Research on Berth-Quay Crane Joint Scheduling Considering Carbon Emission

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***Abstract*—With the increasing awareness of environmental protection, all walks of life a are paying more and more attention to the carbon dioxide emissions brought by their own industries. For the container terminal, a large proportion of carbon emissions come from the fuel consumption of vessels. In this paper, the consideration of carbon emissions is added to the original berth quay crane joint scheduling problem, and the constraints such as vessel preference for berths and quay crane interference are added. A dual-objective nonlinear mixed integer programming model is established to minimize carbon emissions and minimize costs. The model is solved by the Non-Dominated Sorting Genetic Algorithm with Elite Strategy, and the optimal scheduling scheme is obtained. Finally, the calculation examples are verified to prove the effectiveness and practicability of the model and algorithm.**

***Index Terms*—container terminal, berth allocation, quay crane allocation, multi-objective, joint scheduling**

I. Introduction

With the continuous development of Global trade, container transportation has also become a vital means of logistics transportation. For container terminals, berths and quay cranes are scarce resources among them. Therefore, berth allocation and quay crane allocation play a key role in improving the operation efficiency of container terminals. Initially, some scholars studied the allocation of discrete berths, the allocation of continuous berths, and the dispatch of the quay cranes of a single vessel [1]-[3]. These are all researches on a single resource, but these two resources are closely related, if only one type of resource is allocated and optimized, may lead to a waste or overuse of another resource, which cannot effectively improve the overall operating efficiency of the terminal. Therefore, some scholars have raised the problem of berth and quay crane joint scheduling [4], and then others have made various studies on this basis [5]-[8]. On the other hand, with the global warming in recent years, people have become more and more aware of the importance of environmental protection, and carbon emissions have also become a more important evaluation index for terminals.

Based on the above considerations, this paper establishes a dual-objective mixed integer programming model to minimize costs and minimize carbon emissions.

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II. Problem Description

The problem of joint scheduling of berths and quay cranes is actually the problem of reasonably assigning berthing positions, berthing times and quay cranes under the relevant constraints of docks, vessels and quay cranes, and converting them into planar coordinate axes, which can be done with the following time- space diagram Represents, as shown in Fig. 1.

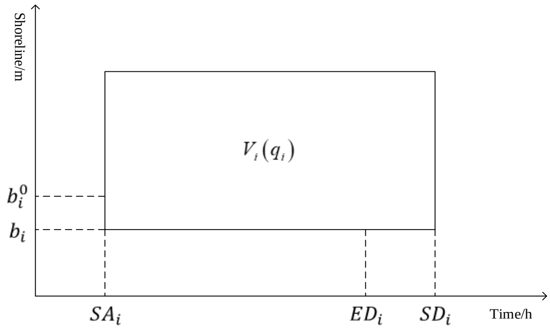

Figure 1. Time-Space diagram

The abscissa and ordinate in the figure represent time and shoreline respectively. Since the problem of joint dispatch under continuous berths is considered in this study, vessels can berth at any position along the shoreline (without considering physical factors such as draught, etc.). The rectangle represents the current vessel's occupation of time and space resources at the dock, the length of the rectangle represents the actual time of the vessel at the port, and the width of the rectangle represents the length of the vessel (including the safety distance between the vessels). i is the number of the vessel, V_i represents the vessel i, b_i represents thepreferred berth of the vessel i, b_i^0 represents the actual berth position of the vessel, ED_i represents the estimated departure time of the vessel.

Under the condition of a given sailing distance, the relationship between the vessel's fuel consumption and sailing speed can be expressed with a concave parabola. The extreme point of the parabola represents the most economical speed of the vessel. When the ship is sailing at this speed, the fuel consumption will reach the minimum under the current given sailing distance. If the speed is higher or lower than the most economic speed, the fuel consumption will increase accordingly.

