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Hybrid Berth Allocation Problem with Fake Berths in Busy Coal Terminal

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Abstract: Due to the sharp increase of coal import in the recent years, nowadays coal terminals in China are heavily congested. Methods are called to ease the vessel queuing and add to the vessel turnover in these terminals. This study presents an idea of utilizing the extra spaces out of the quay boundary, which are treated as fake berths and capable to hold part of one vessel but offering no handling service. A tree-like searching model is proposed for the berth planning problem with the fake berths and a self-designed heuristic algorithm is used to solve the model. Numerical experiments are conducted to verify the effects of the idea.

Key words: Continuous berth allocation problem, spaces out of quay boundary

INTRODUCTION

Once a major coal exporter, China is already by far the world's largest user of coal. According to the statistics from IEA, China imported 290 million ton coals in 2012, nearly 100 tons more than Japan the second importer. In recent years, the international coal prices suffer sharp declines, so as the price of coal shipping. However, no equivalent fall is seen in domestic coal prices and the inland transportation costs keep high at the same time. As a result, import coal becomes the first choice for coal consumers in China, including mainly the thermal power plants, especially those built in coastal areas.

The sharp increase of coal import makes great trouble to some main coal ports in China. The frequency of vessel arrivals races up in the coal terminals, far exceeding their turnover capacity. Despite the fact that the terminals operates 24 h a day and 7 days a week, there are still tens of vessels staying in the anchorage and waiting for berth every day. With the quay length and handling equipments limited, making better use of the quay space is the only countermeasure for the terminals.

A typical layout of the quayside in one coal terminal is shown in Fig. 1. From top to bottom, the gray rectangles stands for vessels berthing at the quay line, the thick line is for the quay line and the little black rectangles laying below the quay are for the bollards, which divides the whole quay line into berths, placed end to end. One vessel could berth covering multiple continuous berths, but two vessels could never occupy the same berth simultaneously. The polygon drawn with double lines are for coal unloaders, some of which could load coal onto some vessel as well. Moreover, the strip is for the conveyer belt, which passes by the unloaders from the bottom, transporting coals from unloader to yard while unloading some vessel, or in an adverse direction while loading some vessel.

In view of the huge number of vessels waiting in the anchorage, the daily berth allocation in a busy coal terminal is to arrange as much vessels as possible to the next 24 h berth plan. The vessels are arranged into the plan in order: the earlier one vessel arrives at the terminal, the prior it will be arranged. Once arranged, a vessel is arranged with some continuous berths and an estimated time period in which the vessel's handling work could be finished. Either the arranged berths of two vessels or their estimated time periods may overlap, but never both of them at the same time. As is in the coal terminal, the more vessels could be arranged in the following 24 h, the better a berth plan is.

Restricted by the activity scope of the ship unloader, the quay could be divided into two parts: the valid quay within the activity scope of the unloader and the invalid quay outside the scope. Similarly, according to the cabin structure and the coal loading conditions, the total length of one vessel could also be divided into two parts: one is the cargo segment in the middle in which there are coal stacked in the cargo cabin and the other is the vacant segments from the bow and stern respectively, in which no coal is stacked. Including the living cabin and some vacant cargo cabin sometimes, the vacant segments of one vessel could be quite long. In the past years when the

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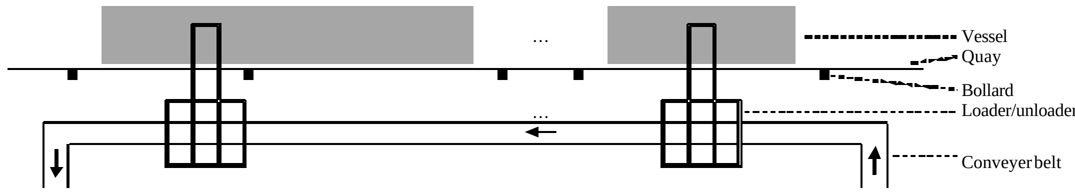

Fig. 1: Layout of the quayside in some coal terminal

coal terminal is not very busy, the invalid quay and vacant segments of the vessel were rarely taken into account while making a berth plan. However, as the terminal becomes very busy nowadays, it is meaningful to take full advantage of the quay space, including the spaces beyond the quay boundary. The details of the quay and coming vessels should be paid close attention to while making the berth plan, in order that more vessels could be arranged in a berth plan.

