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ASSESSING CAPACITY AND IMPROVING UTILIZATION OF ANCHORAGES

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ABSTRACT

Anchorage are important resources for certain hub ports, and they are increasingly in demand during peak periods. We evaluate the capacity of multiple anchorages by reproducing realistic mix of arriving vessels, dwelling time and the current practices in choosing anchoring spots within an anchorage. The model is validated by using historical data. We also propose methods for improving space utilization of anchorages. Our experiments with four real anchorages show that the space utilization is improved by 6 to 10% with MHDF and WALLPACK_MHDF algorithms. This finding opens up possibilities of designating vessel anchoring spots for improved utilizations in the future.

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1. Introduction

In 2009, over 130,000 vessels called at the port of Singapore. They included containerships, general cargo ships, oil tankers, chemical tankers, ferries, cruise ships, etc. Substantial sea space is designated as anchorage areas for various purposes. In recent years, both the traffic volume and vessel size have shown an upward trend, which is expected to continue over the next few decades. The substantial growth of marine traffic has necessitated reassessing the capacities of the existing anchorages and improving their utilization. Likewise, at the Ports of New York and New Jersey, USA, the number of vessels and their sizes has also increased in the past few years (U.S. Environmental Protection Agency 2006). The anchorage space there has frequently been filled to capacity and the Coast Guard proposes to revise the duration for vessels to stay in specific anchorage areas.

There are few published results on the capacity studies of anchorage space. In the study by Bugaric and Petrovic (2007), the anchorage is part of a river terminal system for bulk cargo operations, which has an n -vessel holding area. The anchorage system is simply modelled as a First-In-First-Out queue with a capacity of n . When the queue reaches its capacity, incoming vessels are turned away. Thus, in their study, the capacity of an anchorage is a fixed value, independent of the size of the vessels.

With most open-sea anchorages, however, an anchorage is generally a polygonal region. An anchored ship may be subject to the influence of wind, tides and currents. Hence its position (and orientation) may change over time, but confined within a circular area centred at the anchored point. Therefore, in this case, the space occupied by an anchored vessel may be represented by a disc. Its radius is the length of the vessel plus a minimum safety margin to ensure no collision between two anchored ships at all time. Thus, for the open-sea anchorages, the capacity is affected by the size of vessels and the geometry of the anchorage concerned. Figure 1 shows a few examples which may help illuminate the issues. Figures 1(a) and 1(b) show that two different mixes of vessels produce different levels of utilization in the same anchorage. Figures 1(b) and 1(c) show that two anchorages of the same size (area) but of different shapes can result in different utilization figures. Note that each ship only occupies a small area of the disc in practice.

Thus, even when discs are densely packed in an anchorage, the ships are still free to go in and out of the anchorage.

Figure 1: Different vessel mixes or different anchorage shapes can result in very different utilization

Fan and Cao (2000) presented a more realistic capacity model that may be applied to general anchorages. The capacity of an anchorage is defined as the *maximum* number of vessels that can be accommodated by the anchorage over a period of time. Their study shows that anchorage capacity is a function of the total area of the anchorage, the average percentages of each type of vessels coming to anchor, the average areas occupied by a vessel of each type and the average durations of vessel stays of each type of vessels in the anchorage.

However, in their study, only the area of the anchoring space is accounted for, and they do not keep track of the actual anchoring spots. In reality, the capacity of an anchorage does depend critically on the choices of actual anchoring spots within an anchorage. In Figure 1(b), for instance, if one vessel had occupied the centre of the anchorage, none of the other 3 vessels could have fitted in. A common code for captains and ship masters, therefore, dictates that vessels should stay close to each other in anchorages. But even so, different choices made by the same vessel mix could result in drastic differences in usable space as shown by our experiments presented in Section 9. This speaks of the need of studying the capacity of anchorages with considerations of the anchoring choices. The same applies to the physical layout of an anchorage, the vessel arrival and dwelling patterns, and mix of vessel sizes. For instance, the maximum number of vessels that can be accommodated in an anchorage is likely to be determined by the number of smaller vessels that may visit in a given period of time. An anchorage that can fit in 30 smaller vessels may be able to accommodate only 20 typical vessels. The definition of capacity in Fan and Cao (2000) thus does not reflect the space usable to typical vessels.