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Assuming that the vessel i starts to berth at zero, the fuel consumption f_i of vessel i in the process of travelling m nautical miles from the port to the port can be expressed as [9]:

$$\begin{aligned} f_i &= \frac{1}{24}\cdot\left[a_i^1 + a_i^0\left(\frac{m}{(SA_i - EA_i)}\right)^3\right]\cdot(SA_i - EA_i) \\ &= \frac{1}{24}\cdot\left(a_i^1\cdot(SA_i - EA_i) + a_i^0\cdot m^3(SA_i - EA_i)^{-2}\right) \end{aligned} \quad (1)$$

In the formula: ai0 is the pilot skill coefficient of the vessel i, a_i^0 is the diesel consumption of auxiliary engines of vessel i per sailing day at economic speed (tons/day). Since the carbon dioxide emissions of vessels are directly proportional to the fuel consumption, the corresponding carbon dioxide emissions can be calculated according to the above formula. Using the calculation method of the Intergovernmental Panel on Climate Change, 1 ton of marine oil produces 3.17 tons of carbon dioxide emissions.

III. Mathematical Model

A. Model Assumptions

The content of this article will be based on the following assumptions:

(1) Regardless of the water depth of the shoreline, vessels can berth at any position within the shoreline of the wharf and carry out loading and unloading operations;

(2) All arriving vessels must berth and can only berth once;

(3) Each vessel has a preferred berth, which will incur certain costs if the vessel deviates from the preferred berth;

(4) The vessel shall not change the berth midway after receiving the service;

(5) Each vessel has the upper and lower limits of the number of quay cranes that can be allocated, and the number of quay cranes and the specific quay cranes operated during the loading and unloading of the vessel remain unchanged;

(6) The safety distance between vessels shall be included in the length of the vessels themselves.

B. Parameter Definition

To facilitate the construction of the model, some relevant parameters will be defined below:

1) About the sets

$V=\{1,2,\ldots,N\}$ is the set of ships, with indices i, j, N is the total number of ships;

$R=\{1,2,\ldots,Q\}$ is the set of cranes, with indices q, Q is the total number of cranes;

$T=\{1,2,\ldots H\}$ is the time unit set of planning cycle, with indices t, H is the number of time segments.

2) About the parameter

L: the length of shoreline

l_i: the length of vessel i (including the safety distance between ships)

b_i^0: preferred berth of vessel i

EA_i: expected arrival time of vessel i

ED_i: expected departure time of vessel i

$q_i^{\min}$: the minimum number of quay cranes allowed by vessel i

$q_i^{\max}$: the maximum number of quay cranes allowed by vessel i

α: interference coefficient during quay crane operation

β: berth deviation coefficient

η: the efficiency of quay crane (TEU/h)

m_i: quay crane hours required for vessel i

M: sufficiently large positive integer

φ_i^1: unit distance cost of vessel i's berthing position offset preferred berth

φ_i^2: unit time cost of vessel i delayed departure

φ_q^3: cost of loading and unloading operations per unit time per quay crane

3) Decision variables

b_i: actual berthing position of vessel i

SA_i: actual berthing time of vessel i

SD_i: actual departure time of vessel i

q_{it}: number of quay cranes allocated to vessel i at time t

$$x_{ij} = \begin{cases} 1, \text{if vessel } i \text{ berths below the berth position} \\ \quad \text{of vessel } j \\ 0, \text{otherwise} \end{cases}$$

$$y_{ij} = \begin{cases} 1, \text{if vessel } j \text{ berths after vessel } i \text{ had departed} \\ 0, \text{otherwise} \end{cases}$$

$$z_{ij} = \begin{cases} 1, \text{if vessel } i \text{ is berthed at time } t \\ 0, \text{otherwise} \end{cases}$$

$$\theta_{it}^q = \begin{cases} 1, \text{if crane } q \text{ serves vessel } i \text{ at time } t \\ 0, \text{otherwise} \end{cases}$$

