A Practical Optimal Model of Berth Planning at a Container Terminal* **

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Abstract Nowadays the container transportation service has become an increasingly important means of transportation. Berth resource allocation plays an important role in operation management at container terminals. It directly influences the efficiency of the loading/unloading operation process as well as the service level. This paper establishes a berth allocation model for the container terminals. The model considers the utilization of the berth and quay crane resources, and the distances between the positions of the vessels and the stacks. A case is given and a satisfying alternative of the berth/quay crane distribution can be obtained in terms of the model. It can be used to help planners to make out a berth schedule quickly and reasonably. It is helpful to raise the efficiency of the berth planning, especially for the new planners.

1. INTRODUCTION

Ever since its appearance in 1961, the container transportation service has become an increasingly important means of transportation. Nowadays, more than 60% cargos are transported in containers. Rapid development of container transportation leads to the development of container terminals. In order to meet the increasingly rising demand of container transportation, the container terminals are working hard to raise their operation efficiency. Resource allocation, especially the berth allocation, has become a crucial problem to shorten the waiting time of the ships and to improve the service of the container terminals.

This paper presents a practical optimal model of berth planning at container terminals, which can be used to help the planners to make out a berth schedule quickly and reasonably.

The distribution of the container port resources focuses mainly on the distribution of berths, quay cranes and vehicles. When a container vessel arrives at a container terminal, it will be arranged to enter the berth in a specific position and at a specific time according to the berth planning. Many studies have been focused on the berth planning problem. E.D. Edmond et al^[1] (1978) studied the berth allocation issue and

goods disposal by the lining up model. K.K. Lai et al^[2] (1992) compared three rules of berth arrangement, in which FCFS method was used to take arrival time into consideration. G.G. Brown et al^[3] (1994) and G.G. Brown et al^[4] (1997) researched the static distribution of the watercraft (submarine) berth in military port and established a distribution model by adopting the mixed integral programming and heuristic algorithm, which served for the purpose of maximizing the on-port-shipping profit. W.T. Chan et al^[5] (1996) researched the arrangement of the ships from same type by using the heuristic algorithm. A. Imai et al^[6] (1997) assumed that all the ships were on port for dispatch, then researched the berth allocation problem on the purpose of compromise between delay time and dissatisfaction incurred by the sequence of the lining up, which turned out to be a non-bad answer.

Most of the studies assumed that the berth was divided into several discrete berths, instead of a continuous one. As a matter of fact, the berth is distributed to the vessels continuously. A. Lim^[7] (1998) firstly utilized the concept of continuous berth instead of discrete one, and turn the berth distribution problem into a two-dimension packing problem with limited capacity. Then a heuristic algorithm was presented. This study assumed that the arrival times of all ships are fixed, and, it was mainly focused on how the ships made full use of the berth capacity without thinking about the loading/unloading information or the satisfaction degree of the customers. Y. Guan et al^[8] (2002) researched berth allocation problem in which the berths were along a straight line, and assumed that every job needed a same continuous berth for minimizing the total weighted time of the jobs. Moreover, he adopted a heuristic process to get the answer.

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K.H. Kim et al.^[9] (2003) arranged the berth dispatch through the mixed integral programming model to minimize the redundant cost incurred by the penalty on the shipping delay and not being arranged on the optimal position, and adopting the simulation anneal algorithm (SA) to get the approximately optimal solution.

A. Imai et al.^[10] (2001) firstly put forward the dynamic berth distribution model and heuristic algorithm on the basis of the Lagrangian Relaxation Approach. The model supposed that the frontage of the berth were divided into several discrete berths. P. Legato et al.^[11] (2001) established a simulation model, which distributed the berths according to the different ranks of the ships. A. Imai et al. (2003) studied the dynamic berth allocation problem with priorities. Young-Man Park and Kap Hwan Kim^[12] (2003) established an integer programming model for scheduling berth and quay cranes, and presented a two-phase solution procedure to solve the model. Akio Imai et al.^[13] (2005) presented a heuristic for the berth allocation problem in continuous locations. Jean-François Cordeau et al.^[14] (2005) studied the berth allocation problem in terms of Tabu Search Heuristics. Discrete and continuous cases are discussed respectively.

Here are several aspects that could be improved in the existing researches on berth planning.

