encountering, or running parallel. Equipped with twin propellers, twin rudders, and one bow thruster, the vessels could berth or unberth without the assistance of tugs thanks to their good maneuverability. The ship draft is low, and ship navigation in the fairway and harbor basin is not affected by the tide. Arrival ferries enter Xuwen terminal and berth with the bow towards the land, namely forward berthing. While outbound vessels unberth with the stern forward, then turn in the harbor basin and leave the terminal with the bow forward. At present, ship scheduling in the Xuwen terminal depends on manual experience. Only one ship is allowed to sail in the turning basin at a time, which prioritizes safety but is at the expense of efficiency, resulting in limited utilization of the restricted turning basin.

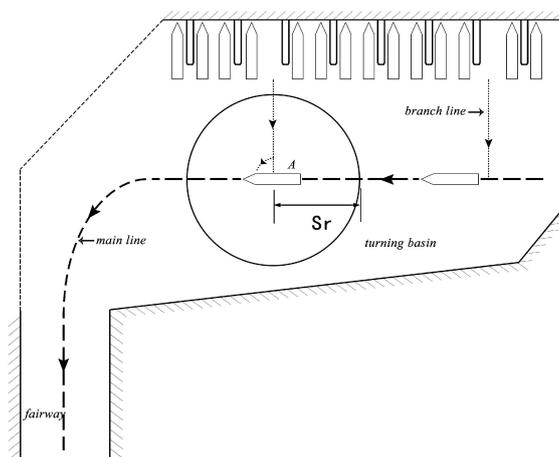
A reopening day refers to the first day following closure days caused by severe weather. When danger comes, all ships must leave Xuwen terminal and seek shelter in a safe anchorage due to the absence of a sheltered basin. After the weather becomes favorable for navigation, shipping companies arrange a corresponding number of ships to return to the terminal based on the number of stranded or delayed vehicles and passengers. Eager crowds always choose the earliest possible voyages on the reopening day, resulting in the first batch of ships occupying most of the berths. If the first ships cannot be scheduled quickly to leave the terminal, there will be no free berths for arrival ferries. The port authority draws up the ship scheduling plan by the principle of first-come, first-served (FCFS). For the first batch of vessels on the reopening day, a former arrival vessel enters the terminal first, assigned to a berth distant from the breakwater entrance. The short intervals between the arrivals of ships, extended in-port sailing time of preceding ships, and uniform handling time contribute to the simultaneous unberthing moment of the first batch of ships. However, the manual method is unable to complete such a high-traffic task in a reasonable time. Therefore, a timely and effective departure scheduling scheme is urgent to avoid bottlenecks and congestion. This study adopts improved traffic regulations in the harbor basin and fairway to enhance departure efficiency.

Figure 3 describes the optimized traffic regulations that need to be followed by any two leaving vessels in the Xuwen terminal. The main line represents the necessary route for any outbound ship to leave the terminal, and a branch line shows the specific route for an outbound ship moored at the corresponding berth. Three subfigures, respectively, depict three steps of the departure process for ship A. (1) The first step involves maneuvering along its branch line, stern-first toward its berth. If there is also another outbound ship in the first step, the distance between the two ships must be no less than $2S_r$. (2) The second step is turning around in the harbor basin, creating a restricted area, also known as a safety domain, which is a circle with a radius of S_r . Other ships are not allowed to enter the

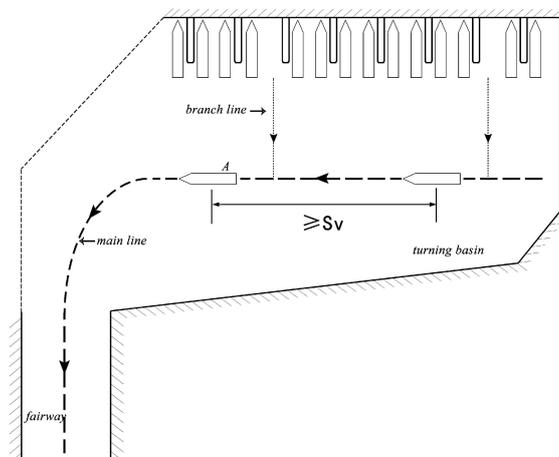
domain. For two ships in the first step, they will turn around simultaneously, so they must maintain a distance of $2S_r$ for safety reasons. (3) The third step involves sailing on the main line through the harbor basin and fairway. When two outbound ships are on the main line, they cannot be less than a distance of S_v from each other.



