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Study of Continuous Berth Allocation Model and Algorithms in Container Terminal Using New Technology

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ABSTRACT
In this paper, under assuming that the container terminal being equipped with twin-40 foot container handling system, we studied the continuous berth allocation problem, as well as quay crane dispatching when the quay cranes between adjacent vessels can transfer during the working period. We established an integer programming model aiming to minimize total time of the vessels staying in container terminal, proposed a new berth allocation algorithm for berths and quay cranes under the situation that the quay cranes can transfer between adjacent vessels. By using the definition of dissatisfaction degree for vessels, we designed a berth allocation algorithm based on twin-40 foot quay crane(T-QC) restrictions and a new quay crane transfer strategy to maximize the work efficiency for vessels. Experiments demonstrated that our algorithms are reasonable, practical and more efficient.

***Keywords* -** Container terminal, twin-40 foot quay crane, berth allocation, quay crane transfer strategy

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I. INTRODUCTION

Since 2010, Shanghai has surpassed Singapore and become the container port with maximum throughput in the world. How to increase throughput and improve the efficiency of vessel operations, as two most important resources for quayside loading and unloading, more efficient allocation of berths and quay cranes have been paid close attention. How to allocate berth location and time reasonably is called "Berth Allocation Problem (BAP)", to assign shoreline quay cranes to vessels for loading and unloading containers is called "Crane Allocation Problem (CAP)" [1].

BAP can be divided into three types of berths: discrete BAP, continuous BAP and mixed BAP. Discrete BAP means that the shoreline is divided into several fixed-size shore sections, each section is physical berth and can only berth one vessel. Continuous BAP means that the shoreline is divided into lots of fixed-size shore sections, each section is only a logical berth, vessel can berth at several continuous berths. Mixed BAP is the combination of discrete BAP and continuous BAP, it has the characteristics of discrete BAP and continuous BAP [2]. Considering whether the vessel has docked at the anchorage at the beginning of the working cycle, it can be divided into static berth allocation and dynamic berth allocation. Among them, continuous dynamic berth allocation is the most complicated and have been studied extensive [3-6].

For continuous dynamic berth allocation problem, Ihsane A [7] discussed the problem of vessel dynamic allocation in the public berth system and designed a heuristic process with Lagrangian relaxation. Ursavas E [8] considered the priority of vessel services, established a berth allocation decision support system under dynamic discrete event simulation models, and embedded optimization algorithms to determine the priority of each vessel, thereby helping the quay port to make strategic and tactical decisions. Tavakkoli-Moghaddam et al. [9] first analyzed the quay crane scheduling problem in detail and proposed a new mixed integer programming model, they proposed an improved genetic algorithm to solve the model and compared the efficiency with the LINGO software. According to the traffic flow in different areas of the port, Zhang X Y et al. [10] constructed the corresponding mathematical programming model with the minimum waiting time in the port as the objective function, and combined the related principles of the simulated annealing algorithm to design algorithm. Wang et al. [11] studied the integration of berth allocation and quay crane allocation under various carbon emission tax policies, such as the adoption of a single tax rate and a sectional tax rate. Li et al. [12] discussed the allocation of continuous berths and special quay cranes, and focused on the impact of quay crane coverage on joint dispatch. Jia S et al. [13] considered the influence of internal anchorages and took the minimum sum of the time penalty cost of arrival vessels as the objective function, constructed a mixed integer programming model, and combined Lagrangian relaxation to solve the problem.

The work introduced above only considered the allocation of quay resources under a single type of quay crane. Generally, a single quay crane can lift two 20-foot containers or one 40-foot container one time, while the T-QC can lift four 20-foot containers or two 40-foot containers at a time, therefore, its efficiency can be doubled theoretically [14]. In view of the characteristics of the T-QC, the containers that can be lifted by T-QC include:

(1) non-dangerous freight containers.
(2) non-refrigerated containers.
(3) non-20-foot heavy containers.
(4) operable containers.

Considering the characteristics of T-QC, this paper introduced the new technology in the continuous berth quayside resource allocation model, formulated the transfer strategy according to the relocation of the quay cranes, and then proposed an allocation algorithm that in accordance with reality.