LITERATURE REVIEW

There have been rarely literatures on berth allocation problems in coal terminals. However, the berth allocation problem in coal terminals is very similar to that of container terminals and there has been much research works on these problems (Steenken *et al*., 2004; Stahlbock and Voß, 2008; Bierwirth and Meisel, 2010). As written in Bierwirth and Meisel (2010). the berth allocation problems could be distinguished by quay layout. In a continuous layout, no partition is made to the quay and the vessels could berth at arbitrary positions within the boundaries of the quay. In a discrete layout, the quay is partitioned into several berths and there is one-to-one relationship between berths and vessels, that is, one vessel berths at one single berth and only one vessel could be served at one berth at a time. In a hybrid layout, the quay is partitioned, while large vessels may occupy more than one berth and small vessels may share a berth. According to this classification, the berth allocation problem studied in this study is a hybrid one, in which it is yet forbidden that multiple vessels share a single berth. Moreover, as the vessels to be planned have arrived at the terminal already, this problem is a static one, without regard to vessels still on their way to the terminal.

Some early models on hybrid berth allocation problems could be found in the beginning of the past decade. Li *et al.* (1998) proposed a scheduling problem with a "multi-job-on-one-processor" pattern, which is motivated by the berth allocation operation. In this pattern, small vessels are allowed to share a same berth. Following their work, Guan *et al.* (2002) developed a heuristic for the problem and performed worst-case analysis. Chen and Hsieh (1999) gave an MIP formulation for the problem incorporating vessel due dates. Nishimura *et al.* (2001) raised a MIP model to deal with the problem of determining dynamic berth assignment to vessels. Multiple vessels are allowed at the same berth simultaneously, in case that the draft is enough and the berth could hold these vessels in length.

Most of the later hybrid models took into account the Quayside Crane Scheduling while allocating berths to arriving vessels. Park and Kim (2005) formulated an integer programming model, considering extra handling costs caused by unanticipated berthing locations, both with unexpected vessel arrivals and departures. They solved the model using a two-phase procedure, in which sub-gradient optimization technique is used first to find a near-optional solution and dynamic programming technique is used later to determine the final solution. In the model proposed by Zhang *et al.* (2010), both the coverage range limitations and the adjustment of quay cranes are properly considered and they argued that their model are more applicable to the actual situation. Meisel and Bierwirth (2009) focused on the productivity of quay cranes assigned to the vessels. In their model, a detailed description is specially given on the cost of speed-up and delay of the vessel handling work.

Continuous Berth allocation problem could be treated as a special kind of hybrid berth allocation problem, in which the quay is partitioned into berths with extremely short berths and no vessel is allowed to share one berth with others. Imai *et al.* (2005) addresses the berth allocation problem in a continuous scheme in a multi-user container terminal. A MIP model is proposed in the study and it is believed that, compared to the discrete scheme, the continuous scheme would lead to higher terminal efficiency, while the scheduling would be a little harder. Lee and Chen (2009) proposed a neighborhood-search based heuristic for the continuous berth allocation problem, in which the berthing position of vessels could be shifted during the handling process. Chang *et al.* (2010) developed an objective programming model for berth allocation and quay crane assignments problem, based on a rolling horizontal approach. They solved the problem using a hybrid parallel genetic algorithm, in which simulation was used for chromosome evaluation. Zhen *et al.* (2011) studied the berth allocation problem under uncertain arrival time or operation time of vessels. It is developed a two-stage decision model. This model makes an initial schedule in the first stage based on anticipation of uncertainty and adjusts the schedule according to the realistic scenarios in the second stage. Raa *et al.* (2011) presented a MILP model for the integrated berth allocation and crane assignment problem, taking into account vessel priorities, preferred berthing locations and handling time considerations. In the mixed integer programming model proposed by Du *et al.* (2011), the fuel consumption and emissions of vessels is taken into consideration. In addition, Hendriks *et al.* (2013) presented a simultaneous berth allocation and yard planning problem. In their problem, the berthing locations of vessels and storage locations of containers were properly determined, hence the driving distances of straddle carriers could be minimized, so as the vessel handling time.

