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An anchorage planning strategy with safety and utilization considerations

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ABSTRACT

Heavy maritime traffic and the subsequent increase in vessel density in anchorages have recently become a focal issue in maritime traffic safety. In this study, we consider the problem of determining the optimal berth locations of incoming vessels in an anchorage area with the goals of maximizing utilization and minimizing the risk of accidents. We introduce novel performance metrics aimed at measuring achievement of these two goals. In this context, we propose a multi-objective optimization strategy and benchmark it against current state-of-the-art anchorage planning algorithms using real-world data as well as Monte Carlo simulations. Our results indicate that the proposed strategy yields much safer berth locations while maintaining similar utilization levels.

1. Introduction

As the world's population soars and countries increase their engagement in international commerce, seaborne shipping continues to expand as a low-cost and carbon-friendly form of transportation that currently accounts for about 90% of the world's commerce. In fact, there are currently over one hundred thousand of commercial vessels actively operating throughout the world [1]. Anchorages are effective means of dealing with maritime traffic congestion and improving the overall quality of seaborne shipping. In addition to easing maritime congestion by serving as a temporary waiting area, anchorages provide important services to vessels such as land services (fueling, legal issues, repairs, etc.), loading/ unloading of cargo, or as a refuge from bad weather conditions. Thus, in general, anchorages play a similar role for vessels as parking lots do for cars and trucks. For this reason, many countries have reserved a considerable part of sea space as anchorages. Coupled with the increasing number of trade routes and the growing demand of global commerce for seaborne shipping, the efficient and safe operation of anchorages have become a crucial task.

Of particular interest is the Ahırkapı anchorage located at southern entrance of the Istanbul Strait, which is illustrated in Fig. 1. In the figure, the diamond-shaped icons represent the anchored vessels detected by radar while the square icons show the vessels detected by Automatic Identification System (AIS). With the Istanbul Strait being one of the most congested restricted waterways in the world, the Ahırkapı anchorage plays a pivotal role in the overall efficiency and safety of international maritime traffic in the Istanbul Strait.

Heavy maritime traffic and the subsequent increase in ship density in anchorages have recently become a focal issue in maritime traffic safety. For instance, a recent study by Aydogdu et al. [3] indicates that while only 20% of all maritime accidents that occurred in Istanbul between 2000 and 2003 took place in the Ahırkapı Anchorage, this number increased to 56% between 2008 and 2011. This high number of accidents in the Ahırkapı anchorage has raised significant safety concerns among local maritime authorities [3]. Accidents in anchorages not only result in potential human casualties and physical damage to vessels, but they also make anchorages partially unavailable until clearance of the accident and thus dramatically hamper overall maritime traffic. Thus, safety issues have become an even more crucial factor in anchorage planning.

Anchorage planning can loosely be defined as determining berth locations of incoming vessels that are optimal with respect to certain performance metrics. Previous academic research on anchorage planning has primarily focused on maximizing the number of vessels that can be placed inside the anchorage. Yet, we are not aware of any existing studies that consider any safety aspects of anchorage planning. Thus, our goal in this work is to contribute to anchorage planning research by incorporating safety considerations along with utilization improvement. Specifically, our contribution in this study is two-fold: (1) we introduce novel performance metrics aimed at measuring safety in anchorage planning, and (2) we propose a multi-objective optimization strategy in order to maximize utilization of the anchorage area and minimize risk of accidents at the same time. Our strategy is called MOAP, which stands for “Multi-Objective

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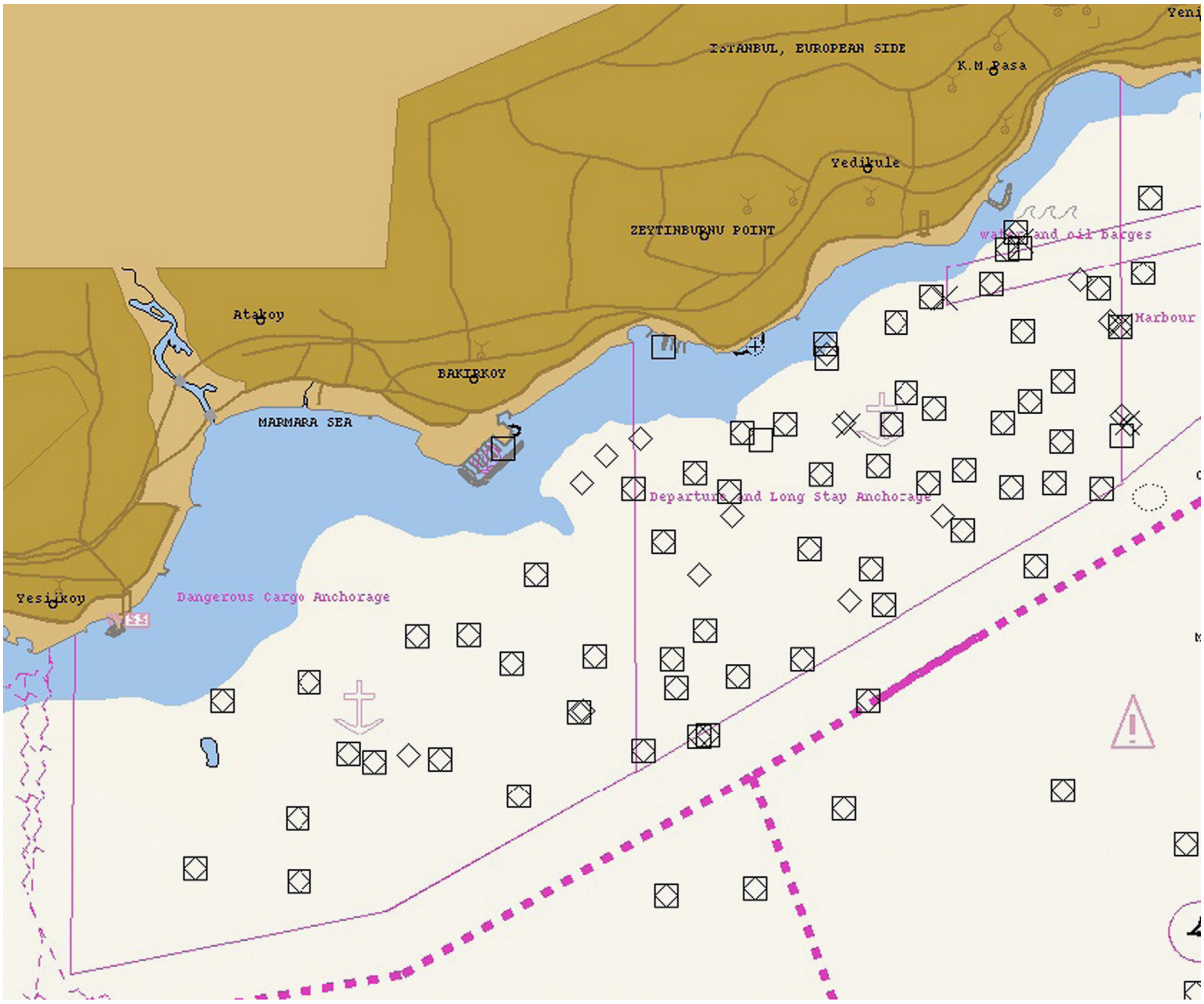

Fig. 1. Ahırkapı anchorage where vessels are depicted by squares.

