

# ANCHORAGE CAPACITY ANALYSIS USING SIMULATION

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## ABSTRACT

With the substantial growth in marine traffic, anchorage space is now in high demand in certain hub ports. To provide decision support for port authorities, we have analyzed the usage of anchorages in recent years. The demands on the anchorages arise from the dynamically changing vessel mix and similarly complex service patterns. The utilization and the capacity of an anchorage space also depend heavily on the dispatching and allocation rules as well as the shape and areas of the anchorage. The complexity of the system studied is therefore beyond the current analytical tools, and hence simulation provides an effective means for the study. In this paper, we present a simulation-based capacity analysis on anchorages. The simulation model built is able to match the current scenarios well, and the analysis by simulation proves very useful in assessing anchorage utilization and capacity for future scenarios.

Keywords: Decision support system, Anchorage capacity, Circle packing, Model development

## 1. INTRODUCTION

The Straits of Singapore play host to an average of about 140,000 vessels annually. These include containerships, general cargo ships, oil tankers, chemical tankers, ferries, cruise ships and many more. Vessels of different lengths, tonnage and carrying different types of cargoes enter Singapore Straits and navigable sea space has to be allocated as anchorage space for vessels that require mooring space for various reasons. In recent years both vessel traffic volume and vessel size have shown an upward trend and are expected to increase significantly over the next few decades. It means that the demand on anchorage space will escalate as well. Similar to Singapore, in the Port of New York and New Jersey, the number of vessels has increased and their sizes have grown in the past few years (U.S. Environmental Protection Agency 2006). The anchorage space has frequently been filled to capacity and the Coast Guard proposes to revise the duration vessels are authorized to anchor in specific anchorage areas.

There are few published results on the capacity studies of anchorage space. In Bugaric and Petrovic (2007), the anchorage as part of a river terminal for bulk cargo unloading is simulated where the anchorage is an n-vessel holding area. The anchorage is abstracted as a First-In-First-Out queue with a capacity of n. When the queue reaches its capacity, incoming vessels are turned away. A vessel will leave the queue when a berth is free at the terminal. Fan and Cao (2000) presented a capacity model for an anchorage. 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. The 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.

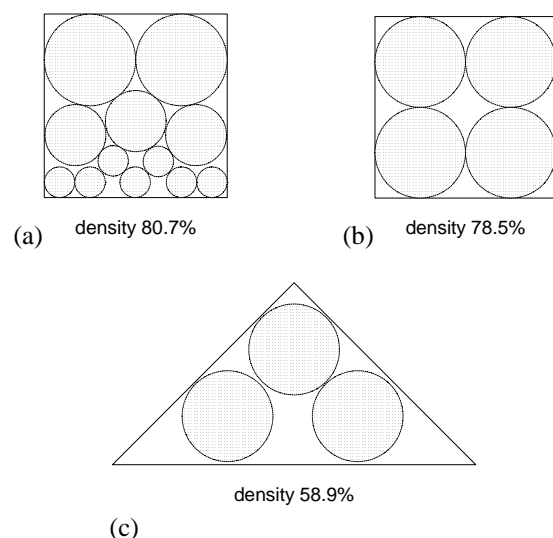


Figure 1: Different vessel mixes or different anchorage shapes can result in very different utilization results.

In actual operations, vessels of different types and sizes come and leave anchorages at all times and therefore the vessel mix in anchorages are changing dynamically. It follows that anchorage utilizations change all the time. Different vessel mixes with regard

to sizes are able to effectively utilize the same anchorage space to different degrees. Figures 1(a) and 1(b) show two vessel mixes producing different utilization results in the same anchorage. A vessel mix may be accommodated into an anchorage with no problem but the same vessel mix may not be able to fit into another anchorage of the same area size but of a different shape. Figures 1(b) and 1(c) show two anchorages with the same area but different shapes result in different utilization figures. This means statistics of averages of various measurements will not present a clear picture about peaks and lulls of the demand and anchorage utilizations and therefore cannot be used as evidence of enough space meeting the demand.