The literatures have provided diverse models on the berth allocation problem, some of which even considered the relationship between berth allocation and vessel handling work. However, in a coal terminal where the vessel handling work is executed by vessel unloader and conveyer belts, various berthing positions of one vessel make hardly any difference to its handling time. Moreover, the extra space beyond the quay boundary is just ignored by the former literature. It is possible that the throughput of the coal terminal could be advanced in case that the extra quay spaces are made full use of while making a berth plan. Therefore, this study is to propose a model for the berth allocation problem with fake berths in busy coal terminal which makes use of the extra quay spaces and an algorithm will be applied to solve the problem. After that, the effect of the new method will be evaluated by numerical experiments.

THE PROBLEM FORMULATION

General description: The model in this study is proposed on the basis of assumptions below:

- Vessels carry coal in the middle cabins. There are vacant ranges from the bow and stern respectively in which no coal is loaded
- The quay is partitioned by bollards into berths, whose lengths are fixed but not the same
- There are fake berths out of the quay boundary, which could be occupied by one vessel, but offers no vessel handling service

Fig. 2: A typical mooring scheme

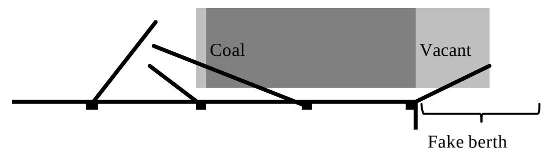

Fig. 3: Illustration of vessel and fake berth

- The time horizon of a berth plan is fixed, which could be divided into basic periods of equal time. No vessels could occupy the same berth in the same period
- The handling efficiency of vessels along the quay is fixed, no matter where one vessel is berthed, or where the coal is stacked in the yard

Bollards are short vertical posts arrayed along the quay line on the quay side. One vessel fixes its mooring ropes to bollards in order to make itself secured to the quay, as is shown in Fig. 2. Once some berth is occupied by two vessels, it is inevitable that the two outermost mooring ropes between them cross each other, which should be forbidden while mooring. As a result, no two vessels are to occupy the same berth.

Fake berths are water regions out of the quay boundary. As shown in Fig. 3, coal is loaded in the dark segment in the middle of the vessel. No coal is loaded in the light segments, which are located at the front and back of the vessel respectively. Although the back of the vessel is located at an fake berth out of the quay boundary, the vessel handling will not be affected. Compared to the traditional way that vessels must be strictly located inside the quay boundary, rational utilization of fake berths is a promising way in increasing the number of vessels arranged in one berth plan.

The notations used in our formulation are listed below:

V	:	Total number of vessels that is to be planned
I	:	Ordinal number of vessels, $1 \le I \le v$
B	:	Total number of berths along the quay line
j	:	Ordinal number of berths, $1 \le j \le B$
T	:	Total number of time periods
t	:	Ordinal number of time periods, $1 \le t \le T$

H_i : Berthing time of vessel i, which could be predicted by the cargo load and the handling efficiency, counted in time periods
L_i : Length of vessel i, including the safety distance on both sides
FR_i : Length of the vacant segments from the bow of vessel i, including the safety distance
Bk_i : Length of the vacant segments from the stern of vessel i, including the safety distance
E_j : A 0-1 constant indicating fake berths. If berth j is an fake berth, then $E_j = 1$, else $E_j = 0$. In this study, it is set that $E_1 = 1$, $E_B = 1$ and $E_j = 0$ when $1<j<B$
C_j : Length of berth j
O_{jt} : A 0-1 constant indicating the occupancy of berth j in period t. If berth j is occupied in period t, then $O_{jt} = 1$, else $O_{jt} = 0$
O : The status matrix, a set of O_{jt}
K_i : Total number of possible berthing patterns of vessel i, $N_i<B$
k : Ordinal number of berthing patterns
m,n : Two integer variables
R_{ik} : Length correlation of vessel i as pattern k

The decision variables are listed below:

b_{ik} : a 0-1 variable indicating the number of berthing plan that vessel i chooses. If vessel i chooses pattern k then then $b_{ik} = 1$, else $b_{ik} = 0$

The dependent variables are listed below:

s_{ijk} : A 0-1 variable indicating the start berth of the k-th pattern of vessel i. If j is the least order number of berths occupied by vessel i following pattern k, then $s_{ijk} = 1$, else $s_{ijk} = 0$
e_{ijk} : A 0-1 variable indicating the end berth of the k-th pattern of vessel i. If j is the largest order number of berths occupied by vessel i following pattern k, then $e_{ijk} = 1$, else $e_{ijk} = 0$
m_{ikt} : A 0-1 variable indicating the mooring period of vessel i following pattern k. If vessel i is to berth to the quay following pattern k in period t then $m_{ikt} = 1$, else $m_{ikt} = 0$
ar_{ik} : A 0-1 variable indicating the arrangement status of vessel i following pattern k. If vessel i could get berthed no later than period T following pattern k then $ar_{ik} = 1$, else $ar_{ik} = 0$

