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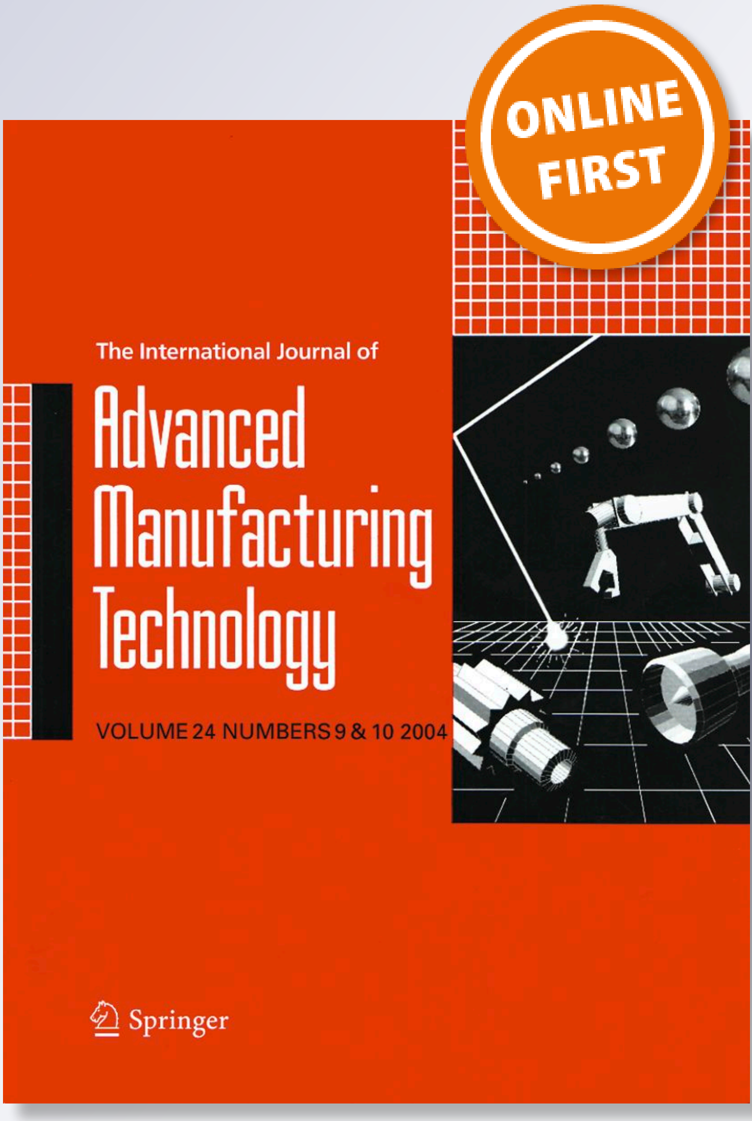

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ORIGINAL ARTICLE

An analysis of shipyard spatial arrangement planning problems and a spatial arrangement algorithm considering free space and unplaced block

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Abstract

The components of shipyard production systems can be classified into products, processes, facilities, space, humans, and schedules. The production capacity of a shipyard may vary depending on how they are operated. Particularly in the case of ships, it is important to efficiently utilize the limited space because they have large blocks, which are semi-finished products made during the shipbuilding process. To efficiently utilize the space, the locations of blocks must be determined taking various factors into consideration when arranging them in the workshop or stock area. This problem can be described as a spatial arrangement problem. However, as the items with fixed arrival dates and departure dates occupy the space for certain periods before being released from shipyards, this problem must be approached from the perspective of a spatial arrangement planning problem for certain periods and not as a simple spatial arrangement problem. In this study, various shipyard spatial arrangement planning problems are classified and defined based on arrangement areas, arrangement items, algorithms, and evaluation factors. In addition, taking the increasing sizes of shipyard blocks into consideration, evaluation factors and algorithms are proposed so that the shape of the free space and the characteristics of unplaced blocks can be considered in the spatial arrangement planning problems of large blocks. The performances of the proposed evaluation factors and algorithms were verified using block data generated by analyzing existing shipyard data product information. The proposed algorithm performed better than the existing algorithm for spatial arrangement planning problems of large blocks. However, the performance of the proposed algorithm was not significantly different from the existing algorithm when the size of the arrangement item was relatively small compared with the arrangement area.