II. MODEL

Based on the operating characteristics of T-QC, we formulated a quayside resource allocation strategy and established a berth and quay crane allocation model. The data provided by the terminal operation system (TOPS) consists of vessel type, estimated arriving time and latest departure time, berth size, load and unload volume, container structure and other data.

2.1 Basic assumptions

To build the quay cranes dispatching model, we need to set up some premise assumptions at first:

(1) Any part of the continuous berth meets the water depth conditions for vessel berthing.
(2) When vessel arriving at the port, it will berth immediately if meet the berth conditions.
(3) Each vessel can only berth once, and the operations cannot be stopped halfway.
(4) The cranes working for one vessel must be adjacent.
(5) Any quay crane cannot cross other quay crane to move to other positions.
(6) The moving time of the quay crane can be ignored.
(7) The safety distance between quay cranes can be ignored.
(8) Each vessel has at most one T-QC to serve it.
(9) The length of vessel has included the safety distance.

2.2 Symbols and formulas

In order to establish the model, some symbols will be used in the text, and their meanings are explained as follows:

L: The total length of berths.
T: The total planned time.
V={1, 2, …, v}: The set of vessels.
B={ $b_{s1,e1},\cdots,b_{sj,ej,\cdots,}b_{sk,ek}$ $\quad 0 \le sj, ej \le L$ }: The set of free berth sections, sj and ej respectively indicate the starting position and ending position of the berth section. The initial only one free berth section is B={$b_{0,L}$}.
Q: The total number of quay cranes.
$C_{b_{sj,ej}} = \{C_{sq},\cdots,C_{eq}\}$: The set of free cranes in free berth section $b_{sj,ej}$.
w_i: The total tasks of vessel i.
$\lambda_i \in \{0,1\}$: $\lambda = 1$, when vessel i can use T-QC. Otherwise, λ =0.
l_i: The length of vessel i.
v_q: The efficiency of quay crane q operating container per hour (units/h).
a_i: Arrival time of vessel i.
e_i: The Latest departure time of vessel i.
$c_i^{\max}$: The maximum number of QCs that vessel i can host.
H_i: The excepted working time of vessel i.
SV_i: The stat working time of vessel i.
BV_i: The berth position of vessel i.
WT_i: The working time of vessel i.
QR_i: The number of QCs allocated to vessel i during working time.
QR_i^t: The number of QCs allocated to vessel i at time t.
$\theta_{iq} \in \{0,1\}$: $\theta_{iq} = 1$, when allocate the QC q to vessel i. θ_{iq} =0, otherwise.
$\sigma_{ij} \in \{0,1\}$: σ_{ij} =1, when vessel i below vessel j and non-overlapping. σ_{ij} =0, otherwise.
$\delta_{ij} \in \{0,1\}$: δ_{ij} =1, the vessel i is on the left side of vessel j and non-overlapping. δ_{ij} =0, otherwise.

$$\text{Min } \sum_{i=1}^{v}(SV_i - a_i + WT_i) \qquad (1)$$

$$\sigma_{ij} + \sigma_{ji} \le 1 \quad (2)$$

$$\delta_{ij} + \delta_{ji} \le 1 \quad (3)$$

$$\sigma_{ij} + \sigma_{ji} + \delta_{ij} + \delta_{ji} \ge 1 \quad (4)$$

$$SV_j - SV_i - WT_i - (\sigma_{ij} - 1)T \ge 0 \quad (5)$$

$$BV_j - BV_i - l_i - (\delta_{ij} - 1)L \ge 0 \quad (6)$$

$$SV_i \ge a_i \quad (7)$$

$$SV_i + WT_i \le T \quad (8)$$

$$\sum_i QR_i^t \le Q \quad (9)$$

$$BV_i \ge 0 \quad (10)$$

$$BV_i + l_i \le L \quad (11)$$

$$w_i / WT_i = \sum_i \sum_q \theta_{iq} v_q \quad (12)$$

$$QR_i^t \le c_i^{\max} \quad (13)$$

Objective function (1) indicates minimize the time in port of all vessels, constraints (2)-(6) indicate that any two vessels keep non-overlapping in space and time, constraint (7) indicates that each vessel can only be allocated berth after arriving at the port, constraint (8) indicates that each vessel must complete the tasks within the specified period, constraint (9) indicates that the number of QCs of the vessel working at every moment does not exceed the total number of QCs, constraints (10) and (11) indicate that the vessel's berthing position is within the shoreline range, formula (12) indicates the relation vessel between the vessel's tasks and the speed of QCs, formula (13) indicates that the number of working QCs of one vessel at any time cannot exceed its capacity the maximum number of QCs.

