Effect of Terminal Layouts on the Performance of Marine Terminals for Mega-containerships

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Abstract

The appearance of over 10,000 TEU containerships (so called Mega-containerships) is determined. In order to operate these ships effectively, the number of these calling ports will diminish, and then feeder ships will transport cargoes from the hub-ports where mega-containerships call to the destination ports. In the hub-ports, handling containers for mega-containerships become huger, thus it is important for terminals to deal with cargo handling as soon as possible. However, the present terminal layout might have the limitation of maximum throughput per time unit. And then the transit time at the ports become longer. Therefore, we investigate the effect on some different terminal layouts with new alternatives. Actually, we discuss the ship-to-berth allocation at some adjacent berths for mega-containerships on three types of terminal layouts. First one is the conventional type consisted by some linear berths, most container terminals in the world are normally this type. Second one is the indented type consisted by linear berths and indented berths which we can handle from both sides of mega-containership simultaneously. Third one is the floating type consisted by linear berths and the floating berth. On this type, mega-containerships can moor between linear and floating berths. The merits of this type are that we can also handle from both sides of mega-containerships simultaneously, and ships can go through between linear berth and floating berths. Thus it is easier for ships to moor and leave berths.

Under such assumptions, we examine the numerical experiments. In most cases, the total service times on the indented type are the longest among three types, these on the floating type are the next longer. Those reasons are that these layouts have the differences of berth occupancy obtained by the time and space axes, and whether the precedence constraints of ship service order needs or not.

Keywords: Berth allocation, Terminal layouts, Mega-containerships, Container terminal, Heuristics

1. Introduction

Some shipping companies are planning to make the appearance of the so-called mega-containership (hereafter referred to as mega-containership) that transports over 10,000 TEU containers per a voyage. Its operation benefits from lower per-transit costs and reduced transit time. Because mega-containerships are extremely capital expensive, the carrier will deploy them in concentrated trade lanes with longer routes and fewer ports of call. Such ports that mega-containerships call must serve them in high priority without any delay in handling. In a port, a specific berth is dedicated to serve the mega-containership where the dedicated berth has to be efficiently utilized while the mega-containership is absent. A straightforward idea is that the dedicated berth serves other ships during that time for higher berth utilization. However, an important issue is that such a usage for the other ships must not delay the mega-containership handling.

The above discussion suggests the mega-containership terminal to be operated as an multi-user terminal (MUT) , which may be defined as those featured with a long quay that serves a number of calling vessels by simultaneously and dynamically allocating them to the quay. An MUT can reduce the required terminal space while handling containers with the same rate of productivity as a dedicated terminal, thus resulting in substantial cost savings in cargo handling costs. One of the issues that affect the efficiency of MUT in operation is how to allocate berths to calling ships in order to increase the entire berth productivity.

To our knowledge, the only example of an MUT that could be used for mega-containerships is an indented terminal at the port of Amsterdam. While an ordinary MUT is featured by the handling system that all calling ships are loaded and unloaded from one side as shown in Fig. 1(a), an indented MUT is characterized by its capability of fast handling from both sides of the ship as shown in Fig. 1(b). However, due to its configuration the indented MUT may also impose a constraint in serving efficiently small feeder ships as portrayed in Fig. 2, i.e., ships at the inner part of the indented berths cannot depart before those ships at the outer part depart.

In this paper, we propose the floating type terminal that consists of linear berths and the floating berth as shown in Fig. 1(c). This new layout has the capability of fast handling from both sides of the mega-containership, but does not need the constraints like Fig. 2. Thus feeder ships can arrive and depart from the right and left sides between the floating berth and a linear berth based to floating berth easily. We discuss the ship-to-berth allocation problem for three terminal layouts, and examine their characteristics.

This paper is organized as followings. The next section presents the literature review of existing studies on the berth allocation problems. The problem formulations are provided in Section 3, followed by Section 4 which describes the solution procedures. Section 5 discusses numerical experiments and finally section 6 concludes the paper.

2. Literature Review

As there is an ever-growing demand of operating MUTs more efficiently due to the continuous increasing container traffic, the issues pertaining to the efficient berth allocation at an MUT have been receiving much attention these days.