Anchorage Planner". In order to be able to evaluate and compare different anchorage planning algorithms, we develop and implement an anchorage simulation system. Within this system, we benchmark MOAP against the current state-of-the-art anchorage planning algorithms using real-world data from the Ahırkapı anchorage as well as synthetic data obtained via Monte Carlo simulations. Our results indicate that MOAP yields significantly safer solutions while maintaining similar utilization levels.

The rest of this manuscript is organized as follows: Section 2 describes the anchorage planning problem in detail and discusses previous work on anchorage planning and disk packing in general. Section 3 defines our performance metrics in order to assess utilization and safety levels in anchorages. Section 4 introduces the MOAP strategy and Section 5 describes details of our anchorage simulation system. Section 6 presents our computational experiments and simulation results. Section 7 provides a summary and our conclusions followed with several directions for future research.

2. Problem description and previous work

Anchorages typically operate around the clock and vessels arrive and leave on a regular basis. Efficient anchorage management entails a large number of issues and our focus in this study is specifically limited to anchorage planning. To this end, accommodating maximum number of vessels inside the anchorage is certainly one of the major objectives of efficient anchorage planning, but it is certainly not the only one. Determination of the berth location for an incoming vessel that minimizes the risk of collisions with other vessels inside the anchorage, for instance, is a major objective as well.

An anchorage can be modeled as a polygon-shaped sea space adjacent to land. Open sea edges from which a vessel can enter the anchorage are called the *entry side* of the anchorage. According to our interviews with Istanbul Strait authorities, arrival and departure paths of vessels inside the anchorage area are required to be perpendicular to the entry side. Vessels are allowed to maneuver inside the anchorage area only at the minimum level for mandatory reasons such as to avoid collision with other vessels. Thus, vessels must minimize their navigation path length from the entry side to their berth locations upon entry and vice versa upon departure.

Even though a vessel's anchor is dropped at a specific position, the exact location of the vessel is largely determined by environmental conditions such as winds, waves, and currents. Given the anchor position, an associated safe anchorage circle for the vessel can be computed using simple geometry as shown in Fig. 2. Specifically, radius of this circle is a function of the vessel's length, anchor chain length, and the sea depth at the anchor position. Let the sea depth be denoted by D and the vessel length be denoted by L. An appropriate length for the anchor chain is then given by $25\sqrt{D}$ [8], and the anchorage circle radius can be calculated by the Pythagorean theorem

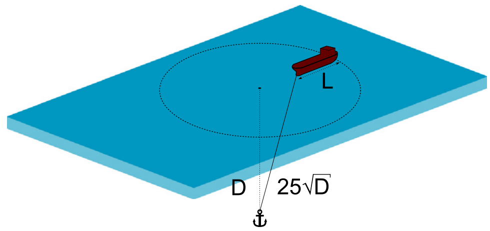

Fig. 2. Illustration of anchorage circle associated with an anchored vessel.

as follows:

$$\textit{Anchorage Circle Radius} = L + \sqrt{(25\sqrt{D})^2 - D^2} \quad (1)$$

Observe that regardless of environmental conditions, the vessel is guaranteed to be inside the associated anchorage circle (we do not consider extreme environmental conditions that might result in a change in the anchor position itself). Without loss of generality, we shall assume that berth location of a vessel is the same as its anchor position and these two terms shall be used interchangeably in this manuscript.

In order to eliminate any risk of collisions, anchorage circles associated with anchored vessels must have no intersection with each other. Thus, the problem of maximizing capacity of an anchorage can be cast as the well-known problem of packing disks with unequal radii inside a polygonal region. A variant of this problem is the NP-Hard circular open dimension problem (CODP) which is concerned with packing a given number of disks with known radii into a rectangular area with a fixed width so as to minimize the rectangle's length [2]. Regarding algorithms for CODP and its variants, Stoyan and Yaskov [24] used a combination of tree search and reduced gradient methods and Hifi and M'Hallah [11,12] proposed evolutionary approaches. On the other hand, Hifi et al. [13] suggested a simulated annealing based approach whereas Rao et al. [21] proposed nature-inspired meta-heuristics. Two specialized greedy heuristics were presented for CODP by Huang et al. [16], and Kubach et al. [17] proposed parallel versions of those heuristics.

So far, only a handful number of studies have considered the problems of anchorage planning, simulation, and management. Balaguer et al. [4] provided a spatial analysis of recreational boats for anchorage capacity estimation based on several different sustainability scenarios. Barros et al. [5] modeled the problem of allocating anchorage positions for vessels in tidal bulk port terminals and proposed a simulated-annealing based solution where the objective was to minimize the total vessel demurrage. Sasa and Incecik [22] proposed a numerical model for simulation of anchored ships under the influence of environmental forces such as wind and waves. By simulating ship motion in anchorages, the authors evaluated the danger of dragging anchor and grounding at strong weather conditions. Burmeister et al. [7], on the other hand, analyzed risk of accidents in anchorages by using frequency models based on collision probabilities.

Bugaric and Petrovic [6] studied a river terminal system for bulk cargo operations where the anchorage area was modeled as a simple first-in first-out queue with a fixed capacity independent of the size of the vessels. A more general model for anchorage area capacity was presented by Fan and Cao [9]. In this study, 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 study suggests that the factors affecting anchorage capacity are types of arriving vessels, average anchor time, and average berth size.

Huang et al. [14] developed a simulation-based model to assess capacity and utilization of anchorages. In this study, for a given collection of vessels and their anchorage times, the capacity of an anchorage is defined as the average utilized area when the anchorage area cannot accept new arrivals weighted by the time required for the next vessel acceptance. A simulation tool was then developed to quantitatively assess anchorage area utilization. Using this tool, the authors evaluated different anchorage planning strategies in terms of efficiency. In particular, the authors proposed two disk-packing algorithms for anchorage planning, namely MHDF and WALLPACK-MHDF, by which they achieved significant improvements over current practices. In our computational experiments, we compare our multi-objective strategy against these two algorithms. The simulation tool and algorithms introduced in Huang et al. [14] were recently used in a marine traffic simulation system for hub ports [15]. In fact, a simulation-based approach was also proposed in Shyshou et al. [23] where the authors investigated the optimal number of anchor handling tug supply vessels required to move an oil rig from one location to another subject to weather and equipment related constraints. We are not aware of any previous studies on anchorage planning that consider any safety aspects of the problem along with utilization considerations.