III. SOLVING

The problem model is established, this chapter will design the berth allocation and quay crane scheduling algorithm based on the characteristics of the T-QCs in the case that the continuous berth and quay cranes can transfer.

3.1 Berth allocation algorithm

After getting the dynamic vessel data for the next 24 hours, the first step is to allocate berths. We make a judgment on the status of the vessel's tasks firstly and confirm whether the vessel can use T-QCs. If the containers attribute of the vessel is that T-QCs can be used and there are free T-QCs on the shoreline, the greedy algorithm *TC-BAP(Twin 40 foot quay crane-BAP)* will be used to allocate berths, if the vessel cannot use T-QCs or the free QCs on the track are all single cranes, The greedy algorithm *SC-BAP(Single quay crane-BAP)* is used to allocate berths, The berth allocation process is as Fig. 1:

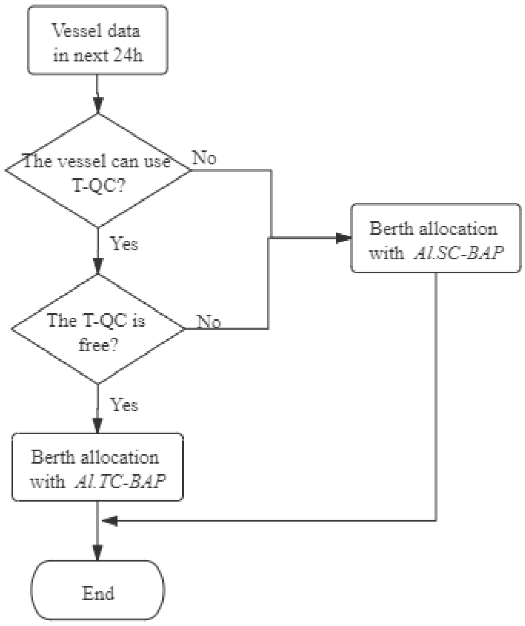

Figure1. Berth allocation flow diagram

For the case of algorithm *TC-BAP*, if the vessel's tasks attribute is can use T-QC, The free berth sections include T-QCs is preferred to berth the vessel under the condition of reaching the vessel's length of the berth, if there are multiple sections that meet the requirement, the section will be chosen where the number of QCs is closest to the expected number of QCs of the vessel. Algorithm 1 is the pseudo code of algorithm *TC-BAP* :

Algorithm 1. TC-BAP

Input: At time t: the data of vessel i , set of free berth sections B , and the initial free berth section is $B = \{b_{0,L}\}$, berth section $C_{b_{sj,ej}}$.

Output: Allocate berth of vessel i : BV_i , starting working time of vessel i : SV_i .

```
for j = 1 to k
    if l_i ≤ ej − sj
        for q = sq to eq
            if v_q == 2
                temp[j] = c_i^max − (eq − sq)
m = 2.
for n = 1 to k
    if abs(temp[m]) > abs(temp[n])
        m = n
BV_i = sm
SV_i = t
Update free berth sections and their berth attributes
```

In the case of algorithm *SC-BAP*, if the vessel cannot use T-QC or there is no free T-QC on the shoreline, it is divided into several single quay crane sections of different lengths, we only need to find the suitable section in the set B that satisfies the length of the vessel and the number of QCs is closest to the expected number of QCs of the vessel.

3.2 Study of the QCs transfer

In the case of QCs can transfer,On the grounds that QCs can only move on the shoreline track, they cannot move across. QCs transfer can only occur between adjacent vessels. After the vessels' berths have been allocated, we can get the berthing position and berthing time of the vessel , then to schedule the quay crane loading and unloading tasks.