Lai and Shih (1992) propose a heuristic algorithm for berth allocation, which is motivated by more efficient terminal usage in

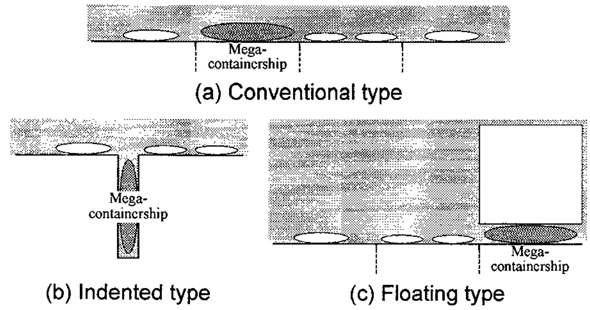

Figure 1. Terminal layouts

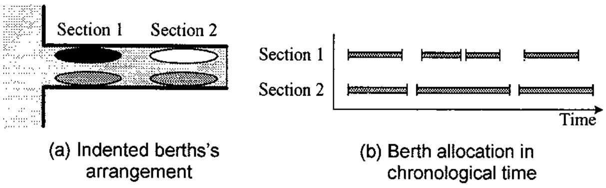

Figure 2. Simultaneous service in the BAPI

the HIT terminal of Hong Kong. Their problem considers a First-Come-First-Served (FCFS) allocation strategy. Brown et al. (1994, 1997) examine ship handling in naval ports. They identify the optimal set of ship-to-berth assignments that maximize the sum of benefits for ships while in port. In this problem, a berth shift occurs when for proper service, a newly arriving ship must be assigned to a berth where another ship is already being served. This treatment is unlikely in commercial ports.

Imai et al. (1997) address the BAP in discrete index referred to as BAPD for commercial ports. Most service queues are in general processed on the FCFS basis. They concluded that in order to achieve high port productivity, an optimal set of ship-to-berth assignments should be found without employing the FCFS rule. However, this service principle may result in certain ships being dissatisfied with their order of service. In order to deal with the two conflicting evaluation criteria, i.e., berth performance and dissatisfaction with the order of service, they developed a heuristic to find a set of non-inferior solutions while maximizing the former and minimizing the latter. Their study assumes a static situation, where ships to be served for a planning horizon have all arrived at the port before the planning process. Such ports are not competitive and this type of situation is not "realistic" due to the long delays experienced in the interchange process at the ports of call. In this context, Imai et al. (2001, 2005a) extended the static version of the BAPD into a dynamic treatment that is similar to the static treatment, but with the difference that some ships arrive while work is in progress. As the first step in this dynamic treatment, only one objective, berth performance, is considered. Their study assumes the same water depth for all berths, although in practice certain ports have berths with different water depths. Nishimura et al. (2001) further extend the dynamic version of the BAPD for the multi-water depth configuration. In some real situations, the terminal operator assigns different priorities to calling vessels. For instance, a terminal in Singapore treats large vessels with higher priority, because they are considered valuable customers for the terminal. Imai et al. (2003) extend the BAPD in Imai et al. (2001, 2005a) to treat ships with different priorities and see how the extended BAP differentiates ship handling in terms of their associated service time.

There is also another type of approach to the berth allocation problem, which is the one with a continuous location index (referred to as BAPC). While in the above mentioned studies the entire terminal space is partitioned into several parts (or berths) and the allocation is planned based on the divided berth space, under this approach ships are allowed to be served wherever the empty spaces are available to physically accommodate the ships via a continuous location system. A ship in wait and in service at a berth can be shown by a rectangle in a time-space representation or Gantt chart, therefore efficient berth usage is sort of packing "ship rectangles" into a berth-time availability box with some limited packing scheme such that no rotation of ship rectangles is allowed. These problems are treated by Lim (1998), Li et al. (1998), Guan et al. (2002), Park and Kim (2002), Kim and Moon (2003), Park and Kim (2003), Imai et al. (2005b). The conclusion of their study is that the best approximate solution is identified with the best solution in discrete location where the berth length is the maximum length of ships involved in the problem. This implies that the solution in discrete location is applicable in practice in berth allocation planning and that an improved solution can be obtained from it.

3. Problem formulation

3.1 Formulation for BAPM with mega-containerships

In this section, we first formulate the BAPD with multiple ships serviced at the same berth in a terminal of conventional form (BAPM) and then the BAP with the same context but in terminals with indented berths (BAPI) and with floating berth (BAPF). In the following discussion, the term "berth" refers to a unit of quay space having a specific length e.g., 400m. The assumptions we made are as following:

(a) The handling time of a ship depends on the berth assigned to the ship.
(b) Up to two ships can be served at the same berth simultaneously if their total length is less than the overall berth length.
(c) There is no precedence constraint in berthing two ships, which are to stay at the same berth simultaneously, as will be applied for the BAPI (Section 3.2 for details).
(d) All berths have the same water depths unlike Nishimura et al. (2001), who first introduced the BAPM.