(a)



(b)



(c)

Figure 3. Optimized traffic regulations between two outbound ships. (a) Two outbound ships are on their branch lines, (b) one outbound ship is turning around, and the other one is on the main line. (c) Two outbound ships are on the main line.

3. Mathematical Model

3.1. Problem Hypothesis

In order to construct the model, several feasible assumptions are made as follows:

(i) Outbound vessels are the optimization objects, and inbound vessels are not taken into account. These outbound ships have the same prepared unberthing time at the beginning of the planning horizon;

(ii) The start and end points of the departure vessel scheduling are from berth to breakwater entrance;

(iii) Note that the number of berths in the model exceeds the actual number by one. A virtual vessel with index 0 is allocated to the virtual berth 0. The start and end moments of vessel 0 are set as the beginning of the planning period;

(iv) Navigation on the one-way waterway is not affected by tides.

3.2. Definition of Variables

The notations for formulating the mathematical model are defined in Table 1.

Table 1. Notation.

Parameters	
I	The set of vessels, numbered based on berths. $I = \{1, \dots, N\}$, where N denotes number of all outbound vessels.
S_r	The radius of the safety domain required for the vessel to turn around.
S_v	The safe clearance required between adjacent vessels in port water.
x_i	The position of vessel i .
T_{btot}	Time required for a ship from berth to turning basin.
T_{turn}	Time required for an outbound vessel to turn around.
T_{ttoi}	Time required for vessel i from turning basin to fairway entrance $i \in I$.
V_0	The average speed of ships from turning basin to waterway.
L	The length of the vessel.
M	A sufficiently large positive constant.
Decision variables	
tb_i	The start departure moment of vessel i , $i \in I$.
tf_i	The moment approaching breakwater entrance of vessel i , $i \in I$.
K_{ij}	$K_{ij} \in \{0, 1\}, \forall i \in I, \forall j \in I$, 1 if vessel j navigates through the fairway after vessel i ; 0, otherwise.
Q_{ij}	$Q_{ij} \in \{0, 1\}, \forall i \in I, \forall j \in I$, 1 if vessel i is closer to breakwater entrance than vessel j ; 0, otherwise.
A_{ij}	$A_{ij} \in \{0, 1\}, \forall i \in I, \forall j \in I$, 1 if the distance between the berth assigned for vessel i and that for vessel j is greater than $2S_r$; 0, otherwise.
B_{ij}	$B_{ij} \in \{0, 1\}, \forall i \in I, \forall j \in I$, 1 if the distance between the berth assigned for vessel i and that for vessel j is greater than S_r ; 0, otherwise.

3.3. The Optimization Model

The optimization mathematical model for departure ship scheduling is described as follows.

$$\min \left\{ \sum_{j \in I} \sum_{i \in I} (tf_j - tf_i) K_{ij} \right\}, \quad \forall i \in I, \forall j \in I \tag{1}$$

$$K_{ii} = 0, \quad \forall i \in I \tag{2}$$

$$tb_i \geq 0, \quad \forall i \in I \tag{3}$$

$$tf_i \geq 0, \quad \forall i \in I \tag{4}$$

$$tf_i = tb_i + T_{btot} + T_{turn} + T_{ttoi}, \quad \forall i \in I \tag{5}$$

$$tb_i - tb_j + T_{btot} + T_{turn} \leq (1 - K_{ij})M + (1 - Q_{ij})M + B_{ij}M + A_{ij}M, \quad \forall i \in I, \forall j \in I \tag{6}$$

$$tb_i - tb_j + \frac{S_r - (x_j - x_i)}{v_0} + T_{turn} \leq (1 - K_{ij})M + (1 - Q_{ij})M + B_{ij}M + A_{ij}M, \quad \forall i \in I, \forall j \in I \quad (7)$$

$$tb_i - tb_j + T_{turn} \leq (1 - K_{ij})M + (1 - Q_{ij})M + (1 - B_{ij})M + A_{ij}M, \forall i \in I, \forall j \in I \quad (8)$$

$$tb_i - tb_j + T_{btot} + T_{turn} + \frac{x_i - x_j}{v_0} \leq (1 - K_{ij})M + Q_{ij}M, \forall i \in I, \forall j \in I \quad (9)$$

$$tb_i - tb_j + \frac{(x_i - x_j) + S_r}{v_0} + T_{turn} \leq (1 - K_{ij})M + Q_{ij}M, \forall i \in I, \forall j \in I \quad (10)$$

$$tb_i - tb_j + \frac{S_v - (x_j - x_i)}{v_0} \leq (1 - K_{ij})M, \forall i \in I, \forall j \in I \quad (11)$$

$$tf_i - tf_j + \frac{S_v}{v_0} \leq (1 - K_{ij})M, \forall i \in I, \forall j \in I \quad (12)$$