- (1) The berth is actually distributed to the vessels continuously. However, most studies are focused on the discrete berth distribution.
- (2) Most studies consider the berth planning problem as a static one. However, berth planning is a dynamic problem.
- (3) Many existing researches on berth planning neglected some important factors, such as the priorities, the distances between the locations of the vessels and the stacks, the limitation of the moving scales of the quay cranes because of the lengths of the electric cables. A few models considered more factors but they became too complicated to be solved.

Because of the above problems, many of the studies on berth allocation have difficulties in applying to the real systems. As A. Lim pointed out, the berth planning problem can be considered as a special case of the two-dimensional stock-cutting problem, which is an NP-hard problem. It is necessary to find a practical and reasonable approach to solve the problem. This paper presents a practical berth allocation model.

2. PROBLEM DESCRIPTION

When a container vessel arrives at the container terminal, it will be arranged to a proper location in the berth along the frontage. Then the quay cranes will unload the containers from the vessel onto the vehicles (and/or load the containers from the vehicles onto the vessel). The vehicles will transport the containers to the specific stacks and then go back to the vessel to take the next container (In loading case, the vehicles will go back to the stacks to take the next containers and then transport it to the vessels). The gantries will move the containers from the vehicles to the stacks (In loading case, the gantries will move the containers from the stacks to the vehicles.). The above process is shown in Figure 1.

We could see from the operation process that berth is an important resource for a container terminal. Berth planning problem is to determine when and where the vessels are going to be located and served. Berth plans influence directly on the utilization of the berth, the efficiency of the operation and the service level of a container terminal. Berth planning is a key job in the operation.

Fig. 1 The Loading/Unloading Operation Process at a Container Terminal

The following factors are usually taken into consideration when making a berth planning.

- (1) The information of the vessels and the cargos, including:
 - the arrival time and the latest departure time of each vessel
 - the priorities of the vessels
 - the amount of the containers needed to be loaded and unloaded, and the locations of the containers on the vessels
 - the lengths of the vessels
 - the least space interval between two adjacent vessels
- (2) The resources available, mainly including:
 - the length of the berth
 - the quay cranes and their efficiencies
 - the allowable moving scales of the quay cranes, which are limited by the lengths of the electronic cables
 - the distances between the vessels and the stacks

The following decisions are to be made in a berth planning:

- (1) the entering/leaving time for each vessel
- (2) the location in the berth to be arranged for each vessel
- (3) the quay cranes to be distributed for each vessel, including how many and which quay cranes to be distributed for each vessel.

3. THE BERTH ALLOCATION MODEL AND ITS SOLUTION

3.1 The Berth Allocation Model

A practical berth allocation model is presented in this section. It can be used to determine when and where each vessel enters the berth and which quay cranes are provided for each vessel. It is helpful for the container terminals to make out their berth planning quickly and reasonably. Here is the model:

$$\text{O.b.} \quad \min \sum_{k=1}^L \sum_{j=1}^N \sum_{i=1}^M z_{ijk} (1 + c_k |(i - p_k)|) (t_k - a_k) \quad (1)$$

$$\text{s.t.} \quad \sum_{k=1}^L x_{ijk} \leq 1 \quad i = 1, \dots, M; j = 1, \dots, N \quad (2)$$

$$\sum_{k=1}^L y_{jk} \leq C \quad j = 1, \dots, N \quad (3)$$

$$\sum_{j=a_k}^N y_{jk} = w_k \quad k = 1, \dots, L \quad (4)$$

$$y_{jk} \leq Q v_{jk} \quad j = 1, \dots, N; k = 1, \dots, L \quad (5)$$

$$v_{jk} \leq y_{jk} \quad j = 1, \dots, N; k = 1, \dots, L \quad (6)$$

$$j \cdot v_{jk} \leq t_k \quad j = 1, \dots, N; k = 1, \dots, L \quad (7)$$

$$(j' - j' + 1) \leq \sum_{j=j'}^j v_{jk} + Q(2 - v_{jk} - v_{j'k}) \quad (8)$$

$$j' = 1, \dots, N-1; j'' = j' + 1, \dots, N; k = 1, \dots, L$$

$$v_{jk} \leq \sum_{i=1}^M \sum_{j=1}^N z_{ijk} \quad j = 1, \dots, N; k = 1, \dots, L \quad (9)$$