The linear formulation of the BAPM is as following:

[PM] Minimize $$Z = \sum_{j\in V}\left\{\sum_{i\in B} f_{ij} - A_j\right\} \quad (1)$$

subject to

$$\sum_{i\in B}\sum_{k\in U} x_{ijk} = 1 \quad \forall j \in V, \quad (2)$$

$$\sum_{j\in V} x_{ijk} \le 1 \quad \forall i \in B, k \in U, \quad (3)$$

$$b_{ij} \ge \sum_{k\in U} \max\{S_i, A_j\} x_{ijk} \quad \forall i \in B, j \in V, \quad (4)$$

$$f_{ij} = b_{ij} + \sum_{k\in U} C_{ij} x_{ijk} \quad \forall i \in B, j \in V, \quad (5)$$

$$\sum_{k\in U} k x_{ijk} \ge \sum_{k'\in U} k' x_{ij'k'} + (\tau_{ijj'} - 1)TM \quad \forall i \in B, j, j' \in V, \quad (6)$$

$$b_{ij} \le b_{ij'} + (1 - \tau_{ijj'})TM \quad \forall i \in B, j, j' \in V, \quad (7)$$

$$f_{ij} \le b_{ij'} + (1 + \omega_{ijj'} - \tau_{ijj'})TM \quad \forall i \in B, j, j' \in V, \quad (8)$$

$$\omega_{ijj'}(L_j + L_{j'}) \le BL_i \quad \forall i \in B, j, j' \in V, \quad (9)$$

$$\omega_{ijj'} \le \tau_{ijj'} \quad \forall i \in B, j, j' \in V, \quad (10)$$

$$\sum_{k\in U}(x_{ijk} + x_{ij'k} - 1) \le \tau_{ijj'} + \tau_{ij'j} \le \sum_{k\in U}(x_{ijk} + x_{ij'k})\Big/2 \quad \forall i \in B, j, j' \in V, \quad (11)$$

$$\sum_{j'\in V} \omega_{ijj'} \le 1 \quad \forall i \in B, j \in V, \quad (12)$$

$$x_{ijk} \in \{0, 1\} \quad \forall i \in B, j \in V, k \in U, \quad (13)$$

$$\tau_{ijj'} \in \{0,1\} \qquad \forall i \in B, j, j' \in V, \tag{14}$$

$$\omega_{ijj'} \in \{0,1\} \qquad \forall i \in B, j, j' \in V, \tag{15}$$

$$b_{ij} \geq 0, f_{ij} \geq 0 \qquad \forall i \in B, j \in V, \tag{16}$$

$$b_{ij} = \sum_{k \in U} A_j x_{ijk} \qquad \forall i \in B, j \in VM, \tag{17}$$

where

$i(=1,\ldots,Q) \in B$ set of berths (Q: the number of berths)
$j(=1,\ldots,T) \in V$ set of ships (F: the number of ships)
$k(=1,\ldots,T) \in U$ set of service orders
TM a very large number
A_j arrival time of ship j
BL_i length of berth i
L_j length of ship j
S_i time when berth i becomes idle for the planning horizon (set to negative value)
C_{ij} handling time spent by ship j at berth i
x_{ijk} =1 if ship j is served as the kth ship at berth i, and =0 otherwise
$\tau_{ijj'}$ =1 if both ships j and j' are served in berth i where j is earlier than j', and =0 otherwise
$\omega_{ijj'}$ =1 if both ships j and j' are served at the same time in berth i, and =0 otherwise
b_{ij} start time of handing ship j at berth i
f_{ij} completion time of handling ship j at berth i
VM set of mega-containerships

The decision variables are x_{ijk}s, $\tau_{ijj'}$s, $\omega_{ijj'}$s, b_{ij}s and f_{ij}s. Objective (1) minimizes the total service time. Constraint set (2) ensures that every ship must be served at any berth in any order of service. Constraints (3) enforce that every berth serves up to one ship in any order of service. Constraints (4) assure that a ship is served after the largest point of time between the time when that ship arrives at the port and the time when the assigned berth becomes idle in the planning horizon. Constraints (5) define the completion time of ship handling. Constraint set (6) guarantees that if ship j is served earlier than ship j', the former takes an earlier service order than the latter. Constraints (7) ensure that if ship j is served earlier than ship j', the former starts it's handling earlier than the latter. Constraint set (8) enforces that if two ships, j and j', are served at the same berth while the former is served earlier than the latter and they do not any time share the same berth, the start of serving the latter is later than the completion of serving the former. Constraint set (9) enables two ships to be served at the same berth if the total of their lengths is no larger than the berth length. Constraints (10) assure that if two ships are served at the same berth regardless of which ship is served first, their service time may be overlapping. In other words, if they are served at different berths, they are never served simultaneously at the same berth. Constraints (11) ensure the proper definition of the variables pertaining to the service precedence of two ships. Also they guarantee that unless both of the two ships are served at the same berth, neither $\tau_{ijj'}$ nor $\tau_{ij'j}$ is set to one. Constraints (12) ensure that a ship can be served at most with one other ship at a berth simultaneously.