3.2.1 Description of the problem of adjacent vessels' QCs transfer

Given one vessel A and its adjacent vessel B, at a certain time t, vessel A is operating, and the set of QCs occupied by vessel A is:

$$QR_A^t = \{C_{As}, \cdots, C_{Aq}, \cdots, C_{Ae}, 1 \le q \le Q\} \quad (14)$$

As , Ae respectively the starting number and the ending number of the QC serving the vessel at this moment. the loading and unloading efficiency of vessel A is $V_A^t = \sum_q \theta_{iq} v_q$.

the tasks of vessel A and vessel B are w'_A, w_B which value is:

$$w'_A = w_A - \sum_{T=a_A}^{T=t} v_A^t (t - a_A) \quad (15)$$

vessel B is required to be assigned QCs after berthing, now it is necessary to determine whether the quay crane of vessel A can be transferred to vessel B.

First define the vessel's dissatisfaction d_i :The dissatisfaction of a vessel is caused by the vessel's inability to load and unload tasks at its expected maximum rate immediately after berthing, which causes the operation time to exceed expectations. Is equal to the actual completion time of the operation minus the ideal operation time [15]. Use symbols in the model to define dissatisfaction with vessel i :

$$d_i = WT_i - H_i \quad (16)$$

If the edged working QC q_0 of vessel A is transferred to vessel B, formula (17)(18) indicate the dissatisfaction of this two vessel.

$$d_A = \frac{w'_A}{V_A^t - v_{q_0}} + t - a_A - H_A \quad (17)$$

$$d_B = \frac{w_B}{V_B^t + v_{q_0}} + t - a_B - H_B \quad (18)$$

It is only necessary to compare the dissatisfaction value of vessel A and vessel B to determine whether transfer the boundary quay crane of vessel A to vessel B.

3.2.2 Decision Algorithm for Adjacent vessels QCs transfer

In the case of the introduction of T-QCs, the status of the vessel will also affect whether the QCs transfer can be judged. This chapter will design a continuous berth allocation approximation based on the migration of adjacent vessels' quay cranes. The implementation of the algorithm is also based on the following principles:

(1) Affected by the physical arrangement of the shoreline, QCs can only be moved between adjacent vessels.

(2) If the vessel is allowed to use T-QC, the default expected working time is to include one T-QC for its operation.

(3) One vessel can only move one edge quay crane for the adjacent vessel at a certain time.
(4) Vessels that have been berthed but not assigned to quay cranes have higher priority, and the longer the waiting time at berth, the higher the priority.
(5) If two vessels arrive at the same time, priority will be given to assigning berths to operations with fewer tasks.

According to its characteristics, the following algorithm CAS is designed:

Algorithm 2. CAS

Input: At time t: the position of vessel A, QCs of vessel A : QR_A^t, the position of vessel B, and the set of QCs of vessel B: QR_B^t.

Output: Whether transfer C_{As} or C_{Ae} to B

```
from t to e_B
    if BS_B < BS_A //vessel B is docked on the left side of vessel A
        if λ_B = 1
            if d_A ≥ d_B
                no transfer
            else
                transfer C_Ae to B
            else if v_{C_Ae} = 2
                no transfer
            else if d_A ≥ d_B
                No transfer
            else transfer C_Ae to B
        Update free berth sections and their berth attributes.
    else …    //vessel B is docked on the right side of vessel A, the same as above
```

3.2.3 Correctness and complexity of the algorithm

The correctness of the algorithm is explained through two aspects. On the one hand, the algorithm can end normally. The algorithm maximizes the utilization of the quay cranes at every moment, means that the arranged QCs can meet the maximum rate of the vessel's work at each time. For any instance, all vessels' tasks will always be completed, the berth will be completely free, and the algorithm will stop at this moment. On the other hand, the algorithm can obtain reasonable results for the allocation of actual continuous berths. Under the previous assumptions, the algorithm processes each vessel according to the resources at the current moment, the vessel meets the physical conditions of non-overlapping in time and space, and the number of allocated shore resources (berths and QCs) will not exceed the allocatable value.

For a given dock, the space complexity of each problem instance is related to the number of vessels. In order to record the distribution information of vessels, the algorithm reserves a certain space for each vessel, the space complexity of the algorithm is $\Theta = O(|V|)$, $|V|$ is the number of vessels.

The algorithm starts from time 0 to process vessels and shore resources, and only considers the berth situation, the quay crane situation, and the operation execution situation at each moment, until the end of the planning period (it is possible that the berth is completely empty and ends early), the time complexity of the algorithm is $\Theta = O(V^2)$.