Keywords Greedy algorithm · Shipyard simulation system · Shipyard information model · Spatial arrangement planning problem

1 Introduction

In most large shipyards, ships were built using the hull block construction method (HBCM). In this method, a ship is divided into several blocks and assembled in a dock [1]. As the size of a block, which is a semi-finished product of a ship, is large, it is important to efficiently utilize space and facilities in shipyards. In particular, maximizing the efficiency of the dock has the greatest impact on improving shipyard productivity. In shipyards, several blocks are assembled to create a bigger block in a workshop near the dock in an effort to reduce the working hours of the processes performed in the dock. This process is called the pre-erection (P.E.) process. Floating docks and floating cranes have recently been used to construct bigger blocks [2]. In general, the maximum capacity of the gantry crane installed in a dock is approximately 1000 t, while the maximum capacity of a floating crane may exceed 3000 t. Therefore, facilities, such as floating docks and floating cranes, are required to construct P.E. blocks. In addition to the facilities, the production systems of shipyards include products, processes, humans, and schedules [3].

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Therefore, the productivity of such production systems can be improved by introducing methods to efficiently utilize the limited space. The P.E. process is usually performed in a P.E. workshop around the dock. P.E. workshops must be efficiently utilized to reduce the P.E. working hours of the entire ship and to produce more P.E. blocks.

In shipyards, it is important to efficiently utilize various spatial factors, such as assembly workshops, stock areas, and P.E. workshops. For this purpose, the locations of assembly members or blocks must be determined considering various factors. This problem can be described as a spatial arrangement problem. However, in shipyards, the items with fixed arrival dates and departure dates, as well as fixed locations, occupy the space for certain periods before being released. Therefore, this problem must be approached from the perspective of a spatial arrangement planning problem and not as a simple spatial arrangement problem. However, it is not easy to solve spatial arrangement problems when both time constraints and spatial constraints are taken into consideration. Even if a reasonable solution is found through a reasonable assumption, there are not many cases where the solution is actually applied in the field. In the field of shipyards, where spatial arrangement planning is required, short-term spatial arrangement planning is manually performed taking production schedules into consideration and arrangement results are reviewed rather than establishing spatial arrangement planning in advance [4].

Nevertheless, various studies have been conducted to systematically establish spatial arrangement planning and to efficiently utilize space. Zheng et al. mathematically modeled the block arrangement planning problem to establish an optimal arrangement plan taking both time constraints and spatial constraints into consideration [5]. In this study, time constraints were considered by defining the arrangement area as a two-dimensional space and the height as the time axis. The proposed algorithm is based on a greedy algorithm, and it was compared with various existing algorithms to review its performance. Kwon and Lee defined the assembly block arrangement planning problem using mixed integer programming [6]. In this study, as in previous studies, time constraints were considered by adding a time axis to blocks placed in a two-dimensional space. Assembly block arrangement planning was performed using a heuristic algorithm that combined the prioritization method and the bottom-left algorithm. Song et al. focused on accurately calculating the capacity of the assembly process using a spatial arrangement simulator [7]. For this purpose, the shipyard block assembly process was precisely simulated and modeled, and the simulation was performed using a commercial discrete event system simulation software. For the simulation, the blocks to be placed in the assembly process workshop were arranged according to predefined rules. The aforementioned study of Eum proposed an arrangement strategy that maximizes area utilization of the entire planning period, as well as area utilization on a certain date [4]. Koh et al. proposed an optimal arrangement algorithm for mega-block workshops taking the block production time and working hours into consideration [2].