As state above, this formulation uses an auxiliary variable $\omega_{ijj'}$ for defining simultaneous service to two ships. The introduction of auxiliary variable $\tau_{ijj'}$ together with $\omega_{ijj'}$ in constraints (7), (8) and (11) enables [PM] to have linear constraints for simultaneous berthing. With respect to objective (11), if none of the two ships j and j' or one of them is served at berth i, the left-hand side does not have a positive value and the right-hand side has a value no more than 0.5; therefore $\tau_{ijj'} + \tau_{ij'j}$ is null. On the other hand, if they are both served at berth i, both of on the left and right-hand sides have 1. This guarantees that either $\tau_{ijj'}$ or $\tau_{ij'j}$ is 1. For constraints (7) and (8), if ship j' begins its handling earlier than ship j, i.e., $\omega_{ijj'} = 0$ and $\tau_{ijj'} = 0$; no relationship among b_{ij}, $b_{ij'}$ and f_{ij} is defined. If ship j is earlier than j', while they are both at berth i but do not share the berth at the same time, i.e., $\omega_{ijj'} = 0$ and $\tau_{ijj'} = 1$; $b_{ij} \leq b_{ij'}$ and $f_{ij} \leq b_{ij'}$. Furthermore, if ship j is earlier than j' and they share berth i at the same time, i.e., $\omega_{ijj'} = 1$ and $\tau_{ijj'} = 1$; then $b_{ij} \leq b_{ij'}$ and $f_{ij} < b_{ij'}$ or $f_{ij} \geq b_{ij'}$. In the last case, however, we optimally have $f_{ij} \geq b_{ij'}$ by beginning the service of ship j' when the berth and ship lengths allow, because all the ships are planned to start handling tasks as possible in order to minimize the objective function. Thus, auxiliary variables $\omega_{ijj'}$ and $\tau_{ijj'}$ are properly defined.

Constraint set (17) ensures that mega-containerships start their handling service as soon as they arrive at the terminal.

3.2 Formulation for BAPI

We next introduce the BAPI with the assumption that mega-containerships are served only at the indented berths, which also serve feeder ships when idle. From this point of view, the BAPI is solved such that the indented berths are efficiently utilized for feeder ships if no mega-containership is served. We assume that as mega-ships have the priority, they are served without any delay when they arrive at the terminal. Feeder ships can be served at the indented berth only when no mega-containerships stay there. As illustrated in Fig. 2, the BAPI imposes the restriction that when a ship stays at section 1 of one berth of the indented berths, no ship can enter and exit section 2 regardless of whether or not there are ships at the opposite side (or berth) of the indented berths across the water basin. In other words, a ship served at section 1 with another ship at section 2 of the same berth, must be moored there no earlier and depart no later than the ship at section 2.

The above restriction does not reflect an actual limit in arriving at and/or leaving the indented berths with a narrow water basin; because the blackened ship at section 2 of Fig. 2(a) may in practice enter or leave the berth, even if in addition to the white ship, the gray ships are moored at the opposite side of the indented berths in Fig. 2(a). Thus, the previous assumption was made mainly due to the simplicity of the formulation. In addition, it is also reasonable because if it decided to move, even in the case that there are no gray ships at the opposite side of the indented berth, the black ship would take a high risk of crashing against the quay wall of the opposite side due to the velocity towards the quay by her side-thrusters.