This paper adopts the berth offset factors and quay crane interference factors proposed by Meisel and Bienvirth [10]. When given the required operating quay crane time m_i, the berth offset Δb_i, and the number of quay cranes allocated q_i to any vessel i, the calculation formula of operating time ω_i is as follows:

$$\omega_i = \left\lceil \frac{(1+\beta\Delta b_i)m_i}{(q_i)^\alpha} \right\rceil, \forall i \quad (2)$$

and the maximum berth offset $\Delta b_i^{\max}$ of any vessel i is as follows:

$$\Delta b_i^{\max} = \max\left\{L - b_i^0, b_i^0\right\}, \forall i \quad (3)$$

Therefore, the maximum and minimum working hours of each ship can be calculated as follows:

$$\omega_i^{\min} = \left\lceil \frac{m_i}{(q_i^{\max})^\alpha \eta} \right\rceil, \forall i \quad (4)$$

$$\omega_i^{\max} = \left\lceil \frac{m_i(1+\beta\Delta b_i^{\max})}{(q_i^{\min})^\alpha \eta} \right\rceil, \forall i \quad (5)$$

According to the above parameters, the following mathematical model can be constructed:

$$\min\ C = 3.17 * \sum_i f_i \tag{6}$$

$$\min G = \sum_i \varphi_i^1 \left| b_i - b_i^0 \right| + \sum_i \varphi_i^2 (SD_i - ED_i)^+ + \sum_i \sum_t \varphi_q^3 q_{it} \tag{7}$$

$s.t.$:

$$b_i + l_i \le L, \quad \forall i \in V \tag{8}$$

$$\underline{SA_i} \le SA_i \le \overline{SA_i}, \quad \forall i \in V \tag{9}$$

$$SA_i \ge EA_i, \quad \forall i \in V \tag{10}$$

$$x_{ij} + x_{ji} + y_{ij} + y_{ji} \ge 1, \quad \forall i, j \in V, i \ne j \tag{11}$$

$$M(1 - x_{ij}) + b_j \ge b_i + l_i, \quad \forall i, j \in V, i \ne j \tag{12}$$

$$M(1 - y_{ij}) + SA_j \ge SD_i, \quad \forall i, j \in V, i \ne j \tag{13}$$

$$z_{it} q_i^{\min} \le q_{it} \le z_{it} q_i^{\max}, \quad \forall i \in V, \forall t \in T \tag{14}$$

$$\Delta b_i = \left| b_i^0 - b_i \right|, \quad \forall i \in V \tag{15}$$

$$\sum_i q_{it} \le Q, \quad \forall i \in V \tag{16}$$

$$(SD_i - ED_i)^+ = \max\left\{ SD_i - ED_i, 0 \right\}, \quad \forall i \in V \tag{17}$$

$$SD_i = \sum_t Z_{it} + SA_i, \quad \forall i \in V \tag{18}$$

$$t \cdot z_{it} + \left(M - \omega_i^{\min} \right)\left(1 - z_{it} \right) \ge SA_i, \quad \forall i \in V, \forall t \in T \tag{19}$$

$$\sum_t (q_{it})^\alpha \cdot \eta \ge (1 + \beta \Delta b_i) m_i, \quad \forall i \in V \tag{20}$$

$$\omega_i^{\min} \le \sum_t z_{it} \le \omega_i^{\max}, \quad \forall i \in V \tag{21}$$

$$\theta_{it}^q + \theta_{it}^{q'} \le 2 - x_{ij}, \quad \forall i, j \in V, i \ne j, \forall t \in T, \quad \forall q, q' \in R, q < q' \tag{22}$$

$$\theta_{it}^{q+1} \ge \theta_{it}^q + \theta_{it}^{q+n} - 1, \quad \forall i \in V, \forall t \in T, \quad \forall q + n \in R, n = 1, 2, 3 \ldots \tag{23}$$

$$q_{it} = \sum_q \theta_{it}^q, \quad \forall i \in V, \forall t \in T, \forall q \in R \tag{24}$$

$$\sum_i \theta_{it}^q \le 1, \quad \forall i \in V, \forall t \in T, \forall q \in R \tag{25}$$

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

$$\theta_{it}^q, z_{it} \in \{0, 1\}, \quad \forall i \in V, \forall t \in T, \forall q \in R \tag{27}$$