In previous cases, spatial arrangement problems were approached from a planning perspective taking time constraints into consideration. When time constraints were not taken into consideration, the method of determining the locations of arrangement items was used. It was confirmed that this method has been frequently used, especially in the nesting area, which aims to efficiently utilize limited resources at any given time. Jeong and Jeon conducted a study to find the most efficient alternative arrangement by rotating members with arbitrary shapes based on their vertices and by using a heuristic algorithm [8]. Sheen approximated arrangement items in pixel forms to define the nesting problem [9]. If an arrangement item was placed at the corresponding pixel, a value of "1" was given; otherwise, "0" was given to determine whether the item overlapped with the placed shape. In the study, an expert system was developed to address the nesting problem using such expression method and a heuristic search method. Besides, various solutions to spatial arrangement problems have been investigated by various researchers for a long time.

Spatial arrangement problems have been widely studied in various fields, including the afore-mentioned areas. The bin packing problem aims to find a solution that can include the largest number of items in a limited space [10]. Various algorithms have already been proposed to address this problem [11], and algorithms and strategies for efficiently filling a three-dimensional object with the shape of a cuboid have been studied [12, 13]. The three-dimensional box filling problem was also applied to solve the problem of loading containers on a container ship [14]. Furthermore, various solutions to spatial arrangement problems were applied to the topside of offshore plants [15, 16], marine wind power generation facility arrangement problems [17, 18], ship layout design problems [19–21], and electric propulsion ship battery positioning problems [22], although applied algorithms and solutions varied.

In this study, algorithms and evaluation factors for spatial arrangement problems that were utilized in various fields were reviewed to address spatial arrangement planning problems in shipyards. Most existing research approaches the spatial arrangement problem from the point of view to utilize the limited space efficiently based on the specific time point. Some studies have considered space and time constraints simultaneously, but have also considered time as another spatial constraint by adding a time axis to a two-dimensional space. Although this method may be effective for considering time constraints, there is a limitation in that it does not reflect characteristics of time constraints. Thus, previous researches did not study the spatial arrangement algorithm or apply the evaluation factors from a long-term perspective, reflecting the characteristics of time constraints. In order to solve this problem, this study investigated the factors that evaluate the spatial arrangement of a specific time point and the factors that can evaluate the spatial arrangement results from a long-term perspective. In addition, evaluation factors that take into account the characteristics of the arrangement items and area were utilized. Flack utilized the number of twist shapes as an evaluation factor in performing optimal layout design taking into consideration the fact that space utilization becomes higher if there are more rectangular remaining spaces in the building layout design [23]. The number of twist shapes means the minimum number of rectangles that can divide arbitrary polygonal shape. The remaining space have more complex shape; twist number has a larger value. In such case, the block to be placed may not be arrangement even if the sum of the remaining space is larger than the area of block to be placed, since the largest part of the remaining space is not big enough for block arrangement. In this study, this concept was used as an evaluation factor to maintain a rectangular shape for the free space in shipyard spatial arrangement planning problems.

It was estimated that minimizing the number of twist shapes could be effective for spatial arrangement planning problems with large arrangement items compared with the area of arrangement, and before confirming this, various space allocation planning problems of the shipyard were classified and analyzed. In addition, an evaluation factor for establishing an efficient spatial arrangement plan was proposed taking the characteristics of spatial arrangement planning problems into consideration. A heuristic algorithm based on a greedy algorithm was proposed to consider various alternatives in the process of searching candidate locations for arrangement items, and algorithm experiment data were generated by analyzing shipyard arrangement area information and block information to analyze the proposed algorithm and verify its effectiveness. Through this process, the geometrical characteristics of each block assembly stage in shipyards were analyzed, and this result will be utilized not only in this study but also in the future. This study is important in order to efficiently utilize limited space in shipyards and other fields where the size of the arrangement item is relatively larger than the arrangement area.