[PI] Minimize

$$Z = \sum_{j \in V} \left\{ \sum_{i \in B} f_{ij} - A_j \right\} \tag{1}$$

subject to (2)-(16)

$$b_{ij} = \sum_{k \in U} A_j x_{ijk} \qquad \forall i \in B^*, j \in VM, \tag{18}$$

$$b_{ij} - (\delta_{ijj'} - 1)TM > b_{ij'} + \sum_{k \in U} C_{ij'} x_{ij'k} + d_{ij'} \qquad \forall i \in B^*, j, j' \in V, \tag{19}$$

$$b_{ij} + \sum_{k \in U} C_{ij} x_{ijk} + d_{ij} - (\phi_{ijj'} - 1)TM \geq b_{ij'} + \sum_{k \in U} C_{ij'} x_{ij'k} + d_{ij'} \qquad \forall i \in B^*, j, j' \in V, \tag{20}$$

$$b_{ij} \leq b_{ij'} - (\phi_{ijj'} - 1)TM \qquad \forall i \in B^*, j, j' \in V, \tag{21}$$

$$b_{ij'} + \sum_{k \in U} C_{ij'} x_{ij'k} + d_{ij'} - (\rho_{ijj'} - 1)TM \geq b_{ij} + \sum_{k \in U} C_{ij} x_{ijk} + d_{ij} \qquad \forall i \in B^*, j, j' \in V, \tag{22}$$

$$b_{ij'} \leq b_{ij} - (\rho_{ijj'} - 1)TM \qquad \forall i \in B^*, j, j' \in V, \tag{23}$$

$$b_{ij'} - (\sigma_{ijj'} - 1)TM > b_{ij} + \sum_{k \in U} C_{ij} x_{ijk} + d_{ij}$$

$$\forall i \in B^*, j, j' \in V, \quad (24)$$

$$\sum_{k \in U} (x_{ijk} + x_{ij'k}) \Big/ 2 - 0.5 \le \delta_{ijj'} + \phi_{ijj'} + \rho_{ijj'} + \sigma_{ijj'} \le \sum_{k \in U} (x_{ijk} + x_{ij'k}) \Big/ 2$$

$$\forall i \in B^*, j, j' \in V, \quad (25)$$

$$\delta_{ijj'} \in \{0, 1\} \qquad \forall i \in B^*, j, j' \in V, \quad (26)$$

$$\phi_{ijj'} \in \{0, 1\} \qquad \forall i \in B^*, j, j' \in V, \quad (27)$$

$$\rho_{ijj'} \in \{0, 1\} \qquad \forall i \in B^*, j, j' \in V, \quad (28)$$

$$\sigma_{ijj'} \in \{0, 1\} \qquad \forall i \in B^*, j, j' \in V, \quad (29)$$

$$d_{ij} \ge 0 \qquad \forall i \in B, j \in V, \quad (30)$$

where

B^* set of indented berths

$\delta_{ijj'}$ =1 if ships j' stays at either section 1 or 2 of the indented berth i before ship j regardless of ship j being at section 1 or 2 (see Fig. 3), and =0 otherwise

$\phi_{ijj'}$ =1 if ship j' stays at section 1 of the indented berth i when ship j stays at section 2, and =0 otherwise

$\rho_{ijj'}$ =1 if ship j' stays at section 2 of the indented berth i when ship j stays at section 1, and =0 otherwise

$\sigma_{ijj'}$ =1 if ship j' stays at section 1 or 2 of the indented berth i after ship j regardless of ship j being at section 1 or 2 (see Fig. 3), and =0 otherwise

d_{ij} the extended time for departure of ship j at section 2 of berth i because of precedence constraint.

The extended time is considered in the case where a departing ship from section 2 of an indented berth is blocked by a ship at section 1.

The decision variables are x_{ijk}s, $\tau_{ijj'}$s, $\omega_{ijj'}$s, b_{ij}s, f_{ij}s, $\delta_{ijj'}$s, $\phi_{ijj'}$s, $\rho_{ijj'}$s, $\sigma_{ijj'}$s and d_{ij}s. Constraints (18) offer priority to mega-containerships at an indented berth. Constraints (19)–(29) ensure that a ship served at section 1 simultaneously with a ship at section 2 comes to the berth later and leave the berth earlier than the ship at section 2. For particular ship j at section 2, there are three cases of the relationship with another ship j' at section 1 or 2 as shown in Fig. 3(a). Constraint set (19) is for case (i), sets (20) and (21) for case (ii) and set (24) for case (iii), respectively. On the other hand, if ship j stays at section 1, there are also three cases as illustrated in Fig. 3(b). Case (i) is defined by constraint set (19), case (ii#) by sets (22) and (23), and case (iii) by set (24). Whether ship j is either at section 1 or 2, one of the three cases is applied. For instance, regarding constraint set (19), with $\delta_{ijj'} = 1$ this constraint set is reduced to $b_{ij} \ge b_{ij'} + \sum_{k \in U} C_{ij'} x_{ij'k} + d_{ij'}$. When $\delta_{ijj'} = 0$, the left-hand sides of the constraint set becomes an enormous number, therefore we do not need to care about the constraint set. Constraint set (25) ensures that constraints (19)–(24) are applied only if ships j and j' are served at the same berth. If neither ship j nor j' stays at berth i, we do not care about constraints (19)–(24). This is guaranteed because the left-hand side of constraint set (25) is –0.5 and the right-hand side is zero, resulting in $\delta_{ijj'} + \phi_{ijj'} + \rho_{ijj'} + \sigma_{ijj'} = 0$. If either ships j or j' stays at berth i, we do not care about constraints (19)–(24) either. This is caused by the fact that the left-hand side of constraint set (25) is zero and the right is 0.5. If both ships stay at the berth, the left is 0.5 and the right is 1; therefore one of $\delta_{ijj'}$, $\phi_{ijj'}$, $\rho_{ijj'}$ and $\sigma_{ijj'}$ is set to one.