$$\sum_{i=1}^M \sum_{j=1}^N z_{ijk} = 1 \quad k = 1, \dots, L \quad (10)$$

$$\sum_{i=1}^{i-1} \sum_{j=1}^N x_{ijk} + \sum_{i=i+b_k}^M \sum_{j=1}^N x_{ijk} \leq Q(1 - \sum_{j=1}^N z_{ijk}) \quad (11)$$

$$i' = 1, 2, \dots, M - b_k + 1; k = 1, \dots, L$$

$$b_k - \sum_{i=1}^M x_{ijk} \leq Q(1 - v_{jk}) \quad j = 1, \dots, N; k = 1, \dots, L \quad (12)$$

$$y_{jk} \leq u_k \quad j = 1, \dots, N; k = 1, \dots, L \quad (13)$$

$$x_{ijk}, v_{jk}, z_{ijk} \in \{0, 1\} \quad (14)$$

in which,

w_k : the total operation time needed for the k-th vessel if the task is finished by one quay crane

b_k : the length of the k-th vessel

p_k : the favorable position for the k-th vessel considering its distances from the stacks

c_k : the deviation coefficient, which reflects the increase of the operation time resulting from one unit of the deviations of the k-th vessel from its favorable position. The total increase of the operation time equals to c_k multiplied by the deviation.

a_k : the arrival time of the k-th vessel

t_k : the actual departure time of the k-th vessel

u_k : the number of the quay cranes provided for the k-th vessel

C : the total number of the quay cranes available at the container terminal

The decision variables are as follows:

$z_{ijk} \in \{0, 1\}$: a zero or one variable. It will be 1 if the k-th vessel starts to enter the berth and arrive at the location i in period j ; otherwise, it will be 0.

$x_{ijk} \in \{0, 1\}$: a zero or one variable. It will be 1 if the k-th vessel is at the location i in period j ; otherwise, it will be 0.

y_{jk} : the number of the quay cranes distributed to the k-th vessel in period j .

$v_{jk} \in \{0, 1\}$: a zero or one variable. It will be 1 if $y_{jk} > 0$; otherwise, 0.

Q is a positive and large enough number.

Eq. (1) is the objective of the model, in which $(t_k - a_k)$

gives how long the k-th vessel stays at the container terminal.

$|(i - p_k)|$ is the space deviation of the k-th vessel, which reflects how far the actual position of a vessel in the berth

from its favorable position. Here, the favorable position p_k means that the containers on the k-th vessel have the shortest total distance (or shortest total time) from that location to the specific stacks. c_k is the deviation coefficient, which reflects the increase of the operation time resulting from one unit of space deviation of the k-th vessel from its favorable position.

The deviation coefficient c_k converts the space deviation to the time loss. The objective is to minimize the sum of the total actual time that a vessel stays at the container terminal and the total increase of the operation time resulting from the space deviations from the favorable positions for all the vessels during the planning period. The latter equals to c_k multiplied by the space deviation of the k-th vessel.

Eq. (2) means that any vessel in the berth cannot be overlapped. Eq. (3) reflects the constraint of the quay cranes available at any time. Eq. (4) expresses that the total task for any vessel must be finished. Eq. (5) and (6) reflect the relationship between y_{jk} and v_{jk} . Eq. (7) describes the relationship between t_k and v_{jk} . Eq. (8) guarantees that the operation process is continuous, i.e., if vessel is served at time i' and i'' , it must be served at any time during $[i', i'']$. Eq. (9) reflects the relationship between v_{jk} and z_{ijk} . Eq. (10) means that the vessel cannot be moved during its operation process. Eq. (12) reflects the relationship between x_{ijk} and

v_{jk} , which means the location of the berth equal to the length of the vessel k must be occupied by vessel k. Eq. (11) guarantees $X_{ijk}=0$ for locations outside the ship length. Eq. (12) ensures that $\sum_{i=1}^M x_{ijk} \geq b_k$ when a ship is served. As a result of

Eq. (11) and (12), we have $X_{ijk}=1$ for $i=i'$ to $i=i'+b_k$, which means that the body of a vessel must occupy a section of continuous interval in the berth. (The berth is divided into M small intervals.). Eq. (13) is the constraint of the maximum number of quay cranes distributed to any vessel in any period. The maximum number of cranes is determined according to the length of the vessel, the amount and locations of the cargo on the vessel, the arrival and latest departure times, the priority of the vessel and the quay cranes available.