In our study, therefore, for a given vessel mix with arrival/dwell time and anchoring patterns, the capacity of an anchorage is defined operationally as the mean (average) utilized area when a new vessel cannot be accommodated, weighted by the time period from the rejection of the vessel to the acceptance of next vessel. After the rejection of one vessel, another one may still be accepted later because it is smaller, or because some vessel has left. Given the vessel mix and dwelling patterns, this effectively usable area can also be translated to the average number of vessels that can be accommodated in the anchorage.

Since no analytically tractable method is known for determining the capacity of anchorages, simulation-based tool will be an effective way to assess quantitatively anchorage utilization levels and to evaluate anchorage capacity. Such a tool will be very useful for (1) assessing whether the existing anchorage space is adequate for future scenarios, (2) evaluating the effects of changing the configuration of the anchorages and/or changing the policies for anchoring, and (3) optimizing space utilization under different operating conditions.

A computer simulation-based planning tool is thus developed. Using this tool, we are able to provide quantitative information about instantaneous, average and maximum anchorage utilizations. The tool allows the user to specify various vessel mixes, vessel arrival patterns, and current or future planned anchorage configurations. The model of the existing practice was validated by setting various relevant parameters of the model with

suitable values and comparing simulation results with the corresponding statistics based on a set of historical data in Singapore.

Using the simulation tool, we are able to investigate the use of disc (or circle)-packing algorithms in optimizing the allocation of space to vessels in an anchorage. Our simulation tool, which emulates realistic vessel arrivals and the choices of anchorages by shipping agents in the current practice, reproduces the existing operating conditions and helps us evaluate the performance of circle packing algorithms in such conditions.

Although the problem of packing non-equal discs in a rectangular area is similar to allocating space to vessels in an anchorage, two features make them different: while the discs are normally given in a batch, vessels usually come one at a time; moreover, while there is hardly any issue of departure or un-packing in the context of disc packing, vessels do leave the anchorage after a duration of time where the departure time is not precisely predictable. These two features also make our problem different from the ship lock optimization problem described in (Verstichel and Berghe, 2009), although there are certain degrees of similarity. In the ship lock optimization problems, ships are represented by rectangular shapes and they are packed into rectangular chambers all at once.

We adapted two disc packing algorithms and incorporated vessel departures. We found that both algorithms can improve the space utilization of anchorages. This finding opens up possibilities of improving anchorage utilization by designating vessel anchoring spots, which may be a feasible option for managing anchorages in the future.

The remaining parts of this paper are organized as follows. We first briefly review some disc packing algorithms in Section 2. Then a typical anchorage system and practice in port cities are introduced in Section 3, which is followed in Section 4 by the description of the architecture of the simulation tool built for anchorage capacity study. The vessel arrival generator, the vessel dispatcher and the anchorage manager of the simulation tool are presented in Sections 5, 6 and 7 respectively. Section 8 describes the evaluation of the simulation tool. Section 9 presents the adapted disc packing algorithms and evaluate their performance in anchorage space utilization against the current practice in four experiments with real anchorages. Section 10 summarizes the findings and suggests a few possible directions for future research.

2. Algorithms for Packing Discs

The problem of packing discs into a rectangular container may be formulated as follows.

Consider a rectangle with width W and height H and a set of n discs with radius $r_1, r_2, \dots, r_n$, respectively. Suppose the centre of the rectangle is at $(0, 0)$. Find, if possible, the centre coordinates $(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)$ of n discs satisfying the following constraints:

- i. $\frac{H}{2} - y_i - r_i \geq 0 \quad i \in \{1, \dots, n\}$
- ii. $\frac{H}{2} + y_i - r_i \geq 0 \quad i \in \{1, \dots, n\}$
- iii. $\frac{W}{2} + x_i - r_i \geq 0 \quad i \in \{1, \dots, n\}$
- iv. $\frac{W}{2} - x_i - r_i \geq 0 \quad i \in \{1, \dots, n\}$
- v. $\sqrt{((x_i - x_j)^2 + (y_i - y_j)^2)} - r_i - r_j \geq 0 \quad i \neq j, i \in \{1, \dots, n\}, j \in \{1, \dots, n\}$

Constraints i to iv ensure that discs remain entirely inside the rectangle and constraint v ensures that discs do not overlap each other.

There are existing algorithms for placing n non-equal sized discs into a rectangle. Before we present the Maximum Hole-Degree algorithm, we first introduce some definitions.