In this work, our goal is to simultaneously maximize utilization and minimize risk of accidents in anchorage planning. Since these two objectives are conflicting in nature and measured on different scales, the problem we consider can be seen to be a multi-objective optimization problem. Such problems arise frequently in virtually all areas of science and engineering where the goal is to optimize multiple value functions that are typically measured on different scales and usually improvement in one set of functions comes at the cost of degradation of another. Thus, unlike single-objective optimization, there are no globally optimal solutions in multi-objective optimization in general, but rather a set of solutions that achieve an acceptable trade-off in the value functions with respect to the preferences of the decision makers. There are numerous multi-objective optimization solution approaches in the literature, with the most commonly used technique being the weighted sum method [18,19]. In this method, the decision makers assign weights to normalized value functions based on their preferences and construct a single-valued objective function that is a weighted sum of the value functions, which can then be solved using traditional single-objective optimization methods. The weighted sum method is a popular, easy to implement, and easy to interpret multi-objective optimization solution methodology; see, e.g., Hanaoka and Saraswati [10], and Naidu et al. [20]. Our MOAP strategy is also based on the weighted sum method.

3. Anchorage performance metrics

This section introduces our performance metrics aimed at assessing utilization and safety in anchorage planning. The first two metrics, area utilization and effective area utilization, are related to assessing utilization. The next two metrics, arrival and departure intersection factors, are aimed at measuring safety. To our knowledge, the last three of these anchorage performance metrics have not appeared in the literature before. The computation of these metrics assumes that vessels only arrive and they do not depart, which is consistent with our simulation methodology that starts with an empty anchorage and ends when the anchorage is full, that is, when it cannot accommodate even the smallest vessel.

3.1. Area utilization

Our first performance metric, *Area Utilization*, is aimed at assessing capacity when the anchorage is full [14]. Area utilization is defined as the ratio of the sum of the anchorage circle areas to the entire anchorage area when the capacity is reached. In the equation below for this metric, N denotes the total number of vessels upon reaching capacity:

$$Area\ Utilization = \frac{\sum_{i=1}^{N} Area(Anchorage\ Circle_i)}{Anchorage\ Area} \quad (2)$$

3.2. Effective area utilization

Our second performance metric is a new snapshot metric for an anchorage, called *Effective Area Utilization*, which measures how well an anchoring strategy is utilizing the anchorage area at any given point in time. This metric is defined as the ratio of the sum of the anchorage circle areas to the area of a bounding rectangle for the current anchorage circles. In Eq. (3) below for this metric, j denotes the current number of vessels in the anchorage:

$$Eff.\ Area\ Utilization_j = \frac{\sum_{i=1}^{j} Area(Anchorage\ Circle_i)}{Area(Bounding\ Rectangle_j)} \quad (3)$$

The bounding rectangle is calculated as the smallest rectangle containing all existing anchorage circles. Specifically, for an anchorage circle a, denote its center as (x_a, y_a) and its radius as r_a. The left-most and right-most points of a are $x_a - r_a$ and $x_a + r_a$ respectively. Similarly, the bottom-most and top-most points are respectively $y_a - r_a$ and $y_a + r_a$. At any time during the simulation, the smallest left-most circle coordinate $x_a - r_a$ is designated as the x-coordinate of the bounding rectangle's left side and the largest right-most $x_a + r_a$ coordinate is designated as the x-coordinate of the bounding rectangle's right side. The y-coordinates of the rectangle's top and bottom sides are determined in a similar manner. The bounding rectangle is then defined as the area in between these four sides. Fig. 3 shows two different anchorage configurations with the same anchorage circles but different bounding rectangles. The configuration in Fig. 3a has a smaller effective area utilization indicating a smaller density and a larger bounding rectangle whereas the one in Fig. 3b has a higher density and a smaller bounding rectangle. In our anchorage performance simulations, we use average effective area utilization given below:

$$Avg.\ Eff.\ Area\ Utilization = \sum_{j=1}^{N} Eff.\ Area\ Utilization_j / N \quad (4)$$

3.3. Arrival intersection factor (AIF)

Our third performance metric attempts to capture the safety of vessels on their way to their berth locations. First, we define "anchor path" associated with an incoming vessel as the path between the entry point of the vessel and its berth location. As mentioned earlier, maritime authorities require that vessels perform minimum amount of maneuvering within the anchorage and therefore the anchorage path needs to be the shortest path between the entry side and the anchor location. We define "arrival intersection" associated with an anchor path as the number of anchorage circles the path intersects. Fig. 4 depicts four anchor paths with different arrival intersections. For paths I, II, III, and IV, arrival intersection values are respectively 0, 1, 2, and 3. In our anchorage performance simulations, we record arrival intersection values of all incoming vessels until the anchorage reaches its capacity, and then we divide the total number of intersections by the total number vessels, a quantity which we call the *Arrival*

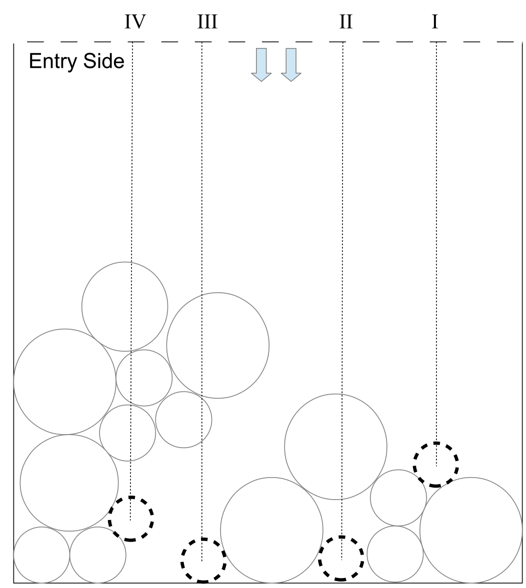

Fig. 4. Anchor paths with different arrival intersection values. For paths I, II, III, and IV, arrival intersection values are respectively 0, 1, 2, and 3.