3.2 The Solution of the Model

A. Lim^[7](1998) proved that the continuous berth allocation model could be simplified as a two-dimension package problem with capacity limitation, which is a NP-hard problem. It is difficult to solve the model. This paper presents a backtracking algorithm to solve the model. The procedure to get the satisfying solution is as follows.

Step 1: Line up the vessels during the planning period according to their arrival times and their priorities.

Step 2: Determine the amount of the quay cranes distributed to each vessel according to the length of the vessel, the amount and locations of the cargo on the vessel, the arrival and latest departure times, the priority of the vessel and so on.

Step 3: Suppose that the original objective value equals to M and M trends to $+\infty$. All the states of the vessels are marked as "waiting for distribution".

Step 4: Distribute the quay cranes and the locations of the berth preliminarily according to the order of the vessels in the line by step 1 and the amount of the quay cranes by step 2. An alternative is obtained. Calculate the objective of this alternative by Eq. (1).

Step 5: Adjust the alternatives

Take out the last vessel N. Try all the possible locations in the berth and the quay cranes for the vessel N-1. Then arrange vessel N again. Some new alternatives can be obtained now. Calculate the objective values for the new alternatives. If there exists a new alternative that has a better objective value than the old one, renew the old alternative and update the old objective value by the better one, respectively. If all the new alternatives do not improve the objectives, keep the old alternative and its objective value.

Step 6: Judge if the running time of the program exceeds the Max Running Time, which is a pre-set threshold time and is supposed to be long enough for running the program to obtain a satisfying solution in most cases. It is determined according to the real system. If the running time exceeds the Max Running Time, stop the program and output the satisfying solution. Otherwise, sign all the vessels as "waiting for distribution" and go to step 7.

Step 7: Continue to adjust the alternatives of the distribution

Take out the last p ($p \leq N$) vessels. Try all the possible locations and the quay cranes for the vessel P-1. Then arrange vessel P, P-1, P-1, ..., N-1 and N in turns. Some new alternatives can be obtained. Calculate the objective values for the new alternatives. If there exists a new alternative that has a better objective than the old one, renew the alternative and update the old objective value. If all the new alternatives do not

improve the objectives, keep the old alternative and its objective value.

Step 8: Repeat step 6 and 7 till the running time of the program has exceeded the Max Running Time, or all the vessels have been adjusted.

The procedure above is as the follows.

Fig. 2 The Procedure

3.3 The Characteristics of the Model

The model above has the following characteristics:

- (1) The model considers the berth as a continuous one, instead of discrete one. It is closer to the real system.
- (2) The objective of the model is to minimize both the total operation time of the vessels and the distances between the vessels and the stacks. Therefore, the model not only considers how to utilize the berth space reasonably, but also tries to decrease the total transport time or distance of the vehicles.

- (3) The deviation coefficient c_k is introduced, which reflects the increase of the operation time because of one unit of the deviations of the k -th vessel from its favorable position.

In terms of c_k , we can convert the space deviation into time loss. In this way, a multi-objective problem, which contains both the operation time and distance, is converted into a single-objective problem that only contains time in its objective.

- (4) The model is closer to the real system by considering

more factors, such as the priorities of the vessels, the efficiencies of different quay cranes, the limitation of the moving range for each quay crane because of the lengths of the electric cables, the lengths and the least space intervals of the vessels.

- (5) The model is a dynamic one.

4. Case

This study was motivated by a problem encountered in Ningbo, a major port city in east China's Zhejiang Province. Ningbo port has the deep-water advantage, and is expected to become the hub port in the western Pacific area.

Our case is dealing with one of the container terminals in Ningbo Port. This terminal has a berth with the length of 1258 meters and the depth of 15 meters. There are 12 quay cranes at this terminal. The berth planning at this terminal is made out mainly by hand. The managers found it time-consuming, and, especially rather difficult for the young planners with less experiences to finish the daily berth planning.

Based on model (1)-(14) and the back-tracing approach, a software of Berth Allocation Assistant System (BAAS) is developed by this study using VB + Access. In terms of this software, a satisfying alternative of berth/quay crane distribution can be obtained in several minutes. Based on this satisfying alternative, the planners only need to slightly adjust the schedule according to the complicated real situation. It saves a lot of time and it is especially helpful to the new planners.