Among them, formula (6) is the first objective function, which is to minimize carbon emissions; formula (7) is the second objective function, that is, to minimize the cost of the terminal, which is mainly composed of three parts: the cost of deviation from the preferred berth, the cost of delayed departure and the cost of quay crane operations; constraint (8) represents the constraint of the berthing position of ships, that is, all vessels must berth within the shoreline of the wharf; constraint (9) expresses the range of berthing time; constraint (10) means that the berthing time of any ship should be later than the estimated arrival time of the ship, and there is no early berthing phenomenon; constraints (11) ~ (13) indicate that there will be no conflict between any two ships in berthing time and berthing position; constraint (14) indicates that the quay crane allocation should start after the ship berthing, and the quay cranes that can be allocated by the vessel must meet the constraints of the maximum and minimum number of quay cranes when berthing; constraint (15) defines the offset of the berthing position of the ship; constraint (16) indicates that the number of quay cranes operating at any time cannot exceed the total number of quay cranes available at the wharf; constraint (17) defines the delayed departure time of the ship; constraint (18) defines the relationship between the berthing time and the departure time; constraint (19) defines the relationship between whether the ship is berthing or not and its berthing time; constraints (20) ~ (21) defines the operation time of any ship , and ensure that the operation time is longer than the required time of quay cranes; constraint (22) expresses the quay crane crossing constraint, avoiding the infeasible assignment of quay crane crossing; constraint (23) represents that the quay crane number assigned by any ship should be continuous to avoid intermediate quay cranes are idle and cannot be allocated; constraint (24) expresses the relationship between the number of quay cranes and allocated quay cranes; constraint (25) represents that any specific quay crane can only be allocated to one ship at the same time; constraints (26) ~ (27) defines the value range of decision variables.

IV. Algorithm Steps

In this study, we use a currently popular multi-objective optimization genetic algorithm — NSGA-II algorithm, which is also called a non-dominated sorting genetic algorithm with elite strategy.

Here, the population size is *pop*, the maximum number of iterations is *gen*, the crowding degree is *cd*, and the solution set is *F*. The basic flow of the algorithm is as follows:

Step 1 Initialize parameters: *pop*, *gen*, *cd*, $F = \varnothing$, generate initial population;

Step 2 Calculate the solution of each individual in the initial population, and perform non-dominated sorting. Then through the three basic operations of the genetic algorithm: selection, crossover and variation, the first-generation offspring population is obtained;

Step 3 Combine the parent population and the offspring population, perform fast non-dominated sorting, and calculate the crowding degree *cd*;

Step 4 In the population obtained from the previous step, select appropriate individuals to form a new parent population based on the non-dominated relationship and the crowding degree *cd*;

Step 5 Generate new progeny populations through the three basic operations of genetic algorithm: selection, crossover and variation;

Step 6 Judge the termination condition: if the maximum number of iterations gen is not reached, go to step 3, otherwise terminate the algorithm and output the result.

V. Calculation Example simulation and Result Analysis

A. Introduction to Calculation Examples

The shoreline length of a container terminal is 1000 m, there are 10 quay cranes in total, and the loading and unloading efficiency of the quay crane is 20 TEU/h. The workload of each ship is represented by the time of a single quay crane operation service. For example, the number of containers that needs to be loaded and unloaded by a ship is 800 TEU, then according to the loading and unloading efficiency of a single quay crane, the task workload of the ship can be calculated as 40 h. The Unit cost in each operation link: the unit distance cost of the vessel deviating from the preferred berth is 100 yuan/m, the unit time cost of the delayed departure of the ship is 150 yuan/h, and the unit operation time cost of each quay crane is 250 yuan/h. The planning period is 60 h, with 1 h as a time period. From time 0, ships will arrive at the port one after another, and the ship is waiting for berthing at a distance of 60 nautical miles from the port.

According to the sequence of arrival of 18 ships in the data of each vessel, such as length, number of tasks, maximum and minimum quay cranes, preferred berth, maximum and minimum speeds are shown in Table I.