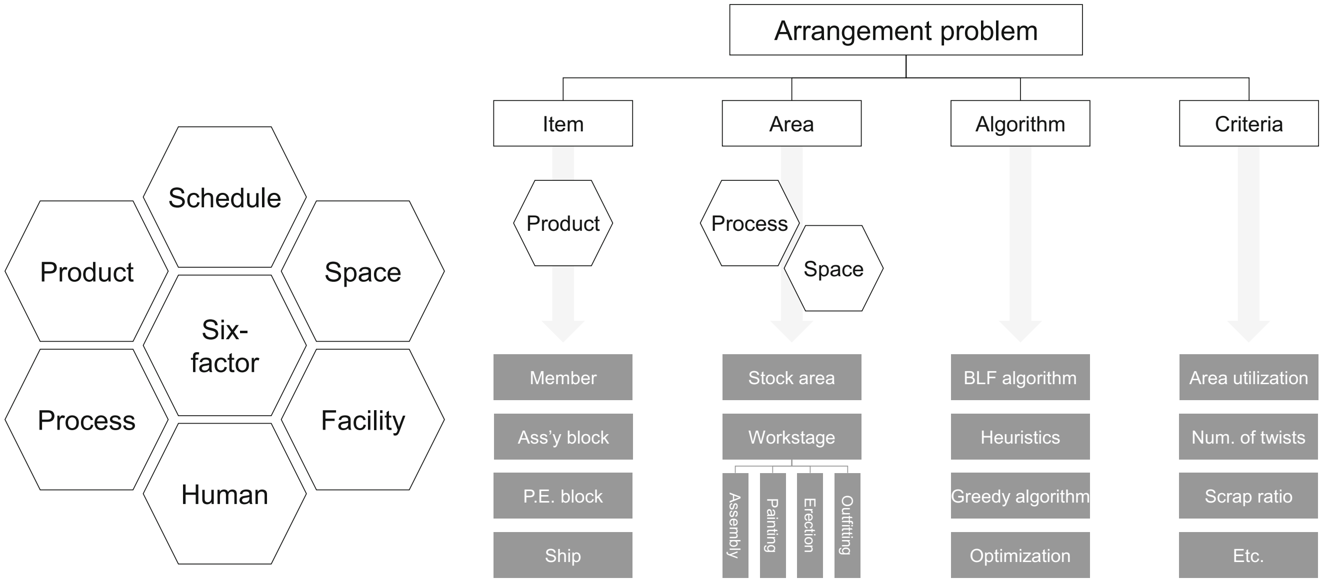
2 Analysis of shipyard spatial arrangement planning problems

Various data from the shipyard to be simulated can be systematized using information models. However, PPR (product, process, and resource) and PPR-S (product, process, resource, and schedule) information models, which are widely used in the manufacturing industry, could not properly reflect the characteristics of shipyards; therefore, the shipyard principal six-factor information model was proposed to address this problem [3]. The shipyard principal six-factor information model expanded the resource factors of the PPR-S information model to space, human, and facility, to reflect the characteristics of the shipyard production process where resource constraints are important as shown in Fig. 1a.

This study aims to systematically address arrangement problems by classifying various spatial arrangement problems occurring in the shipbuilding process using the shipyard principal six-factor information model and analyzing their characteristics. First, to define spatial arrangement problems, it is necessary to clearly identify arrangement items, arrangement areas, algorithms, and evaluation factors. With respect to the arrangement items, product information of the shipyard principal six-factor information model can be used, and members, raw materials, assembly blocks, P.E. blocks, and ships can also be used. The arrangement areas can be defined using product information and spatial information of the shipyard principal six-factor information model. The arrangement areas can be classified into workshops and stock areas based on spatial information. The workshops can be classified into cutting workshops, assembly workshops, painting workshops, erection workshops, and outfitting workshops. This classification can be utilized to classify various arrangement problems that may arise during the shipbuilding process.