The objective Function (1) aims to minimize the total scheduling time of the ship schedule. Equation (2) means that each ship can only be scheduled once. Constraints (3)–(4) ensure that each ship is scheduled after the beginning of the planning horizon. Equation (5) indicates the time vessel i approaching the fairway entrance equals the time vessel i unberthing plus the time passing through the terminal basin. Constraints (6)–(7) are for $0 < x_j - x_i < S_r$. Constraint (6) indicates that the time vessel i finishing turning around is earlier than the time vessel j leaving its berth. Constraint (7) means vessel j can begin turning around when vessel i is S_r away from x_j . The time vessel j begins to turn around is later than the time vessel i finishes turning around, which is aimed at $S_r < x_j - x_i < 2S_r$, constrained by (8). Constraints (9)–(10) are for $x_j - x_i < 0$. Ship j leaves the berth when ship i navigates through the berth of ship j . And ship j turns around after the distance between ship i and ship j is greater than S_r . Constraints (11) and (12) indicate that two ships in consecutive order must maintain a minimum distance of S_v when they navigate in the turning basin or fairway.

4. Algorithm Design

The simulated annealing (SA) algorithm originated from a thermodynamic process in which the temperature of a material system is gradually decreased until it reaches equilibrium. The SA algorithm is widely applied to solve various problems due to its high robustness and ability to obtain the globally optimal solution. In this section, an Adaptive Simulated Annealing (ASA) algorithm is proposed to address the problem of departure vessel scheduling, which is analogous to the Traveling Salesman Problem. Outbound ships are considered stations, and the distance represents the time interval between successive ships arriving at the breakwater entrance. Solutions are encoded by ship scheduling orders. Additionally, a problem-specific decoding rule is given by accommodating the characteristics of the proposed model.

Algorithm 1 illustrates the procedure of the proposed algorithm. Lines 1–3 correspond to the initialization process. $D(m, n)$, the initial distance from the m th station to the n th station, is calculated according to constraints (6)–(12). $\{s_i\}_1^N$, an initial vessel sequence, is generated in ascending order of ship number. The current permutation $\{c_i\}_1^N$ is set equal to $\{s_i\}_1^N$. $\{c_i\}_1^N$ is decoded into a solution, and its corresponding objective value $f_{obj}(\{c_i\}_1^N)$ is calculated. The initial temperature is denoted as T_0 . The conditional rules for searching for the optimal solution are shown in lines 4–5. T means the temperature which is linearly decreased according to the following formula:

$$T = q \cdot T_0 < q < 1 \quad (13)$$

where q is a decrement factor. The constant R indicates the number of iterations per temperature. Then, a next neighbor $\{t_i\}_1^N$ is created by swapping two positions ran-

domly selected in permutation $\{c_i\}_1^N$. The feasibility test mainly excludes permutations that contain repeated ship numbers, and there is no additional special constraint on the departure sequence.