A new berth plan is made following the last one and those vessels arranged but not finished in the last plan will be considered. If in some early period t of the new berth plan, berth j is occupied by some vessel, then the coresponding O_{jt} is set 1. After these value are given, a new berth planning procedure starts. The objective is the maximization of vessels to be arranged in the new berth plan.

$$\text{Max}\sum_{i=1}^{V}\sum_{k=1}^{K_i} ar_{ik}\cdot b_{ik} \tag{1}$$

Where:

$$ar_{ik} = \begin{cases} 1, & \sum_{t=1}^{T} s_{ikt} = 1 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

The possible berthing positions of one vessel could be distinguished into several patterns, indicated by the smallest ordinal number of berths which it occupies. In case that the smallest ordinal number is decided, the largest ordinal number could be determined as well. The berths from the smallest number to the largest number should offer enough berthing space for the vessel, while the largest number of these berths should be minimized. For reason that no vessels are to occupy one single berth, the deviations of actual berthing positions in one pattern makes no difference to the berth plan. As a result, the number of possible berthing patterns could be determined by structure of the vessel in length and the lengths of the berths, as shown in the equations below:

$$s_{ijk} = \begin{cases} 1, & j = k \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

$$e_{ijk} = \begin{cases} 1, & \text{if inequation (5) or (6) holds} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

$$\sum_{j'=k}^{j-1} C_{j'} < L_i - E_k\cdot FR_i - E_j\cdot BK_i \le \sum_{j'=k}^{j} C_{j'} \tag{5}$$

$$\sum_{j'=k}^{j-1} C_{j'} < L_i - E_k\cdot BK_i - E_j\cdot FR_i \le \sum_{j'=k}^{j} C_{j'} \tag{6}$$

$$K_i = \sum_{k=1}^{B}\left(\sum_{j=1}^{B} s_{ijk}\cdot\sum_{j=1}^{B} e_{ijk}\right) \tag{7}$$

Following one berthing pattern of one vessel, the period in which this vessel starts berthing depends on other vessels which are arranged prior to it. One vessel is to berth in one period following some berthing pattern, only if none of the berths in the pattern is occupied by some other prior vessel. Otherwise, the berthing period of this vessel has to be postponed. Vessels are all to berth as early as possible, hence the berthing period of one vessel could be decided as shown in the equations below:

$$m_{ikt} = \begin{cases} 1, \text{ if } \sum_{j=m}^{n} O_{jt} = 0 \text{ and } \sum_{j=m}^{n} O_{j(t-1)} > 0 \\ 0, \text{ otherwise} \end{cases} \quad (8)$$

Where:

Equation 9 is missing (9)

$$n = \sum_{j=1}^{B} j \cdot e_{ijk} \quad (10)$$

On the decision that vessel i is to berth as pattern k in period t', some corresponding elements in **O** are changed, as shown in the equation below:

$$O_{jt} = 1, \text{ if } \sum_{j'=1}^{B} j' \cdot s_{ij'k} \le j \le \sum_{j'=1}^{B} j' \cdot e_{ij'k} \text{ and } t' \le t \le t' + H_i - 1 \quad (11)$$

Vessels are arranged one by one during the berth planning procedure, following a sequence relative to their arrival time. The earlier one vessel arrived at the terminal, the prior it should be arranged in a berth plan. In view that the possible berthing pattern of every vessel is limited and the berthing start period of one vessel is dependent to the vessels arranged earlier, the berth planning procedure could be described in a tree-like searching model.

Tree-like searching model for the berth allocation problem: The searching tree starts from an original node S, where no vessels for a new berth plan has been arranged. The elements in status matrix O at node S depends on only vessels arranged in the last berth plan. The tree branches when determining the berthing pattern of one vessel, each of which leads to a new child node, changing the value of some elements in the current status matrix. Apparently, there are totally V tiers in the searching tree and nodes at the same tier got child nodes as much as each other, as shown in Fig. 4.