Definitions

Corner placement

Given a configuration C , a *corner placement* of a disc c_i outside the rectangle is the placement of c_i into the rectangle so that c_i touches two *items* without overlapping other already placed discs. Here, an *item* may be a side of the rectangle or another disc.

Hole Degree of a Corner Placement

Let $p(c_i, x, y)$ denote a corner placement of a disc c_i whose centre is at (x, y) , and let u and v be the two items (disc or side) touching c_i . The hole degree of the corner placement $p(c_i, x, y)$ is defined as:

$$\lambda = 1 - \frac{d_{min}}{r_i}$$

where r_i is the radius of c_i , and d_{min} is the minimal distance from c_i to the other items excluding u and v .

The Maximum Hole Degree algorithm (Huang et al, 2005) starts by putting two discs at two corners of the rectangle and packs the remaining discs one by one. To place a disc c_i , it will select the corner placement $p(c_i, x, y)$ with the maximum hole degree at position (x, y) . If all discs are packed into the rectangle without violating constraints (i) - (v), the algorithm terminates with success. If a failed configuration is reached, it will try the next pair of discs as the beginning configuration. If all pairs of discs have been tried but no successful configuration is found, the algorithm stops with failure. Clearly, this approach is applicable to packing discs into polygons as well, which makes it very suitable for anchorages of different shapes. We will present our customization of this algorithm for allocating space for vessels in Section 9.

There are algorithms where the packing decision will look ahead to consider discs that are not packed yet (Huang et al., 2005 and Kubach et al., 2009). The objective is to make a packing decision that will lead to a better overall result at the cost of more computations. Intuitively, this look-ahead strategy should yield better packing results. Unfortunately, it will be of limited use to non-batched, individual vessel arrivals, which happen to be the common case. Even though it is possible to predict vessel arrivals in the next few hours since vessels usually inform the port authorities a few hours before their arrivals, accurate prediction of vessel departure time is difficult. This means a simplistic look-ahead strategy that uses the predicted arrivals is unlikely to produce good results in practice.

George et al. (1995) presented several algorithms for packing discs into a rectangle based on a number of heuristic rules. These rules include (i) Rank and use discs from the largest to the smallest; (ii) Pack larger discs in the corners of the rectangle; (iii) Pack discs near the edges and corners of the rectangle; (iv) Move all discs successively as far as possible to the sides of the container; (v) Pack discs with the same diameter together; (vi) Maintain stable configurations of discs; (vii) Select position for discs using randomization. Based on the rules, algorithms SAMEPACK, WALLPACK, STABLE 1, STABLE 2, GENETIC and RANDOM are proposed. Each algorithm uses a subset of the heuristic rules. Among them, WALLPACK, GENETIC and RANDOM have been shown to produce packing results closest to the target solution and consume less computational time than the other algorithms. The WALLPACK algorithm packs discs one at a time, whereas the other algorithms consider discs in a batch and may move a disc from its first assigned location later in order to leave more space to unassigned disc(s). Because it is not practical to ask a vessel to move to a new location after it has anchored, we adapt the WALLPACK algorithm for allocating space for vessels. The adapted algorithm will be presented in Section 9.

3. A Typical Anchorage System

Generally, vessels visit a port for various purposes, such as taking bunkers, going to shipyards for repair, loading and unloading of cargo at a terminal and/or a combination of these purposes. Some vessels may go to an anchorage before visiting the terminal/shipyard,

whereas others may do so after visiting the terminal/shipyard. There are also vessels making more than one visits to anchorages for different purposes without paying visits to terminals or shipyards.

Figure 2: Anchorage areas in Singapore

In a port there may be a few areas that are designated for anchoring vessels (e.g. the Port of Singapore in Figure 2) and these areas may be further divided into a number of anchorages of different shapes and sizes. Each anchorage also has a maximum depth that limits the vessels that can anchor in it. Some of the anchorages are reserved for vessels in certain gross tonnage (GT) groups. Anchorages may be categorized to serve different types of vessels with different purposes of visit. Typically, shipping agents choose anchorages for their vessels before they arrive in the port. They take into consideration a few factors like the vessel's purpose of visit, the vessel's type, draft, gross tonnage, the location of the vessels' entry/exit points into/from the port and the locations of the terminals/shipyards they visit.