A simulation-based tool will be the most effective way to assess quantitatively anchorage utilization levels and to evaluate anchorage capacity. Such a tool will be very useful for assessing whether the existing anchorage space is adequate for future scenarios. The tool will also be useful in evaluating whether changes in the configuration of the anchorages and/or changes in certain policies or practice are effective to satisfy the demand on anchorage space without allocating more physical space.

We define that an anchorage has reached its capacity if the probability of having  $n$  or more vessels not able to find anchorage space is greater than a limit  $p$ . Both  $n$  and  $p$  will be specified by the managing authority of the anchorage.

A computer simulation based planning tool was developed. Using this tool, we are able to provide quantitative information about instantaneous, average and maximum anchorage utilizations. We also analyze the probabilities of vessel overflows, that is, the probabilities of having vessels turned away because there is insufficient space in the anchorages. The management of the anchorage space may decide that the demand on anchorage space has exceeded its capacity when the probability of having at least a certain number of vessels turned away is more than a threshold value. The tool also allows us to conduct experiments to evaluate the effectiveness of different anchorage configurations when space allocated for certain types of vessels is found not enough. The tool allows the user to specify various vessel mixes, vessel arrival patterns, and current or future planned anchorage configurations. The simulation of the typical practice was validated by setting simulation parameters with suitable values and comparing simulation results with the corresponding statistics based on a set of historical data in Singapore.

The rest of the paper is organized as follows. Section 2 introduces a typical anchorage system and practice in port cities. It is followed by the description of the architecture of the simulation tool for anchorage capacity study in Section 3. Then Sections 4, 5 and 6 present the vessel arrival generator, the vessel dispatcher and the anchorage manager respectively. Section 7 describes the evaluation of the simulation tool. Section 8 presents a method to assess what the

space utilization is like when an overflow occurs at an anchorage. Section 10 concludes our work.

## 2. A TYPICAL ANCHORAGE SYSTEM

Generally, vessels come to 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 go to an anchorage before visiting their terminal/shipyard and some do so after visiting the terminal/shipyard. Other vessels will visit an anchorage without going to any terminal/shipyard. Some vessels make multiple visits to anchorages for multiple purposes with or without visits to terminals or shipyards. Bunker vessels visit other anchorages to provide bunker services to other vessels and visit terminals to refill bunker supplies in between their stay in the home anchorages.

In the whole port there may be a few areas that are designated for anchoring vessels 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. These anchorages are 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 a vessel is allowed to stay in an anchorage.

A careful examination of the historical vessel data of a port is carried out to extract patterns and statistical distributions of vessel calls, vessel visits to anchorages, arrival times and dwell times in anchorages.

## 3. SYSTEM ARCHITECTURE

Figure 2 shows the architecture of the simulation system. 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.

Through the GUI, the 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. Existing anchorages can be removed and new anchorages can be added.

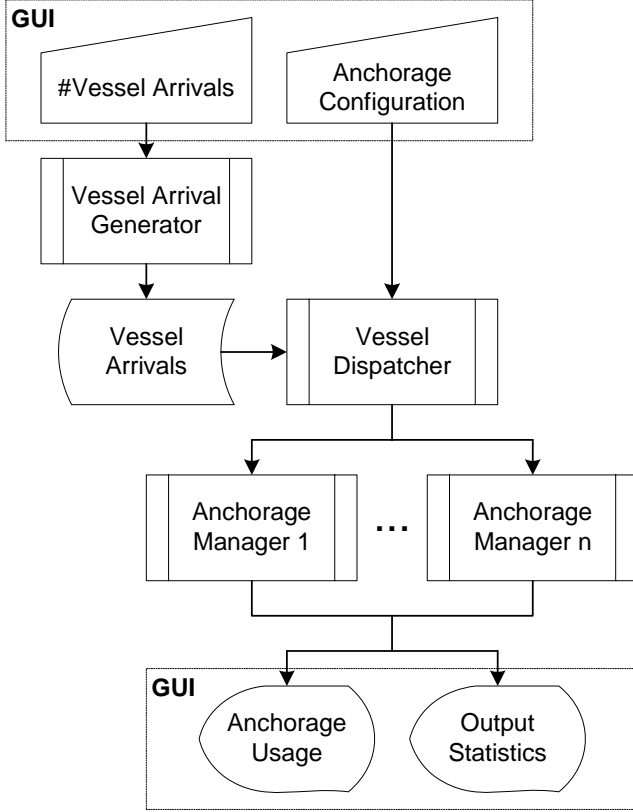


Figure 2: System Architecture

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 corresponding 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.