3.3 Formulation for BAPF

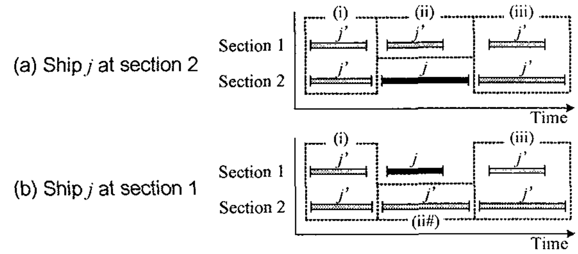

Figure 3. Precedence constraints

We formulate the BAPF in a terminal combined the conventional form berths and the floating berth. We can represent the formulation of BAPF by modified a part of the BAPM. The point which we should change is that mega-containerships are served at one of conventional berths and the floating berth at the same time.

The formulation of the BAPF is as following:

[PF] Minimize $$Z = \sum_{j \in V} \left\{ \sum_{i \in B} f_{ij} - A_j \right\} \quad (1)$$

subject to (2)-(16)

$$b_{ij} = \sum_{k \in U} A_j x_{ijk} \qquad \forall i \in FB, CB, j \in VM, \quad (31)$$

where

FB the floating berth

CB A berth to the floating berth's face

Constraints (17) of BAPM change to constraints (31), mega-containerships are served at the specific berths for them.

4. Solution Procedure

Although the formulations [PM], [PI] and [PF] are linear, it is complicated and it is not likely that an efficient exact solution method exists; therefore, to facilitate the solution procedure we employ a GA-based heuristic, which is widely used in solving difficult problems and has a practical, short computational time.

4.1 Outline of solution procedure

GA is like a heuristic method in that the optimality of the answers cannot be determined. It works on the principle of evolving a population of trial solutions over many iterations, to adapt them to the fitness landscape expressed in the objective function. The objective function value and solution alternatives of [PM], [PI] and [PF] correspond to the fitness value and individuals, respectively.

4.2 Obtaining the objective function

A chromosome representation simply defines the relationship among berth-ship-service order. The start time of handling each ship has to be determined in order to compute the objective function value. The determination of the start time must be made so that ships are served simultaneously at a berth subject to the berth length and ships' entries and departures at an indented berth being physically feasible.

The outline of the calculation process to determine the start time of handling ships in a berth is as shown in Fig. 4. The process determines the position of conventional and floating types, the section of the indented berth where ships are to be served and the start and completion times of their handling, one by one and in ascending order of their service order which was obtained by the GA computation. Notice that if the ship under the process does not depart before the next mega-containership arrives, the ship is served after the mega-containership.