Algorithm 1: ASA algorithm

Input: Problem instance

Output: A feasible solution

- 1: Let D be an $N \times N$ initial distance matrix with elements $D(m, n)$
- 2: $\{s_i\}_1^N \leftarrow$ an arbitrary starting permutation. $\{c_i\}_1^N \leftarrow \{s_i\}_1^N, T \leftarrow T_0$
- 3: Calculate the corresponding objective value $f_{obj}(\{c_i\}_1^N)$
- 4: **while** $T > T_{end}$ **do**
- 5: **for** $r \leftarrow 0$ to R **do**
- 6: Construct a trial permutation $\{t_i\}_1^N$ if feasible.
- 7: **for** $i \leftarrow 1$ to N **do**
- 8: $tb_{t_i} \leftarrow 0, tf_{t_i} \leftarrow 0$
- 9: **end for**
- 10: **for** $i \leftarrow 1$ to N **do**
- 11: $D'(t_{i-1}, t_i) \leftarrow \max\{tf_{t_i} + d(t_j, t_i)\} - tf_{t_{i-1}}, 1 < j < i$
- 12: $tf_{t_i} \leftarrow tf_{t_{i-1}} + D'_i(t_{i-1}, t_i), tb_{t_i} \leftarrow tf_{t_i} - tn_{t_i}$
- 13: **end for**
- 14: Calculate the corresponding objective value $f_{obj}(\{t_i\}_1^N)$
- 15: **If** $f_{obj}(\{t_i\}_1^N) < f_{obj}(\{c_i\}_1^N)$ **do** $\{c_i\}_1^N \leftarrow \{t_i\}_1^N$
- 16: **Else do** $\{c_i\}_1^N \leftarrow \{t_i\}_1^N$ when $random[0, 1] < \exp(-\beta/T)$
- 17: **end if**
- 18: **end for**
- 19: $T = q \cdot T$
- 20: **end while**
- 21: **Return** the solution corresponding to $\{c_i\}_1^N$

Lines 7–13 show the process of decoding a sequence into its solution. tb_{t_i} and tf_{t_i} , respectively, mean the start moment and the end moment of the outbound vessel t_i . $D'(t_{i-1}, t_i)$ represents the actual minimal time interval between vessel t_{i-1} and t_i in vessel sequence $\{t_i\}_1^N$. tn_{t_i} is the sailing time in the terminal basin required for vessel t_i . Fitness function $f_{obj}(\{t_i\}_1^N)$ is obtained according to the objective (1).

Lines 15–17 represent the process of a trial permutation being accepted as a new current permutation. Permutations that improve the fitness function are always accepted. While worse candidate permutations are accepted with a certain probability determined by the Boltzmann probability P , which is defined as:

$$P = e^{-\frac{\beta}{T}} \tag{14}$$

where β is the difference in fitness function between the current and the trial permutation.

5. Experiment and Simulation

This section is devoted to verifying the performance of our approach, and a problem instance is designed based on the data given by the Xuwen terminal. We assume that the number of outbound ships berthed in Xuwen terminal is 16, which means all berths are occupied. These ships are waiting at the berth after finishing handling, ready for scheduling instructions. The ship number corresponds to its berth. A departure sequence is urgent for the 16 ships to leave the terminal as soon as possible. The size of ships in Xuwen terminal

is not much different, and we set the length of ships L to 128 m, the maximum length of all ships. The average speed value from the turning basin to the breakwater entrance V_0 is set as 3 knots. Based on the experience of port staff and shippers, the safety domain radius S_r and safety clearance S_v are, respectively, set as $1.5L$ and $3L$. The time for an outbound ship in the first step and second step of the departure process is defined as 300 s and 120 s, which are statistical averages obtained from VTS data. And T_{ttoem_i} , time for the third step, is related to the position of ship i , as shown in Table 2. The berth number is in descending order of distance from the fairway.

Table 2. Sailing time in the third step of departure process.

T_{ttoem_i}	Value (s)	T_{ttoem_i}	Value (s)
T_{ttow_1}	701.99	T_{ttow_9}	426.66
T_{ttow_2}	666.52	$T_{ttow_{10}}$	391.19
T_{ttow_3}	633.16	$T_{ttow_{11}}$	357.83
T_{ttow_4}	597.69	$T_{ttow_{12}}$	322.36
T_{ttow_5}	564.32	$T_{ttow_{13}}$	289
T_{ttow_6}	528.85	$T_{ttow_{14}}$	252.23
T_{ttow_7}	495.49	$T_{ttow_{15}}$	220.17
T_{ttow_8}	460.02	$T_{ttow_{16}}$	184.70

On the basis of preliminary experiments and experience, the parameters in the ASA algorithm are set as follows: initial temperature $T_0 = 1000$, the minimum temperature $T_{end} = 1$, the decrement factor $q = 0.94$, and the number of iterations per temperature $R = 100$.

The experiments are executed on a computer with an Intel Core i7 Processor of 2.9 GHz and 8 GB of RAM. On the one hand, the effectiveness of the ASA algorithm is examined by comparing it with the FCFS strategy and an improved ant colony algorithm (ACA) [31]. The comparison is implemented in Visual Studio 2019 using C++ programming language. On the other hand, a discrete event simulation model for the departure process in the Xuwen terminal is constructed, capable of further verifying the feasibility of the proposed method. The simulation is performed in the Flexsim platform.