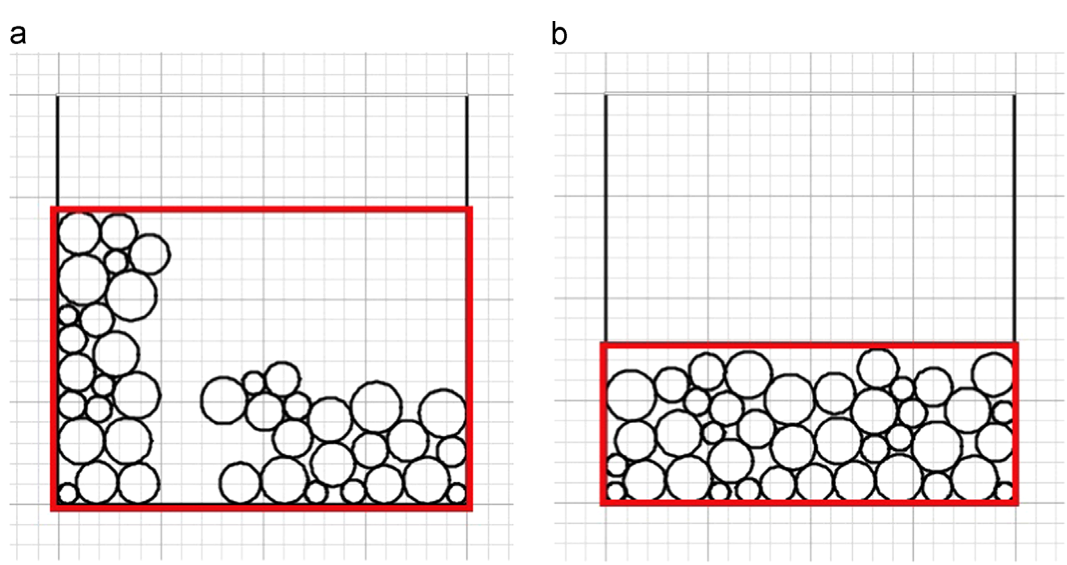

Fig. 3. Two anchorage configurations with different effective area utilizations. (a) Poor effective utilization and (b) good effective utilization.

Intersection Factor (AIF):

$$AIF = \sum_{j=1}^{N} Arrival\ Intersection_j / N \tag{5}$$

Although incoming vessels can enter and navigate inside existing anchorage circles (apparently while avoiding anchored vessels), this is not an ideal situation as it poses as a risk factor. Therefore, it is a safer scenario if there are no anchorage circles intersecting anchorage paths of incoming vessels and AIF can be seen as a metric measuring this safety aspect.

3.4. Departure intersection factor (DIF)

Analogous to arrivals, any departure from the anchorage area needs to follow the shortest path from the berth location to the entry side, which we call the "departure path". We define "departure intersection" as the number of anchorage circles intersecting with the departure path of a vessel leaving the anchorage. Next, we define *Departure Intersection Factor*, DIF_j, of an anchorage as the sum of departure intersection values of current vessels divided by j when there are j vessels in the anchorage:

$$DIF_j = \sum_{i=1}^{j} Departure\ Intersection_i / j \tag{6}$$

Observe that DIF_j is the expected number of anchorage circles intersecting the departure path under the assumption that departure probability of all vessels currently in the anchorage is equal. As an illustration, departure intersection values of the vessels shown in Fig. 5 are 2 for A, 1 for E, and 0 for B, C, D, and F. The DIF of the anchorage is calculated as $(2+1+0+0+0+0)/6 = 0.5$.

In order to measure the performance of an anchorage policy in terms of how well it manages safety of departing vessels in the anchorage throughout the simulation, we calculate Average DIF as in the following equation:

$$Avg.\ DIF = \sum_{j=1}^{N} DIF_j / N \tag{7}$$

It is important to observe that calculation of AIF, an average of whole numbers, is fundamentally different from the calculation of Avg. DIF, which is an average of averages.

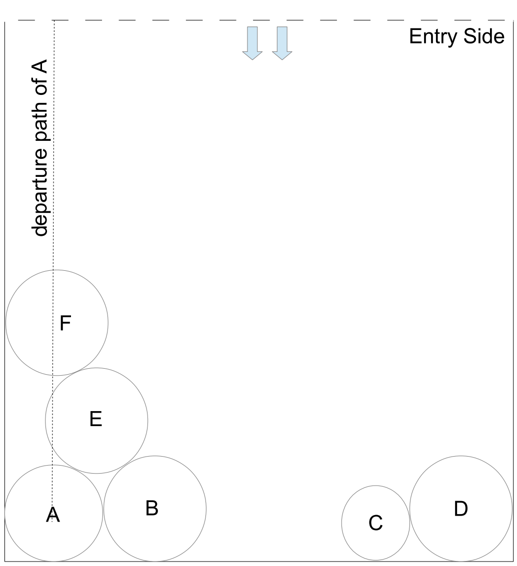

Fig. 5. Departure path of an anchorage.

4. Multi-objective anchorage planner (MOAP)

This section presents our anchorage planning strategy, called Multi-Objective Anchorage Planner (MOAP), that attempts to achieve the dual goals of maximizing utilization and minimizing the risk of accidents. In particular, MOAP attempts to maximize the area utilization and effective area utilization metrics as defined above, and minimize AIF and Average DIF metrics at the same time.

As mentioned earlier, the anchorage planning problem resembles disk packing problems from a capacity maximization point of view. Existing studies on disk packing problems give preference to corner and side locations while searching for candidate positions [2,16,14,17]. The notion of corner locations is inspired from human experience on packing things into a confined space. In line with previous studies, we use corner positions as candidate berth locations in MOAP. The main flow of MOAP is presented in Fig. 6. MOAP consists of two steps: corner point calculation and corner point evaluation. After all corner points have been calculated and evaluated, the best corner point is suggested as the anchor position. Details of these two steps are given below.

4.1. Corner point calculation

Similar to existing studies on disk packing, we define a corner point CP_i associated with circle i as the point where the circle is tangent to at least two items when its center is located at CP_i (see, e.g., [16]). These items can either be existing anchorage circles or sides of the polygon representing the anchorage. We categorize corner points into three types according to the item types they are tangent to. Side-and-Side (SS) corner points are the center of the circles tangent to any two sides of the anchorage area. Side-and-Circle (SC) corner points are the center of the circles tangent to an existing anchorage and a side of the anchorage area. The third type is Circle-and-Circle (CC) corner points which are the centers of the circles tangent to two existing anchorage circles. Fig. 7 illustrates these three different types of corner points. In the corner point calculation step of MOAP, all possible corner points are computed by iterating over existing anchorage circles and sides of the anchorage area. These points are the candidate berth locations to be suggested for an incoming vessel.

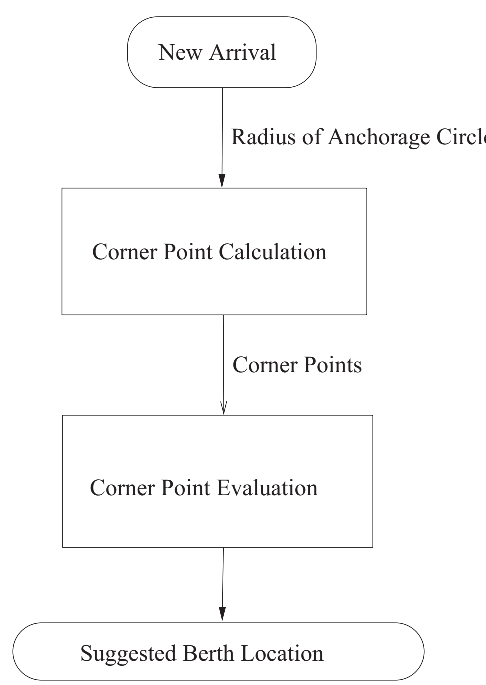

Fig. 6. The MOAP algorithm main flow.