Besides these, the items of spatial arrangement problems include algorithms that define the method of arranging the arrangement items in the arrangement areas. As the representative spatial arrangement algorithms, the bottom-left (BL) algorithm for efficiently utilizing two-dimensional space and the bottom-left-fill (BLF) algorithm that enhances the BL algorithm were applied. Various heuristic problem-addressing methods, a greedy algorithm, and an optimization algorithm that uses expert know-how were also applied [24]. Finally, the item for evaluating arrangement results is also one of the important items for defining arrangement problems. When heuristic problem-addressing methods and optimization algorithms are applied, final results may vary depending on how the arrangement results are evaluated. The most commonly used evaluation factor is the area utilization, which is the sum of the arranged areas at a specific time divided by the total area of the arrangement areas. In this study, as mentioned earlier, the number of twist shapes in the free space was used as an evaluation factor. This classification method of spatial arrangement problems can be used to classify arrangement problems implemented in various industries, as well as shipyards. This method is illustrated in Fig. 1b.

Next, various spatial arrangement problems that occur during the shipbuilding process were defined based on the abovementioned method and the shipyard principal six-factor information model. For this purpose, spatial arrangement problems were classified based on the arrangement items (products) and arrangement areas (processes and space). The arrangement items include steel plates, which are basic



(a) Shipyard principal six-factor information model **(b)** Properties of the shipyard arrangement problem

Fig. 1 **a**, **b** Principal information model and properties of the arrangement problem in shipyards

materials for building ships, members made of cut steel plates, assembly blocks made by welding various members, P.E. blocks made by joining several assembly blocks, and ships, which are the final products. The arrangement areas were classified into workshops and stock areas. The workshops were classified into cutting workshops, assembly workshops, erection workshops, and outfitting workshops based on the shipbuilding process. If shipyard spatial arrangement problems are defined based on such criteria, the problems can be classified into nesting problems for cutting steel plates at cutting workshops, member arrangement problems in assembly workplaces, and block arrangement problems as shown in Fig. 2.

Essentially, various shipyard spatial arrangement problems aim to efficiently utilize space. Nesting problems, however, aim to efficiently use steel plates by arranging as many members as possible on the steel plates. Therefore, unlike other spatial arrangement problems, they do not need to consider the time when the arrangement areas are utilized. In general, nesting problems aim to minimize the area of the steel plates that are left after cutting. As a similar situation frequently occurs in other industries, commercial software is relatively widely used to address such problems. Next, member arrangement problems, assembly block arrangement problems, and P.E. block arrangement problems have the characteristics of determining the locations of arrangement items by considering their arrival and departure sequences in the arrangement areas. These problems are similar to each other, although there are differences in the sizes of the arrangement items, types of facilities used for transportation, and the sizes of the arrangement areas. In particular, the assembly process is generally performed in an indoor workshop that uses cranes. Therefore, the constraints on the arrival and departure paths of products are not strict, and the locations of the products can be determined without considering such constraints.

As dock arrangement problem or quay arrangement problems have large arrangement items and inflexible constraints on arrangement areas, it is not easy to consider various alternatives. However, as the dock and quay are the most important spatial elements in a shipyard, and these are elements with bottlenecks, algorithms and evaluation factors that can maximize long-term area utilization are required rather than arrangement algorithms and evaluation factors that consider a specific time.

Next, stock area arrangement problems can use the most diverse arrangement algorithms and evaluation factors. The stock area of a shipyard is a place where blocks are temporarily stored. In general, various processes in shipyards are sequentially performed by the push-system method. When the previous process is finished and the next process is not ready, the corresponding products wait in the stock area until the next process is ready. The boundary of the stock area is not distinguished by outer walls. Therefore, spatial constraints are not as strict as other arrangement problems. However, when the locations of arrangement items are determined, the locations of the entrance and the exit connected to the inner road of the shipyard must be considered and the paths of transportation facilities must also be considered because cranes cannot be used. Furthermore, as the sizes of arranged products are large and heavy, there are cases in which the time for transportation facility loading and unloading is also considered. As the outfitting process is applied to the stored products in some cases, algorithms and evaluation factors that take the work areas of humans into consideration are required.