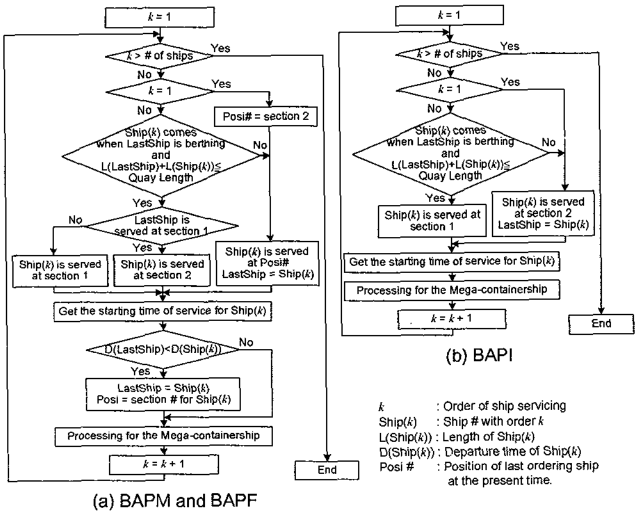

Figure 4. Flow of calculating the start time of ship handling

5. Numerical experiments

5.1 Estimation of ship's handling time

In order to carry out the entire experiment, we carefully set up a major input parameter of the BAPM, BAPI and BAPF, C_{ij}, which defines the handling time of a ship at a specific berth location. In previous studies conducted by the authors dealing with berth allocation problems, no insight was provided for C_{ij} or equivalent parameters. For precise estimation of C_{ij}, we implemented a simulation model of container handling tasks by quay cranes, yard-trailers and yard cranes like RTG at a terminal and performed various cases of simulations by the model. In summary, we obtained a regression model to estimate the handling time using the number of containers to be handled (x_1), the number of yard-trailers hauling containers between a quay crane and container stack on the yard (x_2) and the distance between the quay crane and the container stack (x_3) as explanatory variables. By simulations with four berths, we constructed the following linear model (32) with the coefficient of the determination of 0.88:

$$\log y = 0.75 \log x_1 - 0.77 \log x_2 + 0.29 \log x_3 + 1.71 \tag{32}$$

As shown in model (32), the objective variable and explanatory variables are used as the logarithm of original values. Therefore, we can get the parameter C_{ij}s for feeder ships by the following model, and those for mega-containerships are given by the number of 16,000 containers handled. We show the handling time for ships in Table 1.

$$y = \exp(1.71) \times x_1^{0.75} \times x_2^{-0.77} \times x_3^{0.29} \tag{33}$$

Note that the estimation model (33) was constructed with the data generated by the simulations, which assume a conventional type terminal. Exactly speaking, it is not certain that (33) guarantees that C_{ij} estimation at the indented and floating types; however, we assume that it does.

In order to get the distance between the quay crane and the container stack, we assume that the container block arrangement and corridor system for yard-trailer run are illustrated in Fig. 5, and the container block is assigned for a specific ship randomly with uniform distribution.

5.2 Experiments

The program codes for the BAPM, BAPI and BAPF were implemented in C-language on a Sun Blade 1500 workstation. By preliminary experiments, we identified parameters for GAs as population size=50, mutation rate=0.09 and the number of generation=3,000.

Table 1. Handling time for ships

(hours)	Mega-containership	Feeder ships			
		Avg.	Std.	Min.	Max.
Conventional type	57.0	7.9	2.0	2.0	12.7
Indented type	40.0	8.1	2.0	2.3	12.6
Floating type	40.0	8.0	2.1	2.0	12.8

Avg.: Average, Std.: Standard deviation

Table 2. Ship category

Ship length	# of containers handled	# of quay cranes
50- 99 m	50-300	1
100-149 m	301-600	2
150-200 m	601-900	3

In the experiments, we assess the handling capacity of three terminals as illustrated in Fig. 1. In order to assess there three types from a cost-effectiveness point of view, these terminals are set to have the same size in area and the same quay length as shown in Fig. 5. The handling time at the neighboring berths may be affected by the existence of the mega-containership due to the number of available cranes at the berths. For simplicity purposes we assume the same handling time at the neighboring berths regardless of the mega-containership handling.

It is assumed that ships served at the MUTs are categorized into three classes by associating ship length with the number of containers loaded and unloaded and the number of quay cranes employed as shown in Table 2. These ships arrive randomly at the MUTs for one week, by exponential distribution. A mega-containership has a total of 16,000 containers loaded and unloaded by 7 quay cranes in conventional type and 10 quay cranes in indented and floating types, respectively.

Computation settings we made reflect a relatively busy MUT. We generated three cases with different ship arrival patterns; average interval of 2, 3 and 4 hours by exponential distribution. For each case, we made three scenarios; no calling, one calling and two callings per a week.

Fig. 6 shows the service time including waiting time and the waiting time for three terminal layouts. The value is the average over all the calling ships except mega-containerships. Both of the service times and waiting times with two-hour arrival interval are longer than those with longer intervals. This is because the given average handling times are 8 hours and therefore ships do not likely wait with longer arrival intervals.

Next, comparing among three terminal layouts, we observe that the service times and the waiting times for the conventional type are less than those for the others in most cases. For congested scenarios, i.e., those of 2 hour arrival intervals, the difference is quite typical especially with mega-containership calling such as 1 and 2 callings-per-week cases. This is because a mega-containership occupies two facing berths in the indented and floating types while it occupies only one berth in the conventional type. If the mega-containership handling took one and a half of times as much time in the conventional type as in indented and floating ones.