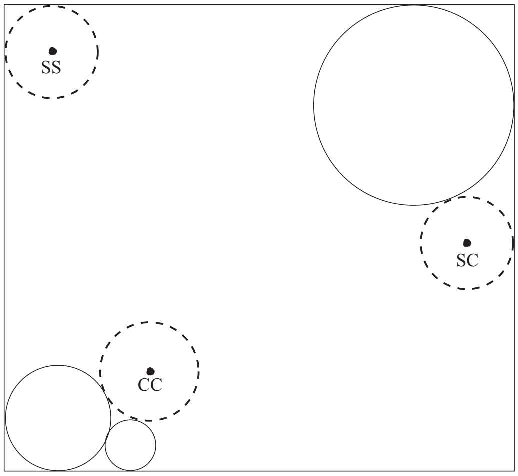

Fig. 7. Three different types of corner points.

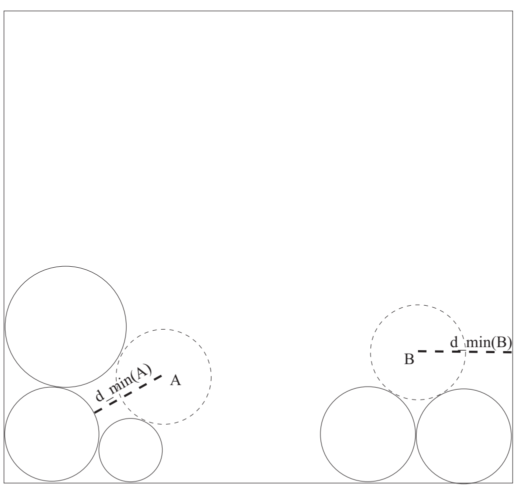

Fig. 8. Hole degree calculation for two different corner points.

4.2. Corner point evaluation

MOAP uses the weighted function below to evaluate a corner point CP_i where $Utilization(CP_i)$ and $Safety(CP_i)$ measure utilization and safety values of CP_i respectively, and $W_{utilization}$ and W_{safety} are the weight parameters:

$$MOAP\_Eval(CP_i) = W_{utilization} \times Utilization(CP_i) + W_{safety} \times Safety(CP_i) \quad (8)$$

Fine-tuning of the above weight parameters are described in detail in Section 6. Similar to previous studies on disk packing, $Utilization(CP_i)$ is set to the "hole degree" of CP_i [2,16,14]. Illustrated in Fig. 8 for two different corner points, hole degree is calculated as in Eq. (9) where r is the radius of the circle associated with CP_i and, d_{min} is the distance from CP_i to the closest circle or side of the anchorage not including the two closest items tangent to CP_i. We chose the hole degree as our utilization value for corner points for two reasons: (1) it is very easy and fast to calculate, and (2) it is commonly used in disk packing algorithms where the objective is to maximize area utilization:

$$Utilization(CP_i) = Hole\ Degree(CP_i) = (1 - d_{min}/r) \quad (9)$$

Regarding the safety value of a corner point, we introduce a new planning metric that attempts to measure how safely the anchorage circles are distributed. This metric is calculated as the normalized distance between the entry side of the anchorage and

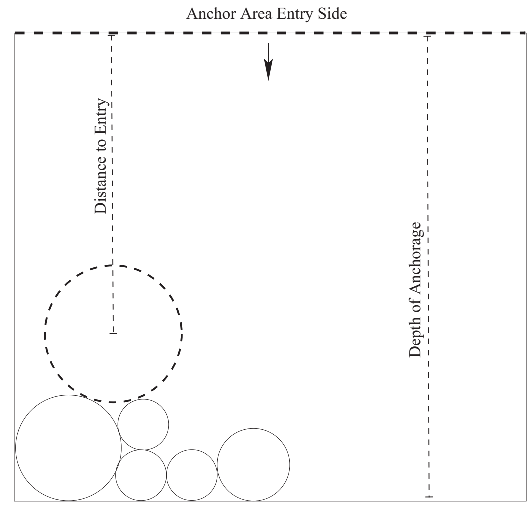

Fig. 9. Illustration of distance-to-entry for a corner point and an anchorage depth.

the corner point, which we call the *Normalized-Distance-to-Entry (NDE)*. This metric is computed as the distance of the corner point to the entry side divided by the depth of the anchorage. It should be noted that depth of the anchorage area refers to its distance along the sea surface from the entry side to land, which is different from the depth of the seawater. NDE equation is given below and it is illustrated in Fig. 9:

$$NDE(CP_i) = \frac{Distance\ To\ Entry(CP_i)}{Anchorage\ Depth} \quad (10)$$

The intuition behind the idea of maximizing distance-to-entry is that by placing incoming vessels away from the entry side, we expect a decrease in the number of intersections of the anchorage circles with the anchor paths of future arrivals as well as with the anchor paths of future departures. We conclude this section with a brief comparison of our two planning metrics, namely hole degree and NDE, with the four performance metrics presented in Section 3. Recall that the four performance metrics, i.e., Area Utilization, Avg. Effective Area Utilization, AIF, and Avg. DIFF, are aimed at measuring safety and utilization of an anchorage planning strategy and they are calculated after completion of a simulation run. On the other hand, the two planning metrics measure quality of a corner point as the planning strategy progresses. The reason we do not consider dynamic versions of the four performance metrics but rather use the two planning metrics for evaluation of corner points is two-fold:

- The two planning metrics are simple heuristics and they are very easy to compute whereas dynamic versions of the four performance metrics involve substantial calculations for evaluation of any given corner point.
- As we illustrate in our computational experiments, the two planning metrics are already quite successful in improving those four performance metrics. In fact, in our limited experimentation, we observed that dynamic versions of the performance metrics resulted in similar anchorage plans as the two planning metrics, but with significant additional computational burden.

5. Anchorage simulation system

To assess the performance of our MOAP strategy, we implemented an anchorage simulation system that allows us to benchmark any anchorage planning strategy with respect to a given length distribution for incoming vessels. Our simulator starts with an empty anchorage and executes until the anchorage cannot accommodate even the smallest vessel. The simulator has five main components: anchorage area, arrival generator, anchorage policy, anchorage manager, and anchorage evaluator. Brief descriptions of these components are given below.

5.1. Anchorage area

An anchorage area is modeled as a polygonal region containing a set of anchorage circles corresponding to currently anchored vessels. Even though anchorage areas typically have non-uniform depth in reality, we assume uniform-depth for simplicity and convenience, and leave modelling of non-uniform depth to future research. A set of adjacent edges of the polygonal representation of the anchorage area is designated as the entry side within which incoming vessels enter the anchorage. The inside area of the anchorage is modeled as a two-dimensional lattice grid graph where each inner vertex has 8 neighbors. This grid graph is used for calculating the anchor path from entry side to the berth location suggested by the anchorage manager.