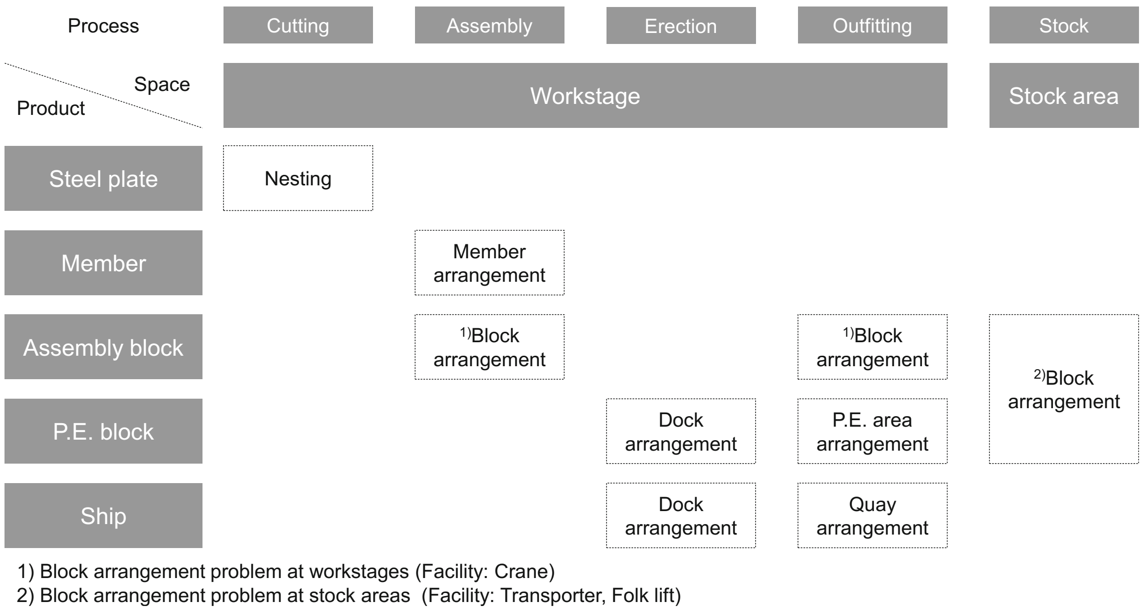


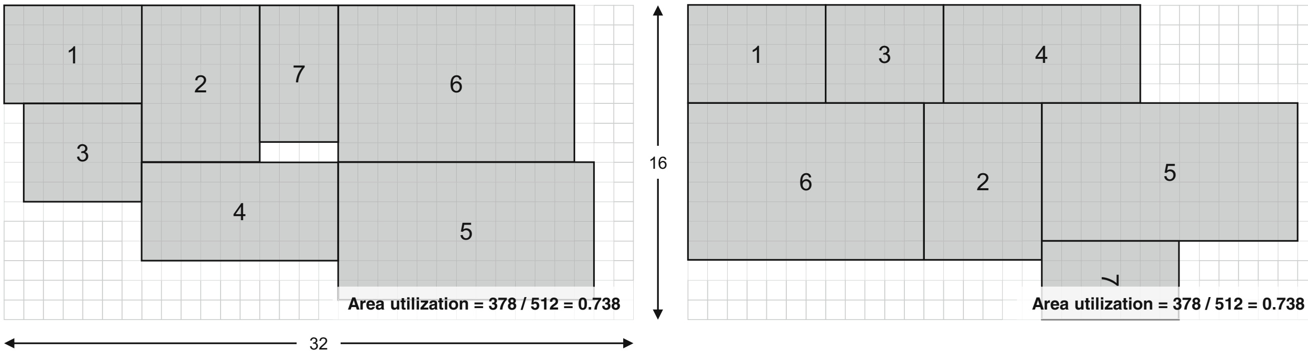
Fig. 2 Classification of arrangement problems in shipbuilding process