TABLE I. Relevant Information of Arriving Ships

number	number of task/h	length /m	mini quay crane	max quay crane	preferred berth /m	expected departure time /h	mini speed	max speed	the diesel consumption per day	the pilot skill coefficient
1	18	120	1	3	20	15	14	30	1.7	0.12
2	20	130	2	3	190	17	16	30	2.0	0.13
3	20	180	1	3	540	20	15	29	2.0	0.15
4	18	180	1	3	720	25	14	28	1.8	0.09
5	28	140	2	4	320	35	16	30	1.8	0.10
6	24	120	2	4	700	38	15	30	1.7	0.11
7	13	100	1	3	10	30	16	29	2.0	0.08
8	12	190	1	3	130	32	15	30	1.9	0.14
9	20	140	2	3	430	22	14	30	1.9	0.13
10	16	180	1	3	540	33	13	30	1.8	0.11
11	14	140	1	3	750	30	16	30	1.9	0.12
12	9	160	1	3	60	29	15	28	1.7	0.09
13	6	180	1	2	180	31	15	29	1.6	0.10
14	12	140	1	3	320	34	14	30	1.7	0.12
15	17	190	2	3	320	35	16	30	1.8	0.13
16	10	100	1	3	200	34	14	30	2.0	0.14
17	7	140	1	2	500	27	15	30	2.1	0.12
18	21	160	2	3	160	30	14	29	2.0	0.11

B. Solve

According to the mathematical model established in this paper, the NSGA-II algorithm is used to solve the dual objective function, and MATLAB R2016a is used for algorithm programming. The basic parameters of the genetic algorithm are set as follows: population size pop is 100, maximum iteration algebra gen is 200, crossover probability is 0.9, and variation probability is 0.1. After solving, the Pareto solution set can be obtained as shown in Fig. 2.

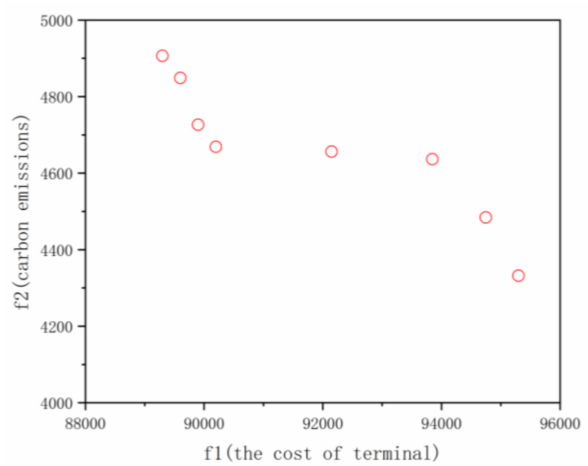

Figure 2. Pareto solution set after optimization.

At the same time, the optimal scheduling scheme shown in Table II can also be obtained. Under this scheme, the cost is 90,200 yuan, and the carbon emission is 4668.8 tons.

TABLE II. THE OPTIMAL SCHEDULING SCHEME OF BERTH-QUAY CRANE

number	Arrival time/h	Berthing time/h	Actual berthing location/m	Actual departure time/h	quay cranes served
1	0	5	0	12	3
2	1	5	200	13	3
3	2	5	510	16	2
4	2	7	720	17	2
5	3	13	320	24	3
6	4	26	700	33	4
7	6	23	0	36	1
8	7	12	120	18	3
9	9	31	430	39	3
10	11	17	540	26	2
11	12	17	740	25	2
12	14	18	40	23	2
13	15	31	180	35	2
14	17	39	320	44	3
15	18	24	290	31	3
16	19	35	190	39	3
17	21	26	490	30	2
18	23	39	150	47	3