The nodes and the corresponding status matrices are indexed according to their position in the searching tree. The notations used for indexing is listed below:

- p : The number of the father node
- c : The number of tier that the father node is at
- WS_p : The cumulated edge weight from **S** to node p.
- p_k : The number of the k-th child of the father node, $1 \le k \le K_{c+1}$
- WP_k : The edge weight from node p to the k-th child of it

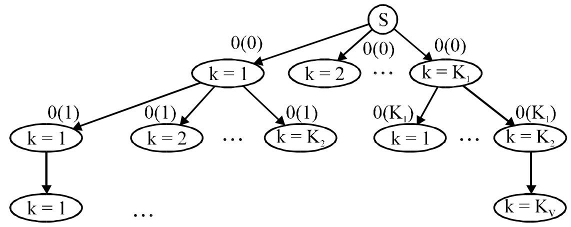

Fig. 4: Searching space of the problem

The relationship of indexes from the father node to the k-th child is described below, in which the tier number of node S is set 0 and K_0 is set 0.

$$p_k = pK_c + k \quad (12)$$

The edge weight from node p to its k-th child node is given by the following equation:

$$WP_k = \begin{cases} 1, \sum_{t=1}^{T} m_{(c+1)kt} > 0 \\ 0, \text{ otherwise} \end{cases} \quad 13)$$

HEURISTIC ALGORITHM

In finding the berth plan that containing as many vessels as possible, the searching tree is to be traversed for the optimal solution. In consideration of the problem scale, exhaustive search would be quite time-consuming. In this study, it is proposed a heuristic algorithm based on A* search algorithm.

A* search is a common algorithm for graph search to find the optimal path from an initial node to one goal node. It keeps an open list of nodes to be expanded and always tries to select the most promising node based on an evaluation function f(x) = g(x)+h(x), where g(x) is the cost from the start node to x and h(x) is the estimated lowest cost from x to the goal node. In case that h(x) is always no more than the true cost h*(x), the heuristic h(x) is admissible and the algorithm is to find the optimal solution for sure.

The aim of the berth planning problem is to find the largest number of vessels that could be arranged into the berth plan. Therefore, the A* algorithm cannot be used in this problem directly, hence we made some changes in the mechanism and formed a heuristic which is used to find asatisfactory solution. The notations used in the heuristic are listed below:

- f(x) : Cost function at node x
- g(x) : Cumulated number of vessels that have been arranged into the berth plan in node x

h(x) : Estimated number of vessels left that could be arranged into the berth plan in node x
R(x) : Set of vessels not arranged at node x

It is quite simple to calculate the value of g(x) by cumulating the weights of the edges on the path from start node S to node x. However, a rational value of h(x) is not that easy to estimate. The berth plan is made up of the vessels' choices on berthing patterns; hence the number of possible berth plans could be quite a few. In view of this, the value of h(x) is decided in assumption that vessels choose their berthing pattern following the same rule, as listed below:

- Vessels in R(x) choose the berthing pattern that leads to the earliest berthing period
- In case that multiple patterns leads to the same earliest period, choose the pattern with the smallest starting berth number

Given that the vessels in R(x) choose their berthing pattern following the same rules, a possible berth plan is easily figured out, based on which the value of h(x) could be determined as well.

The pseudo code of the heuristic algorithm is presented in Fig. 4, in which n_curr is for the current node, n_start is for the start node, n_best is for the solution node and s_open for the open set.

NUMERICAL EXPERIMENTS

Two sets of experiments are conducted in this section. In the first section, the efficiency of the heuristic algorithm is tested with random generated vessels in different numbers. In the second section, we compared our berth allocation method to the traditional way in which vessels are restricted in the quay boundary. In both sets of experiments, the berth lengths are fixed, as the real berth lengths on the quay line of the Coal Terminal in Tianjin Port.

Tests with random generated vessels: We assume that the possible vessel types are all known and vessels in one type is the same in structure, as is shown in Table 1. In this table, L is for the length of vessel in meters, including the safe distances on both sides. FR is the length of vacant segment from the bow in meters and BK is the length of vacant segment to the stern, both including the safety distance on their side. H are for the berthing times, counted in berthing periods.