5.1. Effectiveness Experiment

The performance of AACO is evaluated by comparing it with the FCFS strategy and an improved ACA. According to Zhang, Wu and Liu [31], to apply the ACA to this paper, the problem studied is regarded as finding an open route traversing all ships with a fixed starting vertex, the virtual ship. The parameters related to the ACA are set as follows: the number of ants $m = 20$, the pheromone trails factor $\alpha = 4$, the heuristic information factor $\beta = 3$, the volatilization coefficient $\rho = 0.5$, the number of pheromones carried by each ant $Q = 10$, and the maximum iteration times $NC_MAX = 1000$.

Table 3 compares the scheduling schemes respectively required by ASA, FCFS, and ACA. tb_i and tf_i are the start and end times for an outbound ship, and TST indicates the total scheduling time. # means the ship number.

Following the actual scheduling principle of FCFS, which allows only one vessel to be served in the terminal basin at a time, the vessel that enters the terminal first will leave the terminal first from the further berth, while the ACA and ASA algorithms follow the improved traffic policy, which allows for the simultaneous service of two to three vessels within the harbor basin. In two schemes proposed by ACA and ASA algorithms, the total scheduling times are decreased by about 5500 s and 8600 s, respectively, more than 40% and 60%, superior to FCFS. Moreover, the solution obtained by ASA is 37.8% better than that of ACA, reflecting the superiority of the proposed algorithm in solving the departure scheduling problem. Furthermore, the travel time from the Xinhai terminal to the Xuwen terminal is approximately 1.5 h (5400 s), while the minimum optimization time is only

1.43 h. In other words, when the terminal is at full capacity for outbound ships, they can all complete their departures before the opposite ships arrive at the terminal. Consequently, our proposed method performs well when acquiring an effective solution to tackling the departure scheduling problem.

Table 3. Comparison of ASA, FCFS, and ACA.

Order	FCFS			ACA			ASA		
	Ship Number	tb_i (s)	tf_i (s)	Ship Number	tb_i (s)	tf_i (s)	Ship Number	tb_i (s)	tf_i (s)
1	1#	0.00	1121.99	16#	0.00	604.70	15#	0	640.17
2	2#	1121.99	2208.50	15#	467.65	1107.82	11#	120	897.83
3	3#	2208.50	3261.66	13#	901.93	1610.93	7#	240	1155.49
4	4#	3261.66	4279.35	12#	1371.69	2114.05	3#	360	1413.16
5	5#	4279.35	5263.67	11#	1839.34	2617.17	12#	1090.79	1833.16
6	6#	5263.67	6212.52	10#	2309.09	3120.28	2#	995.99	2082.51
7	7#	6212.52	7128.02	5#	2729.09	3713.42	16#	1897.81	2502.51
8	8#	7128.02	8008.04	6#	3267.68	4216.53	8#	1871.83	2751.86
9	9#	8008.04	8854.70	9#	3872.99	4719.65	4#	1991.83	3009.52
10	10#	8854.70	9665.90	7#	4307.27	5222.77	14#	2757.29	3429.52
11	11#	9665.90	10,443.70	4#	4727.27	5744.96	10#	2877.29	3688.48
12	12#	10,443.70	11,186.10	2#	5161.56	6248.08	6#	2997.29	3946.14
13	13#	11,186.10	11,895.10	3#	5698.04	6751.19	13#	3657.14	4366.14
14	14#	11,895.10	12,567.30	1#	6132.32	7254.31	9#	3777.14	4623.81
15	15#	12,567.30	13,207.50	8#	6877.40	7757.43	5#	3897.14	4881.47
16	16#	13,207.50	13,812.20	14#	7588.31	8260.54	1#	4017.14	5139.13
TST (s)		13,812.20			8260.54			5139.13	

5.2. Simulation

According to the departure process described in Section 2, the navigation of outbound ships in the Xuwen terminal is simulated. Flexsim simulation software provides various simulation entities with different features and functions, which can be used to represent seaside resources in the terminal basin. Figure 4 depicts the simulation layout for the departure process at Xuwen terminal. The Source object is used to create flow items, namely outgoing ships, and releases them to corresponding berths according to a predetermined departure sequence. The berth is represented by the Queue object with a maximum content of one flow item. The Sink object could receive and destroy flow items that have reached the breakwater entrance. Other simulation entities are applied to represent the three steps of the departure process. The first step in the branch line is represented by the Processor object, whose process time is set as T_{btot} . The second step is the turning process, which is also represented by the Processor object with T_{turn} process time. Additionally, a kinematics code is added under the Triggers tab in the Properties window to simulate the turning around process. The third step, navigation on the main line, is represented as the Conveyor object. The speed of conveyors is set as V_0 , and the virtual length is set to equal the actual navigation track.