5.2. Arrival generator

The arrival generator samples incoming vessels from a given vessel length distribution. As discussed earlier, the length of the vessel determines the radius of the anchorage circle. Thus, anchorage circle size distribution is specified via the length distribution of the incoming vessels.

5.3. Anchorage policy

The anchorage policy is the component where the anchorage planning strategy is implemented. This component decides on the berth locations of incoming vessels based on the anchorage planning strategy.

5.4. Anchorage manager

The anchorage manager executes the anchorage simulation system and performs communication between other components. Fig. 10 shows a schematic diagram of the simulator. In particular, steps for anchoring of an incoming vessel are as follows:

1. The arrival generator generates a new arrival from a given length distribution and sends it to the anchorage manager.
2. The anchorage manager receives the arrival and asks the anchorage policy where to place the vessel.
3. The anchorage policy uses the length information of the incoming vessel and decides on the berth location.
4. The anchorage policy sends the berth location information to the anchorage manager. If the anchorage area has become full (i.e., even the smallest vessel cannot find any anchorage place), the anchorage policy sends an "anchorage-full" message.
5. The anchorage manager updates the anchorage area accordingly. It terminates the simulation if it receives an "anchorage-full" message from the anchorage policy.

5.5. Anchorage system evaluator

The performance of the anchorage policy is measured by the anchorage system evaluator. While the anchorage manager executes the simulation, the Evaluator collects performance data, both during the simulation and after the simulation, in order to compute the performance metrics described in Section 3.

Clearly, values of the performance metrics depend on the specific sequence of samples from the vessel length distribution.

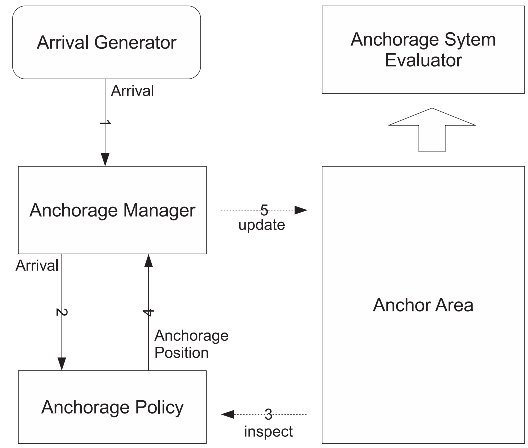

Fig. 10. Schematic diagram of the anchorage simulation system.

For this reason, the simulator performs repeated simulations with different samples from the same length distribution, and the Evaluator reports the average of the performance metric values.

6. Computational experiments

Our purpose in this section is to empirically assess performance of MOAP with respect to the four performance metrics presented in Section 3 that are aimed at measuring both utilization and safety levels in anchorage planning. While doing so, we use three different vessel length distributions and four different anchorage topologies. In particular, we benchmark MOAP on the Ahırkapı anchorage as well as on synthetically generated anchorages and we compare MOAP against two of the current state-of-the-art anchorage planning strategies.

6.1. Vessel length distributions

The first vessel length distribution we use in our experiments is the historical vessel arrival data in the Ahırkapı Anchorage. Table 1 shows the number of arrivals in terms of vessel lengths recorded in the Ahırkapı anchorage in 2013.

6.2. Anchorage area topologies

Our computational experiments are run on four different types of anchorage area topologies, which are depicted in Fig. 11. Note that the first three of the topologies are convex and the last one is non-convex. Also, the first topology is the same as the Ahırkapı anchorage area. All anchorage areas used in the experiments are assumed to have a uniform water depth of 35 m and anchorage circle radii are computed using Eq. (1). The Ahırkapı anchorage and the other four anchorages used in our simulations have a bounding rectangle of 7000 m by 5000 m. In all the four topologies, it is assumed that anchorage area boundaries are open water and that these boundaries are determined by local authorities to mark sea space that can be used as an anchorage.

6.3. Fine-tuning the MOAP weight parameters

As mentioned earlier, MOAP uses a weighted function that measures both utilization and safety to evaluate candidate berth locations. Our goal in this section is to determine a good trade-off between utilization and safety on an empirical basis. To that end, we ran Monte Carlo experiments using all three vessel length distributions and the four anchorage topologies described above within our anchorage simulation system. We performed 50 simulations for each length distribution/topology combination with different safety/utilization weight ratios, which correspond to a total of $50 \times 3 \times 4 \times 7 = 4200$ simulations. We start with equal weights and gradually increase the safety weight. Observe that our utilization of weight ratios is mathematically equivalent to the classical weighted sum method in the literature where the decision maker chooses weights that sum up to 1. For instance, a weight ratio of $W_{safety} = 3$ and $W_{utilization} = 1$ is equivalent to setting $W_{safety} = 0.75$ and $W_{utilization} = 0.25$.

Fig. 12 shows area utilization, effective area utilization, AIF, and average DIF for different W_{safety} and $W_{utilization}$ ratios. These simulation results indicate that while utilization decreases slightly, MOAP safety performance improves substantially up to about a ratio of 10 to 1. Thus, we set $W_{safety} = 10$ and $W_{utilization} = 1$ in the rest of our computational experiments.

6.4. Performance comparison of anchorage planning strategies

We compared MOAP against two recently introduced anchorage planning strategies, namely Maximum Hole Degree First (MHDF) and WALLPACK-MHDF algorithms [14]. Short descriptions of these algorithms are given in Figs. 13 and 14 respectively. The three types of corner points used in WALLPACK-MHDF were previously illustrated in Fig. 7. We implemented anchorage policy modules corresponding to MHDF and WALLPACK-MHDF algorithms to evaluate them within our anchorage simulation system against MOAP. We also performed experiments with a naive random-corner assignment policy, which simply places anchorages one of the available corner points randomly. We used common random numbers for all algorithms, meaning that they were tested on the exact same sequences of vessel arrivals.

Table 1
Ahırkapı anchorage arrival data in 2013.

Vessel length (m)	No. of arrivals
25–50	357
50–75	5266
75–100	18,237
100–125	20,478
125–150	12,587
150–175	2619
175–200	3525
200–225	106
225–250	502

6.4.1. Comparison for the Ahırkapı Anchorage

Our first set of strategy comparison experiments was conducted on the Ahırkapı anchorage with the empirical vessel length distribution shown in Table 1. Table 2 shows the average results over 50 Monte Carlo simulations within our anchorage simulation system. In the table, the column named *Improvement* (%) shows percentage improvement of MOAP over the better of the other two algorithms. The simulation results indicate that MOAP provides comparable area utilization at 0.78, yet it is 35.6% better regarding effective utilization at 0.68. In terms of the arrival intersection factor (AIF) metric, at a mere 0.002, MOAP provides a 98.9% improvement over the other two algorithms. In addition, MOAP provides about 18.5% better average departure intersection factor (DIF) at 3.43. Overall, these results indicate that MOAP places vessels in a much safer way compared to the other two anchorage planning algorithms with practically negligible impact on area utilization. We also observe in Table 2 that all three policies result in similar average travel distances from the entry side to the vessels' berth locations, suggesting that minimization of total travel distances is not an important objective in our problem.