IV. EXPERIMENTAL EXAMPLE

The length of a container terminal is 70 m, the total number of QCs is 8 include 2 T-QCs, the positions of T-QCs are evenly distributed on the shoreline, means that the number 3, 6 are T-QCs, the efficiency of ordinary QC is 1 $units/h$, the efficiency of T-QC is 2 $units/h$. It is assumed that the information of vessels arriving at the container terminal in sequence during the period is shown in table 1.

Table1. Information of vessels

i	a_i	e_i	W_i	l_i	c_i^{max}	λ_i	H_i
1	1	10	24	13	5	1	4
2	3	15	9	18	2	1	3
3	5	15	12	20	3	1	3
4	6	17	18	15	5	1	3
5	9	20	8	14	2	0	4
6	10	18	10	16	3	1	2.5
7	10	22	20	22	4	1	4
8	12	24	18	21	3	0	6
9	15	24	15	18	4	1	3

Berth allocation is performed firstly. According to the algorithm, the berthing time and berthing position of each vessel are as table 2.

Table2. Information of vessels' berth

i	1	2	3	4	5	6	7	8	9
BS_i	0	13	31	0	0	14	30	0	21
TS_i	1	3	5	6	9	10	10	13	15

The distribution of the number of QCs during the operation time of each vessel obtained according to the above algorithm is shown in table 3. For each moment meets the maximum efficiency requirements of vessels in idle quay cranes, the algorithm makes the objective function value is:

$$\sum_{i} (TS_i - a_i + WT_i) = 39 \qquad (19)$$

Table3. The distribution of QCs

Vessle *i*	Working time	Initial workload in each working time	QCs' number assigned to the vessel
1	1~5	24	1,2,3,4,5
2	3~6	9	6,7
3	5~6	12	8
	6~8.8	11	6,7,8
4	6~9	18	1,2,3,4,5
5	9~10	8	1,2
6	10~12	10	3,4,5
	12~13	2	3
7	10~12	20	6,7,8
	12~14.4	12	5,6,7,8
8	13~22	18	1,2
9	15~18.8	15	3,4,5

Fig. 2 is a diagram of the QCs transfer plan for vessels operations during the period drawn accordingly. In order to be more intuitive, the QCs and vessels are marked. Each large rectangle represents a vessel, the length of the rectangle represents the length of the vessel, and the width represents the operating time of the vessel. Each rectangle has a vessel number, which identifies the number of the QC used during the vessel's operation, with the underlined number is the number of T-QC.

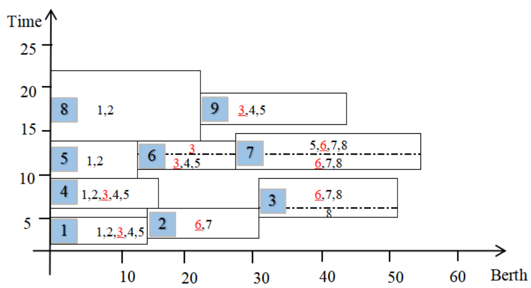

Figure2. Adjust berth-QC allocation

It can be seen from the experimental results that after introducing of the new technology T-QC, for vessels that can use T-QCs, under the distribution of the crane transfer algorithm, the vessel can load and unload containers at every moment according to the maximum work efficiency and educing the vessel's time in port, and for some vessels that cannot use T-QCs, for example, vessel 8 originally requires 3 single QCs, for the impact of the position of the T-QCs on the shoreline, only two single quay cranes can be used, and the operation time of it has not been optimized. In general, the stay time of all vessels during the limited time has been shortened, the effect of increasing the utilization rate of berths and quay cranes has been realized.

V. CONCLUSION

With the rapid development of the maritime transportation industry, research on container freight ports has gradually become a hot topic. Through the actual situation of the Shanghai Yangshan Port wharf, this paper introduced the new technology T-QC into the model, an integer programming model with the goal of minimizing the time of the vessel in container terminal is established, the berth and QC allocation algorithm is proposed for the situation where the QC can transfer between adjacent vessels. We found that the model can reduce the working hours of some vessels, however, due to the position allocation of the T-QCs on the shoreline, special vessels may not be able to allocate the expected number of QCs. Generally speaking, the algorithm makes the efficiency of QC play better in actual situation.

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