After a vessel arrives in the port, the pilot or vessel captain chooses an anchoring position in the anchorage when the vessel needs to go into the anchorage. If the anchorage of the vessel's choice is full, the pilot or the captain will choose another anchorage which is designated to provide space for the same type of vessels. There is no restriction on the duration that a vessel is allowed to stay in an anchorage.

To model the real-world scenario, we carried out careful examination of the historical vessel data of a port and extracted patterns and statistical distributions of vessel calls, vessel visits to anchorages, arrival times and dwell times in anchorages.

4. Architecture of the Simulation Tool

Figure 3 shows the architecture of the simulation system built for the anchorage capacity study. The system consists of a vessel arrival generator for generating vessel arrivals to anchorages, a vessel dispatcher for simulating incoming vessels' choice of anchorages, and for each anchorage there is an anchorage manager for emulating pilots' decisions to choose anchoring positions for incoming vessels in each individual anchorage. At the front end, there is a graphical user interface (GUI) for the user to specify the simulation parameters and the anchorage specification. There is also an output GUI for displaying the utilization status of individual anchorages during simulation runs and the output statistics after simulation runs.

Figure 3: System Architecture

Through the GUI, the simulation tool allows the user to input the total number of vessel calls for the period of the simulation and the distribution of calls among the different vessel types. The user is also able to specify different anchorage configurations. The dimensions, depth, and usage for each anchorage and the distance between any two anchorages can also be defined. Each anchorage is a polygonal shape. Within an anchorage, the depth may be different in different parts of the anchorage. Existing anchorages can be removed and new anchorages can be added.

The output statistics include

- Instantaneous utilization, indicating the occupancy of an anchorage at time instance t :

$$U_t = \frac{\sum_i Space_i}{Area} \quad (1)$$

where i is the index of vessels that anchor at the anchorage at that point of time; $Space_i$ denotes the space taken by vessel i and $Area$ denotes the area of the anchorage.

- Average utilization, indicating the occupancy of an anchorage over the time period of interest:

$$U_a = \frac{\sum_i Space_i \times Dwell_i}{Area \times Duration} \quad (2)$$

where i is the index of vessels that anchor at the anchorage during the period; $Space_i$ denotes the space taken by vessel i and $Dwell_i$ denotes its dwell time at the anchorage; $Area$ denotes the area of the anchorage and $Duration$ denotes the simulation time period of interest, e.g. a day or a month.

- Number of overflows, indicating the occurrences when no suitable anchorage space can be allocated to a vessel. It is an indicator of the extent the anchorage space is packed and in order to accommodate such “extra” vessels, certain anchoring rules have to be violated in actual operations.

5. Vessel Arrival Generator

The demand on anchorages of a port is driven by the arrivals of vessels calling at the port. However, not all vessels calling the port need anchorage space. Meanwhile, some vessels call at anchorages more than once during a visit. It is of practical importance to relate the number of vessel calls at a port to the number of vessel visits to its anchorages. The correlation between the two can be analyzed from historical data. Therefore the first component in modelling vessel arrivals to anchorages consists of a translation mechanism that maps the number of vessel calls to the demand on anchorages, that is, the number of arrivals at anchorages. The second component is a Non-stationary Poisson Process that assigns an arrival time to each generated vessel.

In the analysis of historical data of a port as an example, the relationship between the number of vessel calls and the number of visits to anchorages is established by regression analyses and we get, for each type of vessels:

$$y = a * x^b \quad (3)$$

where y is the number of vessel calls at anchorages and x is the number of vessel calls at the port of a particular type of vessels. For different types of vessels, the values of a and b are different. Based on the historical data we have, a varying from 0.23 to 1.22 and b from 0.98 to 1.30. With the knowledge of this correlation, it is possible to predict the demand on anchorage space based on the predicted number of vessel calls to the port.

Vessel attributes like the vessel length, gross tonnage and draft are expected to affect the anchorage utilization. So they also need to be generated for each vessel based on the historical distribution of each vessel type. The distributions of vessel lengths of the vessels in the historical data are analyzed. It is also found through data analysis that for each type of vessels, vessel gross tonnage and vessel draft are both related to the length of the vessel by Equation (3) with different values for parameters a and b . With the generated vessel length, the vessel draft and gross tonnage can be generated for each vessel, based on the correlation found between them in the historical data.

