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Integrated Scheduling Optimization of One-Way Channel Ships Entering and Leaving the Port, and Tugboat Distribution

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Abstract: With the rapid development of shipping industry, the volume of maritime logistics is also increasing. Tugboats are the first service station for ships, and the working efficiency tugboats directly affects the ship's attendance rate and the port's service efficiency. Some domestic ports use one-way channel design due to the limitations of geographical position and natural factors. However, due to the particularity of the channel, the ships are entering and leaving the port in a disorderly manner and the tugboats are running empty, which causes problems in the port. Therefore, the port is in urgent need of improving the cooperative dispatching ability of one-way channel and tugboats.

Keywords: Port management; One-way channel; Ship dispatching; Tug configuration

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1. Introduction

At present, some domestic and foreign scholars have carried out detailed research on issues faced in ports. In a study, Zheng H et al. [1] combined the characteristics of one-way channel and considered the practical constraints of ships' arrival and departure as well as berths, providing effective suggestions for the time-setting of one-way channel ports. Wu Y et al. [2] studied the integrated optimization of berth allocation and ship scheduling for continuous berths in one-way channel under the influence of the alternate time period of arrival and departure, tidal constraints, and ship berth preference, and verified the effectiveness of the scheme and algorithm with examples.

In terms of tug configuration, Yi J et al. [3] established single-berthing-based and multi-berthing-based tug system simulation models, and found out the advantages and disadvantages of three-tug operating modes through analysis and comparison. Yang Z et al. [4] considered the problems of tugboat quantity and horsepower configuration, and designed a system simulation model to solve the port tug distribution according to the characteristics of tugboat configuration. Bi X et al. [5] designed the tugboat distribution scheme under full load and ballast conditions and calculated the results according to the actual condition of Zhanjiang Port.

Existing studies have provided valuable suggestions for the improvements of ports, but most of them are from the perspective of either one-way channel [6] or tug distribution [7], and few studies have combined both one-way channel and tug distribution [8]. However, in reality, the time constraint of one-way channel [9] and the tugboat distribution [10] have always been the key factors restricting the efficiency of port service.

Therefore, it is of practical significance to study the integrated optimization of the entering and departing order of ships and tugboat distribution in one-way channel for the port development.

2. Problem description

Normally, in a port with a one-way channel, due to the port channel restrictions, ships will generally enter and leave the port at different stages: when the ship arrives at the port, it can immediately enter the port with the assistance of the allocated tug; after a ship departs, it can only enter the port at the next arrival time. The same applies for outbound operations.

In the actual operation of the port, due to the particularity of the one-way channel, a large number of ships arriving at the port during the departure period wait outside the anchorage, resulting in congestion. In the arrival period, due to the uneven distribution of tugs and port congestion, ship delays are very common, which seriously affects the port's efficiency. Therefore, this paper mainly considers the idling rate of tugs and the service efficiency of ports and other factors, then proposes an appropriate entry sequence for the port of one-way channel, and arranges appropriate tugs as its auxiliary operation.

In summary, the problem can be described as follows: A fixed plan is needed for a port with one way channel. Therefore, the port authorities will be able to arrange a schedule for the ships entering and leaving the port. Besides, when the number of tugs is fixed, the order of entering and leaving of ships and the optimal configuration scheme of tugs can be obtained with the goal of minimizing the total operating cost of tugs.

3. Mathematical modelling

3.1. Model hypothesis

(1) Hypothesis 1: The berths are fixed, and berth shifting is not considered;
(2) Hypothesis 2: Tidal effects are not considered;
(3) Hypothesis 3: The tugboats carry the same load and moves at the same speed;
(4) Hypothesis 4: The port can obtain the ship arrival information in advance;
(5) Hypothesis 5: At the same time, the ship can only choose to either enter or leave the port, not both at the same time.

3.2. Symbol description

3.2.1. Parameter

The collection of ships is i (i = 1,2,3... , m); j is the set of all tug types owned by the port (j= 1,2,3... , n); N_{ij} is the number of tugs j required by the article i vessel; Ta_i is the time of arrival of ship i; Tb_i is the time required for loading and unloading operations of ship i; Tc_i is the expected maximum loading and unloading time of the ship; Td_i is the estimated time of departure of ship i; HT is the length of the ship's voyage on the fairway during the inbound or outbound hours; KT is the sailing time of the tugboat on the channel when it is empty; AQ is the safe interval of time reserved for navigating a fairway; O_1 is the fuel consumption of the tug in a single operation; O_2 is the fuel consumption of the tugboat on empty drive; C_j is the cost of type j tugboat; RT_i is the time when the ship enters port (when w is odd) and CT_i is the time when the ship leaves port (when w is even)

3.2.2. Decision variable

y^w_i = 1 indicates that the ship i berthed in time period w; otherwise, it is 0;
x_{ijp}^{w} = 1 indicates that the entry and exit of ship i in time period w is assisted by p tugboat of type j; otherwise, it is 0

3.2.3. Process variables

KW_{jp}^{w}=1 means the inner tugboat base of type j tugboat during period w; KW_{jp}^{w}=0 means the outer tugboat base of type j tugboat during period w; Type j p tugs is outside tug base, the calculation formula is as follows $KW_{jp}^{w} = \left(KW_{jp}^{1} + \sum_{i=1}^{w-1} z_{jp}^{l} + \sum_{i=1}^{n}\sum_{l=1}^{w-1} x_{ijp}^{l}\right)$, n this formula, z_{jp}^{l} represents the number of empty runs of p tugboat of type j;