#### 4. 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 modeling 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. 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 generated vessel according to historical distribution of each vessel type. The distributions of vessel lengths can be obtained from analysis of historical data. 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 (1) with different parameter values for  $a$  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 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.

Table 1: Comparing generated demand on anchorage with historical data

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

Different distributions may also be specified by the user through the input GUI if it is necessary.

Arrival of vessels to a port is a complicated dynamic process that is dependent on shipping lines' planning and is very sensitive to economic activity fluctuations. Considering the whole port as a complete service facility, the arrival process would be best modeled as a Poisson process. This is based on the facts that: (1) even though the arrivals of individual vessels are scheduled, when the vessel traffic to the whole port is considered, the distribution of the inter-arrival times becomes random and fits well the exponential distribution; (2) the unpredictable weather conditions and possible delays in service by other ports of call further randomize the arrivals. Statistical tests on 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 suitable in our study.

## 5. VESSEL DISPATCHER

As described in Section 2, shipping agents 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. Modeling vessels' choice of anchorages is complicated, as 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. Agents' preferences are unknown to us, may be numerous and may not be general. 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, instead of applying rules to emulate their (agent, pilot, control centre) anchorage choices, we

propose to mine the historical data of a port to figure out how its main anchorages were used as the end results of their choices. From the mining results, the probability (weightage) distribution for each type of vessels in choosing various anchorages can be obtained and the process of choosing an anchorage based on these weightages for a vessel is shown in Figure 3.

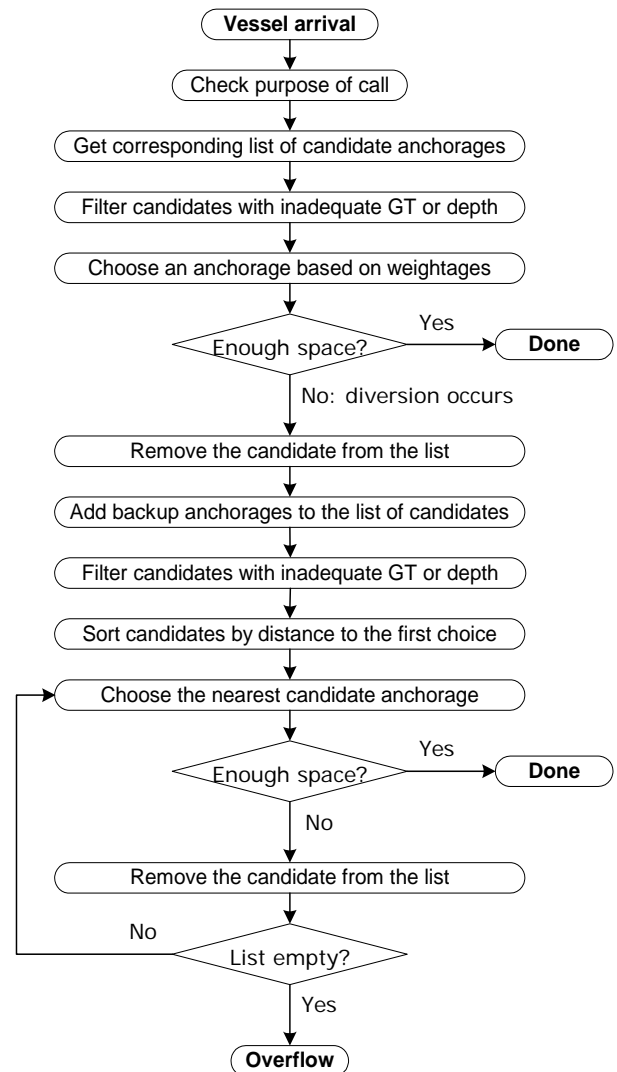


Figure 3: Process of choosing an anchorage for a vessel

## 6. VESSEL DISPATCHER

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 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 times within the space of a circle. A minimum safety clearance also needs to be maintained between any two anchoring points at all

times. 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.