Table 1: Comparing generated demand on anchorage with historical data.
TA: Oil Tankers; VLCC: Very Large Crude Carriers; CH/LPG/LNG: Chemical/Liquefied Petroleum Gas/Liquefied Natural Gas Carriers; FR: General Cargo Carriers; CO: Coasters; BA: Barges; CNTR: Container Vessels; BC: Bulk Carriers; BK: Bunkers.

Vessel type	% difference	Vessel type	% difference	Vessel type	% difference
TA	1.3	FR	2.0	CNTR	0.7
VLCC	-1.4	CO	6.4	BC	-0.3
CH/LPG/LNG	-0.2	BA	-0.7	BK	0.6

Table 1 shows the percentage differences between the generated numbers of arrivals to anchorages for each type of vessels and the numbers from the port’s historical data in 2006. This indicates the success of the translation scheme that maps vessel calls to the demand on anchorages.

Arrival of vessels to a port is a complicated dynamic process that is dependent on shipping lines’ planning and is very sensitive to economic fluctuations. For individual shipping lines that operate in a container terminal, or individual oil or chemical terminals

which practice stock control (Van Asperen, 2003), their vessel arrivals at a terminal are generally scheduled and are not a random process individually. However, for an international hub port, multiple shipping lines are operating in multiple terminals. The distribution of the *combined* inter-arrival times of all the vessels of a certain type becomes random. In addition, the unpredictable weather conditions and possible delays in service by other ports of call further randomize the arrivals. Statistical tests on the historical data confirmed that the inter-arrivals for each vessel type agreed reasonably well with the exponential distribution. So the Poisson distribution for the arrival process is used in our study. The values of the distribution parameters are set according to historical distributions. The simulation model can accept other distributions for vessel arrivals. We, however, only used Poisson distribution in our experiments.

Figure 4: Process of choosing an anchorage for a vessel

6. Vessel Dispatcher

As described in Section 3, shipping agents often choose anchorages for their vessels. Therefore the role of the vessel dispatcher is to simulate the shipping agent's choice of anchorage for its incoming vessel. Modelling vessels' choice of anchorages is complicated, because a number of parameters have to be taken into consideration, for example, purpose of vessel call, vessel type, vessel gross tonnage and vessel draft. Moreover, each type of vessel may choose any of a few candidate anchorages. There are no fixed regulations and rules for the selection among these candidates so it may be based on agents' preferences. The agents' preferences are unknown to us. It is unrealistic to summarize a comprehensive set of rules that emulate the preference of clients when they select among the candidate

anchorages. There are also some unforeseen circumstances in actual operations that would affect the choice of anchorage.

Therefore, our experiences are that it is difficult to apply ad hoc rules to emulate their (agent, pilot, control centre) anchorage choices. An alternative is to mine the historical data of a port to figure out how its main anchorages were used as the end results of their choices. The probability (weightage) distribution for each type of vessels in choosing various anchorages is obtained. The process of choosing an anchorage based on these probabilities for a vessel is shown in Figure 4. As a result, the Vessel Dispatcher distributes a realistic vessel mix to each of the anchorages.

7. Anchorage Manager

In most ports, pilots and captains are free to choose the anchoring positions for their vessels in an anchorage. Therefore the role of the anchorage manager in the simulation tool is not to assign anchoring positions for vessels but to simulate the pilots' decisions in choosing an anchoring position. We present an algorithm here to simulate how pilots choose an anchoring position in an anchorage.

When a vessel anchors in an anchorage, the space it occupies is more than the width and length of the vessel. Due to wind and current, a vessel may be at different positions at different time within the space of a disc. A minimum safety clearance also needs to be maintained between any two anchoring points at all time. So each vessel will occupy a circular space with a radius of the length of the vessel plus half the minimum safety clearance. In this way, the distance between the two anchoring points is at least the sum of the two vessels' length plus the minimum safety clearance.

Figure 5: Four typical anchoring scenarios

In a hub port where anchorage space is highly contested, pilots and captains usually anchor their vessels close to at least one of the anchored vessels, so that the anchoring space is better utilized than if a completely random position is chosen. Four typical anchoring scenarios are discussed for elaborating how anchoring positions are decided in the system based on the usual practice of the pilots and captains. Figure 5 shows these scenarios where a solid-boundary disc represents a vessel that has already anchored, and a dash-boundary disc represents the candidate choices for anchoring an incoming vessel. The four scenarios are

- Type 1: *vessel-side corner* formed by a border line of the anchorage and an existing vessel.