Here is an example using the real data at this terminal. Table 1 shows the vessel information of the terminal during the period from 4:00pm, May 20 to 4:00pm, May 21 in 2004.

Table 1 The Vessel Information During 2004/05/20 (16:00~2004/05/21 16:00 at the container terminal in Ningbo)

No. of the vessels	The arrival time	Priority	Favorable location	The amount of the quay cranes needed	the amount of the containers unloaded (TEU)	the amount of the containers loaded (TEU)	the lengths of the vessels (M)
1	2004-5-19 22:30	3	1	4	723	370	277
2	2004-5-20 11:30	3	3	4	421	290	292
3	2004-5-20 17:00	3	2	1	58	35	64
4	2004-5-20 18:30	3	1	2	90	155	158
5	2004-5-20 19:00	3	1	1	87	30	85
6	2004-5-20 22:30	3	4	3	0	300	195
7	2004-5-20 23:00	4	3	4	723	280	196
8	2004-5-21 02:30	3	2	1	56	0	72
9	2004-5-21 04:00	3	2	3	341	0	183
10	2004-5-21 09:00	3	1	5	856	75	295
11	2004-5-21 11:00	3	4	2	241	270	110
12	2004-5-21 15:30	3	2	1	61	46	72

(resource: a container terminal in Ningbo port)

Table 2 is the alternative of the berth/quay crane distribution obtained by BAAS.

Table 2 The Berth/ Quay Crane Distribution Planning

No. of the vessels	The entering time	The departure time	The positions of the heads of the vessels* (M)	The positions of the sterns of the vessels* (M)	The positions of the quay cranes used*
1	2004-05-19 22:30	2004-05-20 16:43	358	635	5, 6, 7, 8
2	2004-05-20 11:30	2004-05-20 23:21	748	1040	9, 10, 11, 12
3	2004-05-20 17:00	2004-05-20 21:39	655	719	4
4	2004-05-20 18:30	2004-05-21 00:37	18	176	1, 2
5	2004-05-20 19:00	2004-05-21 00:51	196	281	3
6	2004-05-20 22:30	2004-05-21 03:30	533	728	6, 7, 8
7	2004-05-20 23:50	2004-05-21 12:23	784	980	9, 10, 11, 12
8	2004-05-21 02:30	2004-05-21 04:18	18	90	1
9	2004-05-21 04:00	2004-05-21 09:40	350	533	5, 6, 7
10	2004-05-21 09:00	2004-05-21 18:26	18	313	1, 2, 3, 4, 5
11	2004-05-21 12:23	2004-05-22 01:09	1090	1200	11, 12
12	2004-05-21 15:30	2004-05-21 20:51	333	404	6

. The positions of the heads/ sterns of the vessels and the positions of the quay cranes used are described by the distances from the most left location of the frontage.

The alternative in Table 2 is shown in Fig.3, in which the X-coordinate axis represents the positions of the vessels, the Y-coordinate axis represents the time, and the rectangles represent the vessels in the system. The words on the first line in the rectangles are the names of the vessels. The numbers after "CR" signed in the rectangles are the order numbers of the quay cranes distributed to the vessels.

Fig. 3 The Berth/Quay Crane Distribution Schedule

In this case, the Max Running Time is set to be 60 seconds. This Max Running Time is determined by experiments, in which we found that actually the objective value would hardly be improved if the running time was longer than 50 second. The planners of the port examined the results and thought that the results were good enough. For the container terminal, it usually takes about four to six hours for a planner to finish a daily berth plan. Time is greatly saved by using our Berth Allocation Assistant System.

5. Conclusions and Further studies

This paper establishes a berth allocation model for the container terminals. The model considers the utilization of the berth and quay crane resources, and the distances from the position of the vessels to the stacks. A satisfying alternative of the berth/quay crane distribution can be quickly obtained in terms of the model. It is helpful to make out berth plans reasonably and quickly, especially for the new planners.

Further studies could be focused on two problems. Firstly, we only know the results are good enough for the port, but we do not know how far the solution is from the optimal solution. Secondly, the model only runs 24 hours' data each time. 48 hours' data take too long calculation, and sometimes even lead to the failure of getting a solution.

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