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 4 shows these scenarios where a solid-boundary circle represents a vessel that has already anchored, and a dash-boundary circle 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.

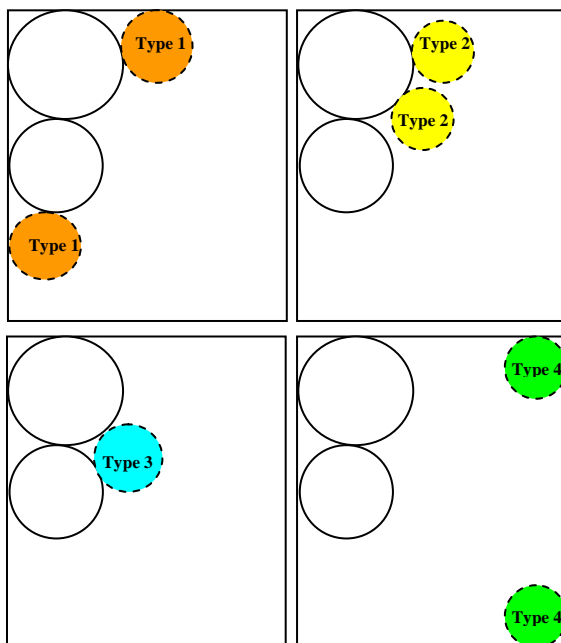


Figure 4: Four typical anchoring scenarios

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 modeling the pilots' choice for anchoring positions for these typical scenarios. This is shown in Figure 5.

## 7. EVALUATION

To evaluate whether the system works correctly and 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 6 summarizes the results.