6.4.2. Comparison for synthetic anchorages

Our next set of experiments was conducted on the four types of anchorage topologies illustrated in Fig. 11 with the previously described Uniform and Beta-distributed vessel lengths. We conducted 50 Monte Carlo simulations for each anchorage topology/vessel distribution combination. Table 3 summarizes the results of these experiments. As before, the column *Improvement* (%) represents the percentage improvement of MOAP over the better of the other two algorithms. The table indicates that MOAP performance on synthetic anchorages is similar to that of the Ahırkapı anchorage in general. In particular, Table 3 suggests that there is a slight reduction in MOAP performance in terms of area utilization when compared against the better of MHDF and WALLPACK-MHDF, yet this reduction is merely 1% on the average. This is primarily due to the safety preference of MOAP in exchange for a slight degradation in area utilization. As for the effective area utilization, MOAP outperforms the other two algorithms by up to 47.8%. Thanks to the NDE metric used as the safety measure, MOAP tries to place

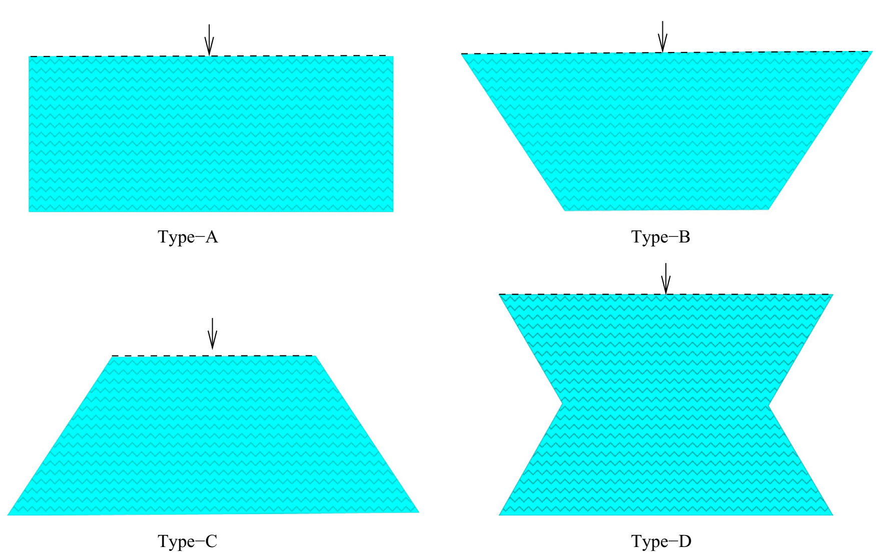

Fig. 11. Four types of anchorage area topologies considered in our experiments. The arrows show the entry side of the anchorages.

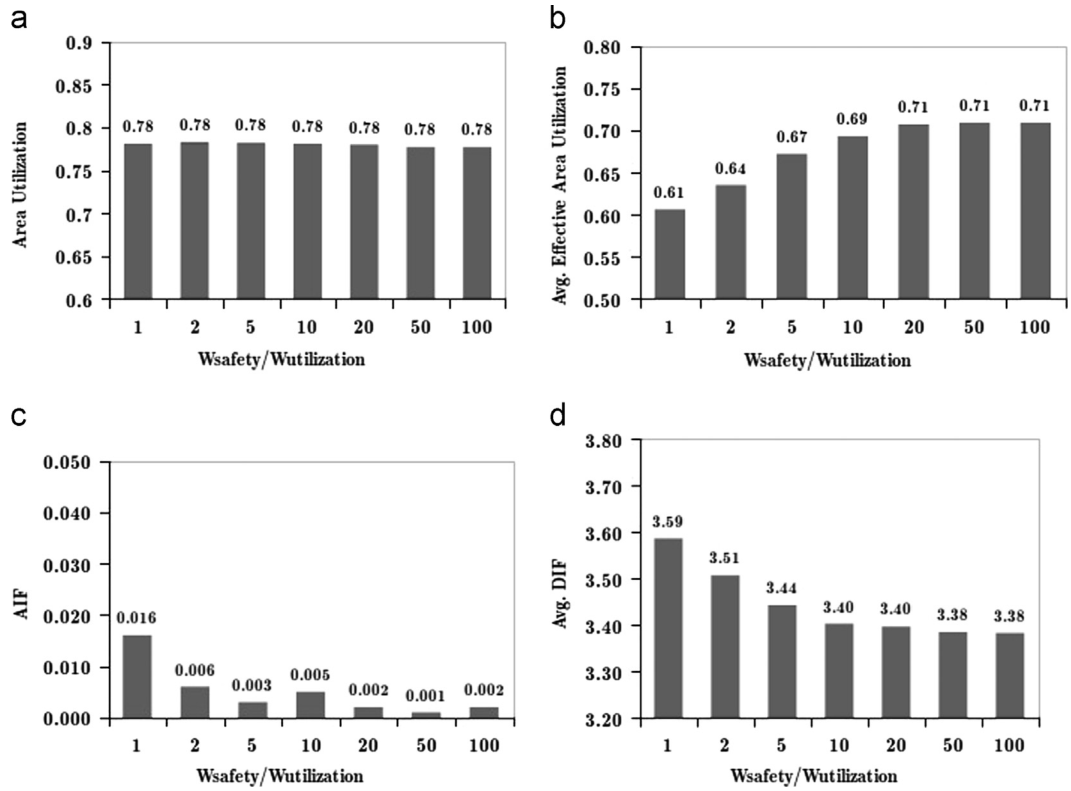

Fig. 12. The performance of MOAP with different weight ratios. (a) Area utilization, (b) average effective area utilization, (c) AIF, and (d) average DIF.

incoming vessels further away from the entry side of the anchorage and this behavior tends to improve effective area utilization.

Table 3 also shows that MOAP performs much better in terms of the safety metrics. It achieves, on the average, about 96.4% improvement on AIF performance at 0.012, and 21% improvement on average DIF at 3.27. Poor safety performance of MHDF and WALLPACK-MHDF algorithms is perhaps to be expected as these algorithms are designed for maximizing capacity only without any safety concerns. On the other hand, MOAP is designed specifically to simultaneously address utilization and safety issues. Consequently, as illustrated in our computational experiments, MOAP achieves much better safety levels in exchange for a slight degradation in area utilization. In addition, Table 4 indicates that the total number of vessels placed by all three policies are very close to each other across our simulations.