Once the simulation model is constructed, the optimal solution obtained from the ASA algorithm, as shown in Table 3, is implemented. And Dashboards module can provide a real-time assessment of navigation situations during the departure process. The visualization results are depicted in Figure 5, where the vertical axis represents the number of service vessels in three departure steps. As can be seen from the figure, the maximum content in the first and third steps could reach up to three ships. Meanwhile, the maximum content in the second step is limited to two ships, which conforms to the actual restriction that only two ships are allowed to turn around simultaneously in the restricted turning basin. The five common fluctuations shown in the three subfigures indicate that the optimal solution divides the 16 outgoing ships into five batches based on the improved traffic rules. The

Idle periods of the branch line correspond to busy periods of the main line, and vice versa, which is in line with the departure flow. The relationships between vessels during the sailing are intuitive, and there are no ship conflicts. The above analysis shows that the departure sequence generated by our proposed model and algorithm is a practical solution.

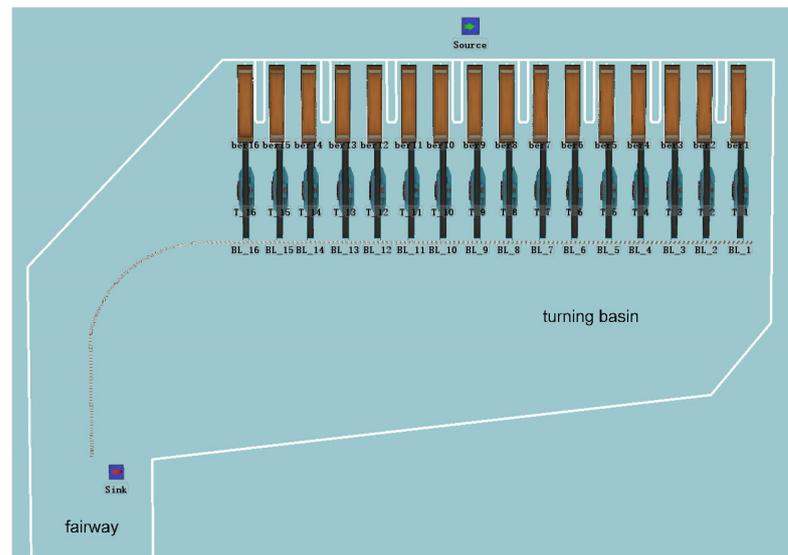


Figure 4. Simulation layout of Xuwen terminal.