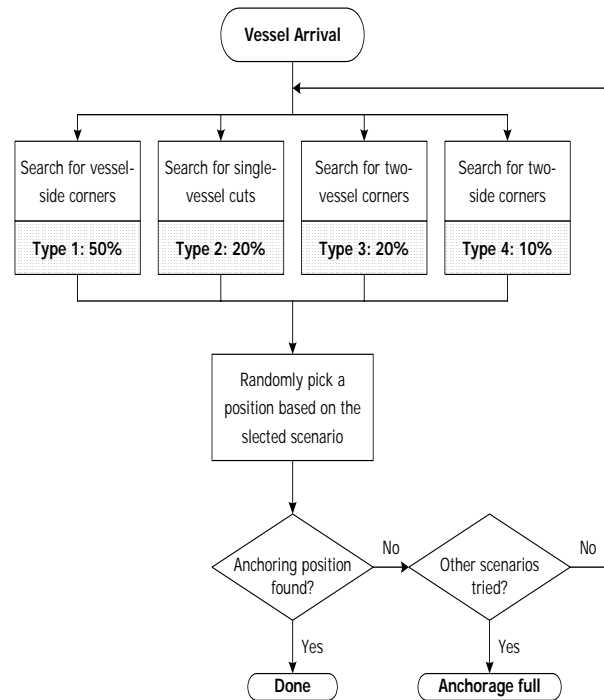


Figure 5: Anchoring algorithm

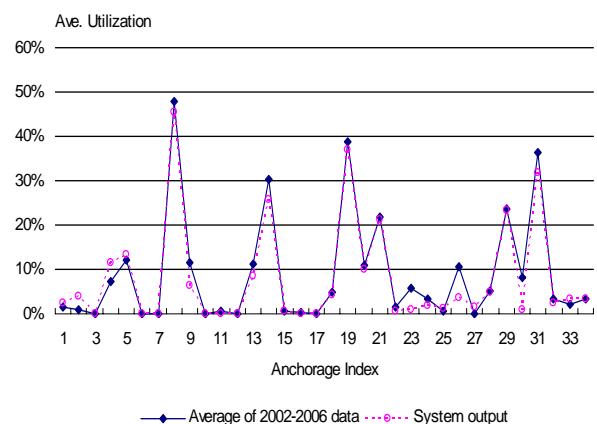


Figure 6: Comparing System Output and Historical Statistics

Most of the utilization figures from system output fit well with the historical averages. Note that in Section 4, 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 is set correctly, it is able to emulate the operations of an anchorage system well.

## 8. ASSESSING SPACE UTILIZATION NEAR CAPACITY

The space taken by a vessel in an anchorage is represented as a circle with the vessel length plus a safety margin as the radius and to ensure safety, any two circles are not allowed to overlap. This means that the maximum utilization of an anchorage is lower than 100%. For example, in a scenario illustrated by Figure 7, the anchorage cannot accommodate any vessels longer than 120m, although its utilization at that point is 61.55%. However it is able to accommodate smaller vessels by filling them in the gaps in between existing vessels. Therefore, the achievable maximum utilization of an anchorage is decided by a few parameters, namely anchorage size, shape and vessel mix (of size), while vessel mix is the combined effect of anchorage dispatching rules and vessel arrival patterns. As these parameters vary in different anchorages, there is no single maximum utilization figure applicable to all anchorages. Assessing space utilizations near capacity for anchorages of different shapes and sizes, and receiving different vessel mix, is of great importance in evaluating anchoring space usage under future traffic scenarios.

Table 2: Space utilization when overflow occurs

Utilization	Percentage	Utilization	Percentage
5%	0.00%	55%	20.24%
10%	0.00%	60%	48.57%
15%	0.00%	65%	24.26%
20%	0.00%	70%	0.80%
25%	0.00%	75%	0.00%
30%	0.00%	80%	0.00%
35%	0.02%	85%	0.00%
40%	0.14%	90%	0.00%
45%	0.99%	95%	0.00%
50%	4.97%	100%	0.00%

Assessing space utilization near capacity mainly involves two tasks, namely, generating high but realistic vessel traffic to individual anchorages so as to create sufficient and representative overflow instances, and recording the instantaneous utilization at the points of overflow. One simple way to generate such traffic is by disabling all but one anchorage so that all associated vessels will be directed to that particular anchorage. As an example, Table 2 summarizes the overflow instances at one of the anchorages. Columns 1 and 3 in the table show the space utilization figures when an overflow occurs at the anchorage. Columns 2 and 4 show the percentages of overflows that occur with the corresponding utilization figures.

As shown in Table 2, for that particular anchorage and the vessel traffic, overflow could occur at the anchorage when utilization is as low as 35%, although most of the time it occurs only when utilization is at a higher level of around 60%. This confirms that even at the same anchorage, the maximum possible utilization

varies with the size of incoming vessel and the vessel mix at that time. On average, overflow can happen when utilization reaches 57.10%. It should be noted that for a different anchorage and different vessel mix, overflows may occur at a different utilization level. From our experiments for 17 anchorages, we found that this utilization figure varies from 35.1% to 61.1%

## 9. CONCLUDING REMARKS

We have developed a reconfigurable tool for assessing the capacity of anchorages. It allows the user to input various vessel mixes and volumes in vessel arrivals for current or future scenarios. It also allows the user to specify current or planned anchorage configurations, e.g. to add, remove or change the sizes and shapes of the anchorages. The user can also change the types of vessels that use an anchorage.

Our system proves to be a useful decision support tool for assessing the impacts of different vessel demands, anchorage configurations, anchoring practices and policies. We used this tool to assess the anchorage utilization figures when vessel overflow occurs and we can also use the tool to compute the probability that a certain number of vessels cannot be accommodated in an anchorage. For future work, we plan to design and evaluate algorithms for improving anchorage utilizations.

## ACKNOWLEDGMENTS

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