3.3. Model building

$$\min z = \sum_j C_j \times \left(O_1 \sum_w \sum_i \sum_p x_{ijp}^{w} + O_2 \sum_w \sum_p z_{jp}^{l}\right) \tag{1}$$

$$\sum_w y_i^w \sum_p x_{ijp}^{w} = N_{ij} \tag{2}$$

$$\sum_w y_i^w \sum_p x_{ijp}^{w} \sum_p x_{ilp}^{w} = 0, \ j \neq 1 \tag{3}$$

$$(w-1)T_0 \leq RT_i < wT_0, \ \text{w is odd number} \tag{4}$$

$$(w-1)T_0 \leq CT_i < wT_0, \ \text{w is even number} \tag{5}$$

$$(w-1)T_0 \leq RT_i + HT < wT_0, \ \text{w is odd number} \tag{6}$$

$$(w-1)T_0 \leq CT_i + HT < wT_0, \ \text{w is even number} \tag{7}$$

$$Ta_i \leq RT_i + HT + Tb_i \leq Tc_i \tag{8}$$

$$CT_i \geq Td_i \tag{9}$$

$$\sum_{w=1} x_{ijp}^{w} \leq 2 \tag{10}$$

$$RT_i \geq RT_n + AQ, \ \text{i} > n \tag{11}$$

$$CT_i \geq CT_n + AQ, \ \text{i} > n \tag{12}$$

Equation (1) is the objective function, which is to find out the minimum total operation cost of tugboat. Equation (2) is that the number of tugs assisted by the ship is equal to the number needed; Formula (3) indicates that one ship can only be assisted by one tug. Equations (4) and (5) indicate that ships must carry out inbound and outbound activities at corresponding inbound and outbound periods. Equation (6) and (7) indicate that the ship must finish the corresponding operation within the corresponding time period. Equation (8) means that the ship enters the port after its arrival. Equation (9) indicates that the actual departure time is not earlier than the estimated time; Equation (10) means that each ship is served by tugboat twice at most. Equations (11) and (12) represents the safe time interval of ships entering and leaving the port.

4. Analysis of numerical examples

4.1. The example described

Domestic ports have a one-way channel as discussed earlier, and it alternates inbound and outbound operations in a period of 2 hours. There are two tugboat bases inside the port and two tugboat bases outside.

Taking 24 hours as a cycle, it takes 0.3 hours for the tugboat to guide the ship through the channel. The safe interval between the two ships is 0.25 hours and the speed is 6 knots; the single operation cost of the tug is RMB 12,001,401,600. Other required parameters are as follows (**Table 1** and **Table 2**).

Table 1. Shipping schedule

Assembly of incoming vessels (I)	Arrival time (t_{ai})	Arrival stage	Loading and unloading time (hour) (t_{0i})	Departure time (t_{di})	Vessel type (Ai)	Distance (nm) (d_{3i})	Departure stage
1	0:36	1	0	4:15	Small	8	3
2	2:36	2	2	5:00	Small	9	3
3	3:30	2	1	6:49	Big	9	4
4	5:50	3	0	7:18	Small	10	4
5	9:30	5	0	12:40	Big	9	7
6	10:00	6	2	15:20	Big	10	8
7	12:17	7	1	15:40	Small	8	8
8	14:58	8	0	22:36	Big	8	12
9	16:53	9	1	21:35	Small	8	11
10	22:42	12	0	23:56	Big	10	12

Table 2. Matching between ship and tug

The type of tugboat	Small	Medium	Large
Small ships	1	1	1
Large ships	2	2	1

4.2. Experimental process

After 8 days, the optimal solution was obtained, and the experimental results are shown in **Table 3**:

Table 3. Configuration costs and waiting time

Number of tugs	Tug ratio	Waiting time (h)	Total cost (Yuan)
7	2/2/3	98.35	456202
	1/3/3	95.36	482670
8	1/2/5	96.45	562548
	1/3/4	99.52	504566
	2/2/4	94.23	492552
	2/3/3	96.78	483561
	3/2/3	94.13	472599
9	4/2/3	94.78	535220
	4/3/2	95.20	521211
	3/4/2	94.75	511420

Based on calculations, the total cost is lower and the speed is faster when 8 tugs are configured and the proportion of tugs is 3 small, 2 medium, and 3 large tugs. Therefore, this configuration is considered as the optimal allocation scheme.

5. Conclusion

In this paper, the inbound and outbound scheduling and tugboat distribution scheme of one-way channel are studied. According to the characteristics of one-way channel, a mixed integer linear programming model was established considering realistic constraints such as tugboat horsepower, and solved by genetic algorithm, which provides suggestions for the actual operation of ports.

The limitation of this paper is that it only considers the integrated scheduling of ship entering and leaving port and tugboat distribution, and fails to take into account the problems of shore bridge and berth in practical problems, as well as the influence of tidal constraints. Therefore, in future studies, the influence of tidal and other factors on the scheme should be studied, and at the same time, the integrated scheduling optimization of tugs, quay Bridges and berths should be considered.

Disclosure statement

The author declares no conflict of interest.

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