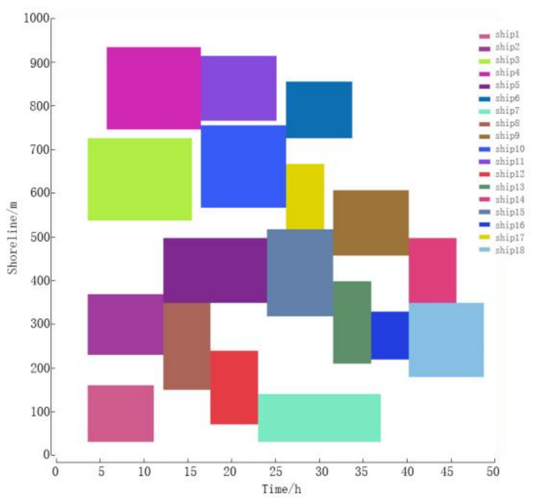

Figure 3. Gantt diagram

In order to show the scheduling results more intuitively, the corresponding Gantt diagram is also drawn in this paper. It can also be seen from Fig. 3 that there is no overlap between the time at port and berthing position of the ships. This indicates that the scheme is feasible, which also confirms the effectiveness of the model and algorithm.

VI. CONCLUSION AND OUTLOOK

In response to the national environmental protection policy, this article adds the consideration of carbon emissions to the original quay crane-berth joint scheduling problem, hoping to reduce the operating cost of the wharf while also reducing carbon dioxide emissions. In order to be article takes full account of the actual berth of each ship affected by the preferred berth and the changed working hours due to the mutual interference among the quay cranes.

On this basis, a dual-objective programming model is established to minimize the carbon emissions and the cost of the terminal. The model is solved by using NSGA-II algorithm in MATLAB. Finally, the optimal scheduling scheme is obtained, and the corresponding Gantt chart is given to verify the validity of the model. Hopefully, it can provide certain support to the decision-makers of the terminal, which has certain practical significance.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Rui Yang conducted the research; Rui Yang and Junqing Sun analyzed the data; Rui Yang wrote the paper; all authors had approved the final version.

REFERENCES

[1] A. Imai, H. C. Chen, E. Nishimura, *et al*., "The simultaneous berth and quay crane allocation problem," *Transportation Research Part E: Logs and Transportation Review*, vol. 44, no. 5, pp. 900-920, 2008.

[2] K. H. Kim and K. C. Moon, "Berth scheduling by simulated annealing," *Transportation Research Part B*, vol. 37, no. 6, pp. 541-560, 2003.

[3] P. Legato, R. Trunfio, and F. Meisel, "Modeling and solving rich quay crane scheduling problems," *Computers & Operations Research*, vol. 39, no. 9, pp. 2063-2078, 2012.

[4] Y. M. Park and K. H. Kim, "A scheduling method for Berth and Quay cranes," *Or Spectrum*, vol. 25, no. 1, pp. 1-23, 2003.

[5] X. Ling and H. U. Zhihua, "Berth allocation problem with quay crane assignment of container terminals based on rolling-horizon strategy," *Journal of Computer Applications*, vol. 33, no. 10, pp. 2969-2973, 2013.

[6] W. Xu, L. Shixin, Z. Ruiyou, and W. Jia, "Integrated berth ang quay crane allocation multi-objective algorithm for container terminal," *Journal of System Simulation*, pp. 1178-1188, 2018.

[7] L. Chengji and W. Yu, "Simultaneous berth and quay crane scheduling under uncertainty environments in container terminals," *Computre Engineering and Application*, vol. 53, no. 7, pp. 212-219, 2017.

[8] A. Agra and M. Oliveira, "MIP approaches for the integrated berth allocation and quay crane assignment and scheduling problem," *European Journal of Operational Research*, 2017.

[9] Z. Gang, *International Shipping Management*, Dalian Maritime University Press, 2006.

[10] C. Bierwirth and F. Meisel, "A follow-up survey of berth allocation and quay crane scheduling problems in container

terminals," *European Journal of Operational Research*, vol. 244, no. 3, p. 675, 2015.

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J. Sun, P. Li, and M. Han, "The Hybrid Optimization Strategy GATS for the Quay Crane Scheduling," *DCDIS Series B*, vol. 14, no. S2, pp. 797-801, 2007 (ISTP: 233GM).
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