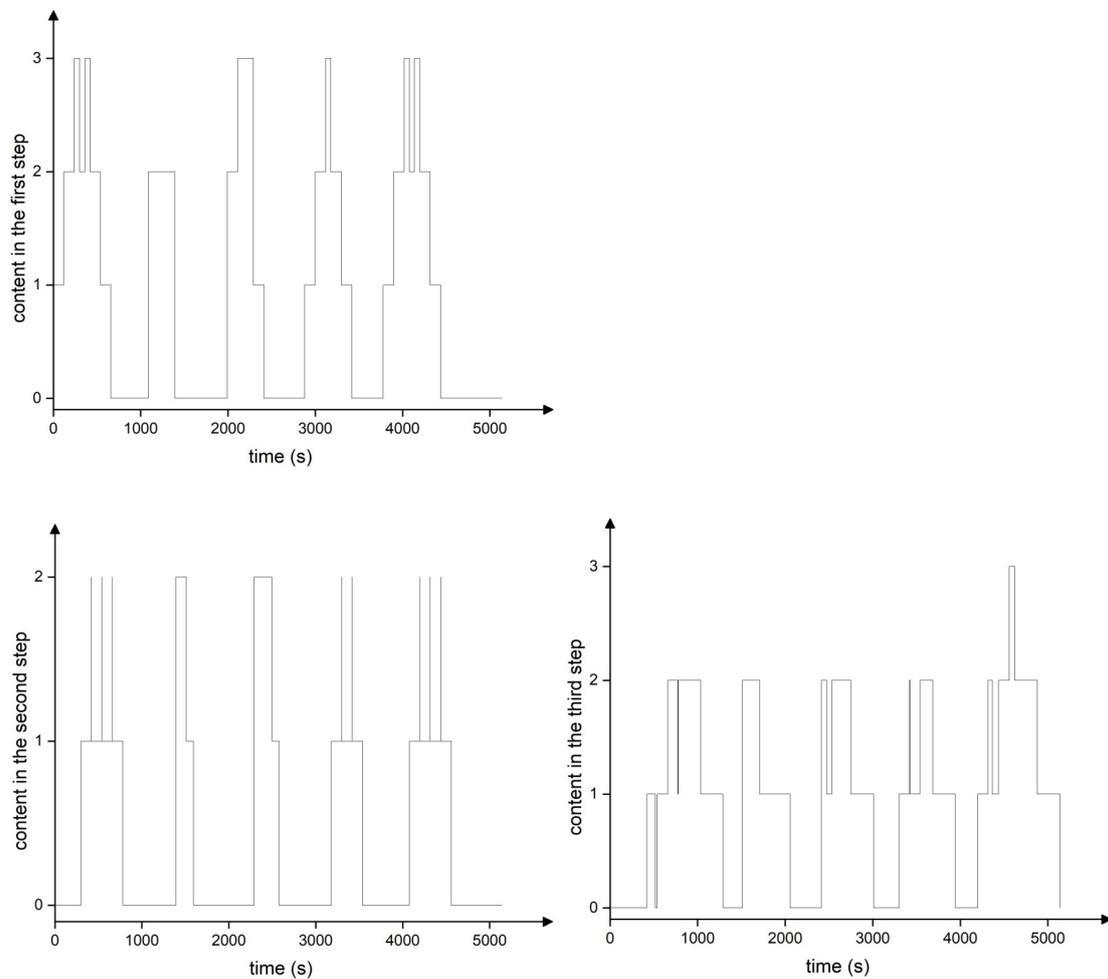


Figure 5. Simulation results of departure process.

6. Discussion and Conclusions

In response to the outbound vessel scheduling problem that occurred on the reopening day of Xuwen terminal, this paper enhances the scheduling efficiency in a way that optimizes the traffic rule of the turning basin. A mathematical formulation is then presented, which takes into account several restrictions related to traffic safety and aims to minimize the total scheduling time. A corresponding ASA framework is introduced, where a problem-specific decoding method is applied. The data of the Xuwen terminal are adopted in the experiment and simulation. The result of the experiment has proved that our proposed method is superior to FCFS and ACA, with a 62.8% and 37.8% total scheduling time optimality average gap. The simulation conducted on the Flexsim platform suggests that the optimal vessel sequence is a reasonable solution. In summary, the application of our method to the decision-making of the reopening day helps to evacuate stranded passengers and vehicles and avoid traffic problems both at sea and on land.

It has been observed that daily traffic can still result in congestion due to inflexible operation plans. Robust schemes can alleviate this issue, especially in short-passenger RoRo shipping with a high frequency of inbound and outbound ship traffic. The entire cross-strait dispatch is extremely sensitive to various sources of uncertainty, such as sailing speed and handling time. Therefore, for future work, we aim to explore ways to prevent such cases and develop real-time, robust, and flexible solutions.

Author Contributions: Conceptualization, Q.J. and J.L.; methodology, Q.J. and R.L.; software, Q.J. and J.L.; validation, R.L. and J.L.; formal analysis, Q.J.; investigation, Q.J. and R.L.; resources, R.L.; data curation, Q.J.; writing—original draft preparation, Q.J.; writing—review and editing, R.L.; visualization, Q.J.; supervision, J.L.; project administration, R.L.; funding acquisition, R.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 52171346; the Natural Science Foundation of Guangdong Province, grant number 2021A1515012618; the special projects of key fields (Artificial Intelligence) of Universities in Guangdong Province, grant number 2019KZDZX1035; the program for scientific research start-up funds of Guangdong Ocean University, grant number R19055.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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