Computational time is the main factor of interest since the heuristic algorithm returns a unique solution. To evaluate the mean computational time in different problem scales, we tested the algorithm with instances of various number of vessel arrivals. For every problem sacle, 20 instances are generated and the mean, upper and lower computational times are recorded in seconds, as in shown in Table 2 below:

Table 1: Parameters of vessel types

Type no.	1	2	3	4
L (m)	120	200	280	320
Avg FR (m)	15	20	40	45
Avg BK (m)	22	50	58	70
Min H	2	4	5	6
Max H	3	5	6	8
rate	0.3	0.5	0.15	0.05

Table 2: Computational time of instances in various problem scales

Problem scale	5	10	15	20	25	30	35
Mean Time	0.26	0.64	1.95	3.36	7.42	7.75	8.23
Upper Time	0.67	0.35	2.86	6.27	9.81	10.13	12.43
Lower Time	0.18	1.03	1.24	2.57	6.24	6.54	7.26

```
Heuristic Algorithm
Create a node with no vessel arranged as n_start and create the status matrix
Calculate the total cost of n_start
Put n_start into s_open
WHILE s_open is not empty
set the node with the largest cost as n_curr
IF n_curr is in the highest tier of the tree
return n_curr as the goal node
remove n_curr from s_open
FOR each node in the neighbor nodes of n_curr
Prepare the status matrix according to that of its father node
Calculate the cost of this node
IF at least one vessel in R(n_curr) could be arranged in the first T periods
Add this node to s_open
```

Fig. 5: Pseudo code of the heuristic algorithm

It could be observed from the table above that, the mean computational time grows very quickly as the problem scale increases when the scale itself is not very large. However, the increase slows down when the problem scale becomes large enough (roughly no less than 25 in the table). Those nodes at which no more vessel could be arranged into the first T periods will be moved directly out of the open set (Fig. 5), hence the mean computational times in large problem scales are saved from sharp increasing.

Comparison to the traditional way of berth allocation: In this section, we compare the berth plans made using our berth allocation method to those made in the traditional way. We select 30 scenarios from the coal terminal just before a new berth plan is made, out of which we make two berth plans from each scenario. The first plans are

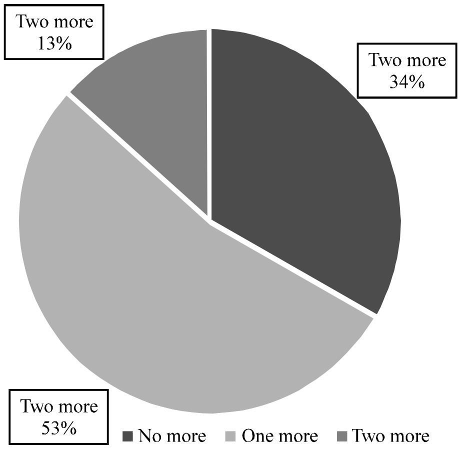

Fig. 6: Statistics of the vessel increments

Table 3: Comparison of the berth allocation methods

No.	TRA	FB	No.	TRA	FB	No.	TRA	FB
1	33	34	11	24	26	21	13	13
2	21	23	12	26	26	22	22	22
3	31	32	13	34	35	23	28	29
4	23	23	14	26	27	24	32	33
5	19	19	15	23	23	25	30	31
6	28	28	16	19	19	26	21	22
7	16	17	17	27	29	27	22	22
8	27	28	18	34	35	28	24	26
9	17	17	19	20	21	29	26	27
10	15	16	20	30	31	30	23	24
						Avg.	24.46	25.26

made in the traditional way, in which no fake berths are taken into consideration and vessels must berth inside the quay boundary. The second plans are made using the method described in this study and vessels are allowed to occupy the fake berths. The number of vessels arranged in the berth plans are recorded in Table 3 below, in which TRA is for the number of vessels in the first plans, FB is for the number in the second plans.

Based on the records in Table 3, we analyzed the increments from FB to TRA in the scenarios statistically, as shown in Fig. 6. Using the method presented in this study, 53% of the berth plans arranged with one more vessel, 13% of them are arranged with two more and one berth plan is arranged with 0.8 more vessels on average. It is obvious that the method presented in this study is really effective in arranging more vessels into one berth plan. However, the effect seems quite limited.

CONCLUSION

This study presents an idea of utilizing the extra spaces beyond the quay boundary (fake berths) when making berth plans, in order that more vessels could be arranged in the same planning horizon. A tree searching models is proposed to describe the problem, so as a heuristic algorithm to solve the model. It is verified by numerical experiments that, the idea could indeed increase the vessels arranged in one berth plan. We think that the idea presented in this study should be an effective method in easing the congestions in the coal terminals.

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