- Type 2: *single-vessel cut* is a position next to one existing vessel only.
- Type 3: *two-vessel corner* formed by two existing vessels.
- Type 4: *two-side corner* formed by two border lines of the anchorage.

In a survey conducted among 10 pilots (experienced and not so experienced), it was found that about 50% of them preferred Type 1, 20% preferred Type 2, another 20% preferred Type 3, and the remaining 10% preferred Type 4. Therefore the distribution was applied to the simulation tool when modelling the pilots' choice for anchoring positions for these typical scenarios. This is shown in Figure 6.

Figure 6: Anchoring algorithm (Current Practice)

8. Evaluation of Simulation Model

To evaluate whether the system works correctly and models the current practice accurately, we use the historical data of a port as an example. We set the simulation parameters to suitable values and configure the anchorages accordingly. The yearly average utilizations of individual anchorages were used as the indicators for comparing the outputs of the simulation tool with historical statistics. Figure 7 summarizes the results.

Most of the utilization figures for the 34 anchorages of various shapes from system output fit well with the historical averages. Note that in Section 5, we have confirmed that the generated numbers of arrivals to anchorages for each type of vessels match the numbers from the historical data. It was therefore accepted that if the parameters of the simulation tool are set correctly, it is able to emulate the operations of an anchorage system well. In the Introduction, we pointed out that the capacity of an anchorage is affected by the vessel mix and the choices of actual anchoring spots within the anchorage. Our anchorage utilization results show that the Vessel Arrival Generator, the Vessel Dispatcher and the Anchorage Manager together simulate realistically the mix of arriving vessels and the choices of anchoring spots of vessels. This provides us an accurate benchmark for evaluating methods of improving anchorage utilization and capacity. For example, by replacing the current practice in the Anchorage Manager with a new space allocator, we can evaluate against current practice its effectiveness in improving anchorage capacity while still allowing shipping agents' freedom to choose which anchorage to use.

Figure 7: Comparing System Output and Historical Statistics

9. Improving Anchorage Utilization via Disc Packing Algorithms

With the same vessel mix and arrival pattern for an anchorage, space utilization will depend on the way anchoring positions are chosen. We adapted the Maximum Hole Degree First algorithm (MHDF) for our use. While the original algorithm will choose the disc with the maximum hole degree each time from discs yet to be packed, we choose a location that yields the maximum hole degree for the vessel that arrives at an anchorage. The algorithm is shown in Figure 8.

We also combined the WALLPACK algorithm and the MHDF to allocate space for vessels as they arrive at the anchorage. The main principles of the original WALLPACK algorithm are to pack larger circles in the corners of the rectangle and to pack circles near the edges and corners of the rectangle. We use these same principles but, among the locations that are near the edges of the rectangle, we choose a location that yields the maximum hole degree. The algorithm, called WALLPACK_MHDF, is shown in Figure 9.

```
// called when a vessel arrives at an anchorage

1. Find all two side cut corner positions;
2. Find all vessel side cut corner positions;
3. Find all two vessel cut corner positions;
4. Allocate a position with the largest hole degree to the vessel, exit;
5. Report anchorage full.
```

Figure 8: The adapted MHDF Algorithm

```
// called when a vessel arrives at an anchorage

1. If a two-side cut corner position is available, allocate the space to the vessel, exit;
2. If one or more vessel side cut corner positions are available, allocate a position with the largest hole degree to the vessel, exit;
3. Find all two vessel cut corner positions, allocate a position with the largest hole degree to the vessel, exit;
4. Report anchorage full.
```

Figure 9: The WALLPACK_MHDF algorithm

Experiments are conducted to compare the performance of Current Practice (CP) shown in Figure 6, the MHDF Algorithm shown in Figure 8 and the WALLPACK_MHDF algorithm shown in Figure 9. We evaluate their performance in the maximization of the utilization of anchorage space. Monthly utilization of the anchorage space is calculated according to Equation (2). Experiments are conducted with four real anchorages A, B, C and D respectively shown in Figure 10. It can be seen that these anchorages have different shapes and sizes. In each of the four experiments, we generate high but realistic vessel traffic to one anchorage by disabling all other anchorages. So all associated vessels will be

directed to this particular anchorage. Each experiment was run over a total of 21 months and the average monthly utilizations with 95% confidence intervals are given in Table 2.