We discussed the berth utilization by the mega-containerships in reasoning the service time tendency. We look into the berth utilization to some more extent. We define the berth occupancy rate (%), in terms of time-space resource, by the mega-containership as the following formulation:

$$\text{Berth occupancy rate (\%)} = ST \times BS \Big/ 7\text{days} \times 24\text{hours} \times \#\text{ of berths} \tag{34}$$

where

ST the staying time of mega-containerships
BS the berthing space used by mega-containerships

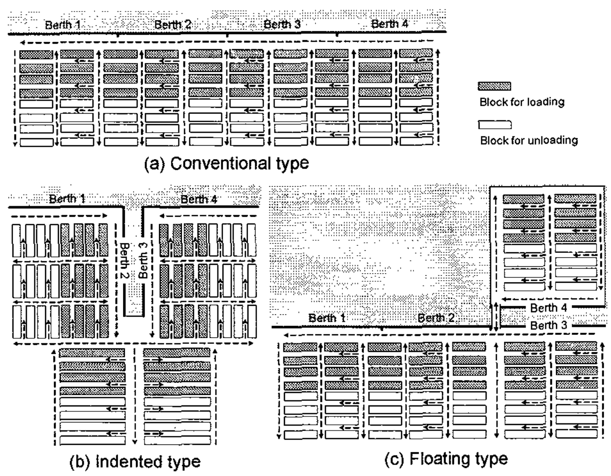

Figure 5. Corridors for yard-trailer route

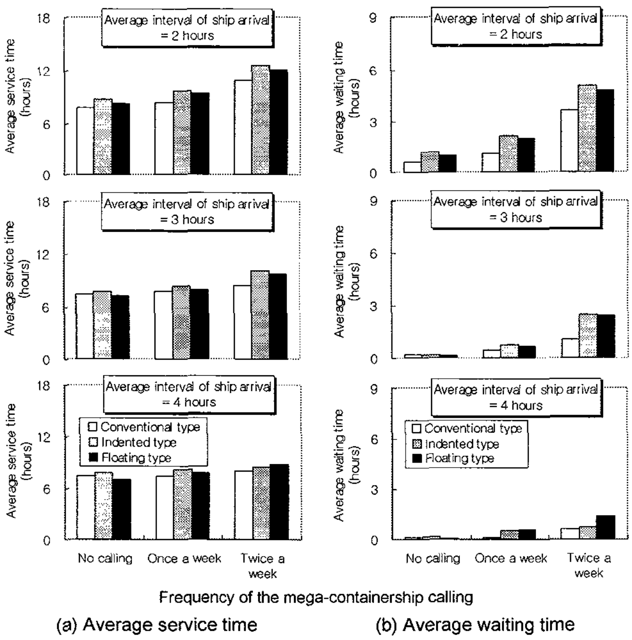

Figure 6. Service time and waiting time for feeder ships

Table 3. Berth occupancy of mega-containerships

	Frequency of the mega-containership calling	
	Once a week	Twice a week
Conventional type	8.5 %	17.0 %
Indented type	11.9 %	23.8 %
Floating type	11.9 %	23.8 %

Parameters ST and BS are 57 and 1 for the conventional type, and 40 and 2 for the indented and floating ones, respectively. Table 3 shows the occupancy rates for three types when mega-containerships call. The rate is higher for the indented and floating types than for conventional one. Therefore, the service times and the waiting times for conventional type is less than those for the indented and floating ones.

Next, we compare between the indented and floating types with the same occupancy of mega-containerships. We observe that the service times for the latter are less than those the former in most cases. This is because feeder ships can arrive and depart from berths 3 and 4 in floating type by relaxing the precedence constraints of berths 2 and 3 in indented type. Thus as mentioned above, we can get those results in cases of mega-containerships no calling and one calling per a week. However, in case of mega-containerships two calling per a week, the service times and waiting times for floating type are longer than those for the indented one in longer interval of ship arrivals.

6. Conclusion

This paper introduced a new terminal layout for mega-containerships, which is considered to be more efficient for serving mega-containership. In order to assess the capability of the floating type terminal for mega-containerships as well as small feeder services, we carried out numerical experiments for the conventional, indented and floating types of the same size. From the results, it was concluded that while the indented and floating type terminals served the mega-containership faster than the conventional one, the average service time per ship of the formers were longer than the one in the conventional type. However, when the mega-containership calls the terminal once a week, the service time for floating type terminal was shorter than that for indented one. The floating type is more efficient for an entire shipping service, which includes mega-containerships and small feeder ships.

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