7. Summary and conclusions

The issue of anchorage planning, which is the task of determining optimal anchor locations for incoming vessels with respect to capacity and safety, is a challenging problem which can be well aided by multi-criteria decision making approaches. Previous studies consider only the utilization aspects of anchorage planning while ignoring any potential safety issues. Our study is aimed at meeting this need by presenting a multi-objective anchorage planning strategy with the goals of maximizing utilization and minimizing risk of accidents, which we call MOAP. To this end, we introduce novel performance metrics aimed at measuring achievement of these two goals. Namely, in addition to the area utilization metric commonly used in the literature, we introduce a new metric aimed at measuring effective area utilization. Furthermore, we introduce two new safety metrics, called arrival and departure intersection factors, which respectively measure the number of anchorage circles a vessel's arrival and departure path intersects.

```
// Called in Anchorage Policy upon new arrival

1. Find all corner points.
2. Return the one with the largest hole degree value.
3. If anchorage-full condition is satisfied report "anchorage-full".
```

Fig. 13. MHDF algorithm.

```
// Called in Anchorage Policy upon new arrival

1. Find all corner points of type SS.
2. Return the one with the largest hole degree value.
3. If none, find all corner points of type SC.
4. Return the one with the largest hole degree value.
5. If none, find all corner points of type CC.
6. Return the one with the largest hole degree value.
7. If anchorage-full condition is satisfied report "anchorage-full".
```

Fig. 14. WALLPACK-MHDF algorithm.

Table 2
Ahırkapı experiment results. MOAP improvement percentages are reported in comparison with the better of the MHDF and WALLPACK-MHDF algorithms.

Performance metric	MHDF	WALLPACK MHDF	RANDOM CORNER	MOAP	Improvement (%)
Area utilization	0.777	0.785	0.76	**0.780**	**−0.64**
Average eff. area utilization	0.500	0.391	0.497	**0.678**	**35.6**
AIF	0.365	0.176	0.228	**0.002**	**98.86**
Average DIF	4.349	4.206	3.665	**3.429**	**18.47**
Average travel distance (m)	4079	4100	4103	**4129**	**−0.01**

Table 3
Synthetic experiment results in terms of area utilization and average effective area utilization. MOAP improvement percentages are reported in comparison with the better of the MHDF and WALLPACK-MHDF algorithms.

Performance metric	Area utilization					Avg. eff. area utilization				
	MHDF	WALLPACK-MHDF	RANDOM CORNER	MOAP	Improvement (%)	MHDF	WALLPACK-MHDF	RANDOM CORNER	MOAP	Improvement (%)
Uniform										
Type-A	0.783	0.792	0.775	**0.782**	− **1.3**	0.524	0.419	0.499	**0.685**	**30.7**
Type-B	0.780	0.791	0.774	**0.778**	− **1.6**	0.525	0.399	0.505	**0.668**	**27.2**
Type-C	0.784	0.793	0.775	**0.784**	− **1.1**	0.477	0.375	0.459	**0.635**	**33.1**
Type-D	0.723	0.746	0.725	**0.725**	− **2.8**	0.452	0.350	0.432	**0.588**	**30.1**
Beta										
Type-A	0.780	0.786	0.762	**0.781**	− **0.6**	0.489	0.411	0.501	**0.695**	**42.1**
Type-B	0.779	0.786	0.760	**0.779**	− **0.9**	0.515	0.391	0.492	**0.678**	**31.6**
Type-C	0.778	0.787	0.761	**0.783**	− **0.5**	0.439	0.370	0.455	**0.649**	**47.8**
Type-D	0.730	0.732	0.731	**0.727**	− **0.7**	0.511	0.345	0.430	**0.603**	**18.0**
Average	0.767	0.776	0.755	**0.769**	− **1**	0.496	0.381	0.470	**0.654**	**32.1**

Performance metric	AIF					Average DIF				
	MHDF	WALLPACK-MHDF	RANDOM CORNER	MOAP	Improvement (%)	MHDF	WALLPACK-MHDF	RANDOM CORNER	MOAP	Improvement (%)
Uniform										
Type-A	0.252	0.388	0.378	**0.004**	**98.4**	3.720	4.330	3.431	**2.975**	**20**
Type-B	0.213	0.265	0.338	**0.008**	**96.2**	4.798	5.273	3.473	**3.779**	**21.2**
Type-C	0.268	0.974	0.414	**0.007**	**97.4**	3.479	3.864	3.250	**3.007**	**13.6**
Type-D	0.561	1.647	0.528	**0.082**	**85.4**	4.756	4.979	3.083	**3.865**	**18.7**
Beta										
Type-A	0.500	0.228	0.228	**0.001**	**99.6**	4.524	4.831	3.871	**3.448**	**23.8**
Type-B	0.282	0.161	0.197	**0.003**	**98.1**	4.284	4.392	3.808	**3.506**	**18.2**
Type-C	0.588	0.907	0.267	**0.004**	**99.3**	4.460	4.961	3.748	**3.264**	**26.8**
Type-D	0.590	1.403	0.415	**0.024**	**95.9**	3.975	3.835	3.434	**3.085**	**24.3**
Average	0.465	0.705	0.302	**0.012**	**96.4**	4.211	4.478	3.640	**3.271**	**21**

Table 4
Synthetic experiment results in terms of total number of vessels. MOAP improvement percentages are reported in comparison with the better of the MHDF and WALLPACK-MHDF algorithms.

Performance metric	Total number of ships anchored				
	MHDF	WALLPACK-MHDF	RANDOM CORNER	MOAP	Improvement (%)
Uniform					
Type-A	192.80	196.02	193.04	**193.16**	− **0.015**
Type-B	289.94	293.86	280.48	**292.44**	− **0.005**
Type-C	180.94	184.48	181.24	**180.86**	− **0.020**
Type-D	271.22	274.72	262.44	**273.62**	− **0.004**
Beta					
Type-A	168.42	171.42	169.48	**168.92**	− **0.015**
Type-B	252.70	256.50	245.74	**255.20**	− **0.005**
Type-C	113.14	117.56	118.46	**113.92**	− **0.031**
Type-D	169.04	170.28	166.62	**168.62**	− **0.010**
Average	204.78	208.11	202.19	**205.84**	− **0.013**

In order to benchmark MOAP's performance, we implemented an anchorage simulation system that allows for different incoming vessel length distributions as well as different anchorage topologies. Within this simulation system, we compared MOAP against two state-of-the-art anchorage planning algorithms on the Ahırkapı anchorage in the southern entrance of the Istanbul Strait and on various synthetic anchorages. Our simulation results indicate that MOAP consistently yields much safer solutions while maintaining similar utilization levels when compared to the other two algorithms.

As for future research, we plan on adapting our algorithm to account for vessel arrival and departure events and optimize our performance metrics in the steady-state in a more realistic modelling and simulation environment where vessels arrive and depart on a regular basis. In addition, we plan on extending our algorithm to handle more realistic anchorage areas with non-uniform sea depth.

Future work might incorporate environmental forces such as wind, waves, and sea current. Moreover, we made the simplifying assumption in this work that vessel arrival and departure paths are straight lines from the berth locations to the entry side of the anchorage. Future studies might account for exact vessel locations within anchorage circles and investigate more realistic anchorage paths via maneuvering around other vessels inside the anchorage.

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