Table 2: Comparison among anchoring algorithms

Average monthly space utilization(%)	Current Practice(CP)	MHDF	WALLPACK_MHDF
Anchorage A	58.3038±0.2052	63.7681±0.1116	64.6519±0.1142
Anchorage B	59.2457±0.1732	62.8219±0.1144	63.7795±0.1161
Anchorage C	58.4514±0.1474	63.0181±0.1276	64.1895±0.1098
Anchorage D	58.2743±0.1677	63.3167±0.1117	62.8829±0.1232

Table 3: Percentage improvement of space utilization of anchoring algorithms over current practice

	MHDF	WALLPACK_MHDF
Anchorage A	9.4	10.9
Anchorage B	6.0	7.7
Anchorage C	7.8	9.8
Anchorage D	8.7	7.9

Figure 10: Anchorages (from top) A, B, C and D

The results of all the four experiments show that it is possible to improve the average space utilization by using either MHDF or WALLPACK_MHDF. Table 3 shows the percentages improvement in space utilization of MHDF and WALLPACK_MHDF over the current practice. MHDF improves the space utilization from the current practice by between 6.0% and 9.4% while WALLPACK_MHDF by up to 10.9%. This means the proposed algorithms are able to increase the effective usable space in an anchorage and therefore increase its capacity. Figures 11, 12 and 13 show the snapshots of Anchorage A. Clearly, MHDF and WALLPACK_MHDF are able to pack the vessels closer to each other. This leads to less space wasted in between the vessels and higher efficiency in using the available space. This also confirms that different choices of the same vessel mix could result in drastic differences in usable space. The difference between MHDF and WALLPACK_MHDF can be explained by this: MHDF favours a position closer to existing vessels and will put a vessel into a ‘hole’. This may waste some space unless the hole is a perfect fit. WALLPACK_MHDF favours the corners and the edges of the anchorage where another vessel may be packed next to the current one later. In such situations, WALLPACK_MHDF wastes less space and therefore performs better.

Figure 11: A snapshot for Current Practice (Anchorage A)

Figure 12: A snapshot for MHDF (Anchorage A)

Figure 13: A snapshot for WALLPACK_MHDF (Anchorage A)

It is observed that in the current practice, vessel captains choose the anchoring positions in an anchorage. Our study shows that using the proposed algorithms will achieve better space utilization which may allow more vessels to use the anchorages. The change required in practice can be implemented without much difficulty or inconvenience to vessels. The shipping agents are still free to choose the anchorage they want to use, usually one that is near the vessel's entrance or exit point from/to her ocean journey, or one that is near the terminal/shipyard to be visited by the vessel. Instead of choosing an anchoring spot, a vessel could receive from the port administrator the latitude, longitude specification of the assigned anchoring point when arriving at the anchorage and anchor there. Since the

algorithms choose anchoring positions next to existing anchored vessels, it is not difficult to anchor at the assigned spot with reference to these vessels.

Note that, in the preceding experiments, we still allocate space incrementally, i.e., only when a vessel arrives at the anchorage. We expect greater improvements if advanced booking of space can be done with the reasonably accurate predictions of the departure times of vessels already anchored. This could be a future research topic.

10. Concluding Remarks

We have presented a study of the capacity of anchorages with a new definition of capacity which, we believe, is more realistic. We evaluate the capacity of multiple anchorages by reproducing realistic mix of arriving vessels, dwelling time and the current practices in choosing anchoring spots within an anchorage. This is achieved by a reconfigurable tool we built. The tool allows the user to input various vessel mixes and traffic volumes for current or future scenarios for an international hub port with multiple anchorages. It also allows the user to specify alternative anchorage configurations, e.g., to add, remove or change the sizes and shapes of the anchorages. Different practices of choosing anchoring positions can also be experimented easily.

Our system proves to be a useful decision support tool for assessing the impacts of different vessel demands, anchorage configurations, anchoring practices and policies. Using this tool, we conducted experiments with four real anchorages of different shapes and sizes. The results show that the space utilization can be improved by allocating anchoring positions to vessels by using our adapted MHDF and WALLPACK_MHDF algorithms. This finding opens up possibilities of improving anchorage utilization by designating vessel anchoring spots, which may be a feasible option for managing anchorages in the future.

Future work may include investigations into a look-ahead approach in allocating anchoring points to vessels, together with estimated vessel departure time. Another direction is to study various ways of dispatching vessels to the given anchorages to optimize space utilization in the multi-anchorage system.

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