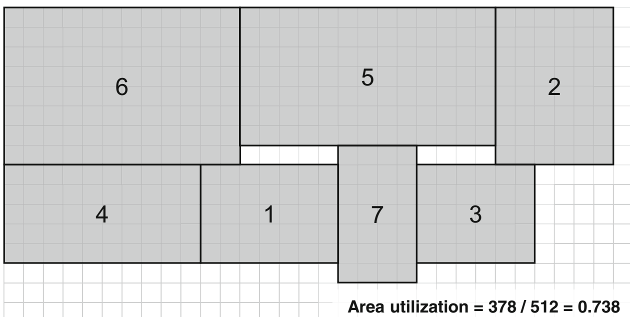
In general, in a shipyard where large merchant ships are built, the HBCM is used in which a ship is divided into several blocks and the blocks are constructed for shipbuilding. As the process progresses, assembly blocks, P.E. blocks, and erection blocks are constructed, and finally, a ship is built by assembling several erection blocks in the dock [1]. As low-level blocks are assembled to make high-level blocks, the product sizes increase as higher-level blocks are constructed. In terms of spatial arrangement, the relative size of an arrangement item to the arrangement area is an important factor. The low-level assembly blocks have small products compared with the size of the working area for the assembly process. In this case, arrangement items can be generally placed at various locations in the free space. Therefore, in the case of arranging small-sized items, the improvement of the arrangement algorithm cannot significantly enhance the arrangement results. However, in the case of large-sized arrangement items, such as P.E. blocks and erection blocks, the arrangement results can be significantly improved depending on how their locations are determined. Therefore, in this study, solutions to large-block spatial arrangement problems are proposed taking their characteristics into consideration.

Next, various evaluation factors can be applied to evaluate the spatial arrangement results. Among these, the area utilization, which represents the ratio of the total projected area of the placed products to the total work space area, is frequently used. As all the items cannot be placed in a situation where multiple arrangement items must be placed simultaneously in a limited space, the area utilization can be calculated differently depending on the algorithm that determines the arrangement order and arrangement locations. However, in the case of arranging the arrangement items of the same combination in a sufficiently large space, since different arrangement orders or arrangement locations always produce the same area utilization, it is difficult to evaluate the arrangement results with only the area utilization (Fig. 3).

In such cases, an additional evaluation factor is required to derive independent evaluation results for different arrangement results. In this study, an evaluation factor based on the shape of the free space unoccupied by arrangement items is proposed. In particular, when large arrangement items, such as P.E. blocks, are placed, the arrangement possibility of unplaced blocks may vary according to the shape of the free space. While an arrangement item can be placed at various locations regardless of the shape of the free space when its size is relatively small compared with the arrangement area, it may not be placed, even if the area of the free space is larger than that of the unplaced block, when its size is relatively large (Fig. 4).

In this study, algorithms and evaluation factors are proposed to efficiently address arrangement problems with arrangement items relatively larger than the arrangement areas. In addition, product information, workshop information, and stock area information of shipyards were analyzed to clearly define various shipyard spatial arrangement planning problems, and based on this, the target arrangement items and arrangement areas of this study were clearly defined. In Section 3, shipyard spatial arrangement planning problems are mathematically modeled and evaluation factors are expressed based on





No.	Length	Width	Area
1	7	5	35
2	8	6	48
3	6	5	30
4	10	5	50
5	13	7	91
6	12	8	96
7	7	4	28
Total			378

Fig. 3 Limitation of area utilization as criteria for block arrangement assessment

the modeling results. In Sections 4 and 5, evaluation factors and algorithms for evaluating the spatial arrangement results are described in detail, respectively. In Section 6, data required for spatial arrangement problems are summarized by analyzing actual shipyard information. Finally, in Section 7, the evaluation factors and algorithms proposed in this study are applied to various types of experiment cases and the results are analyzed.

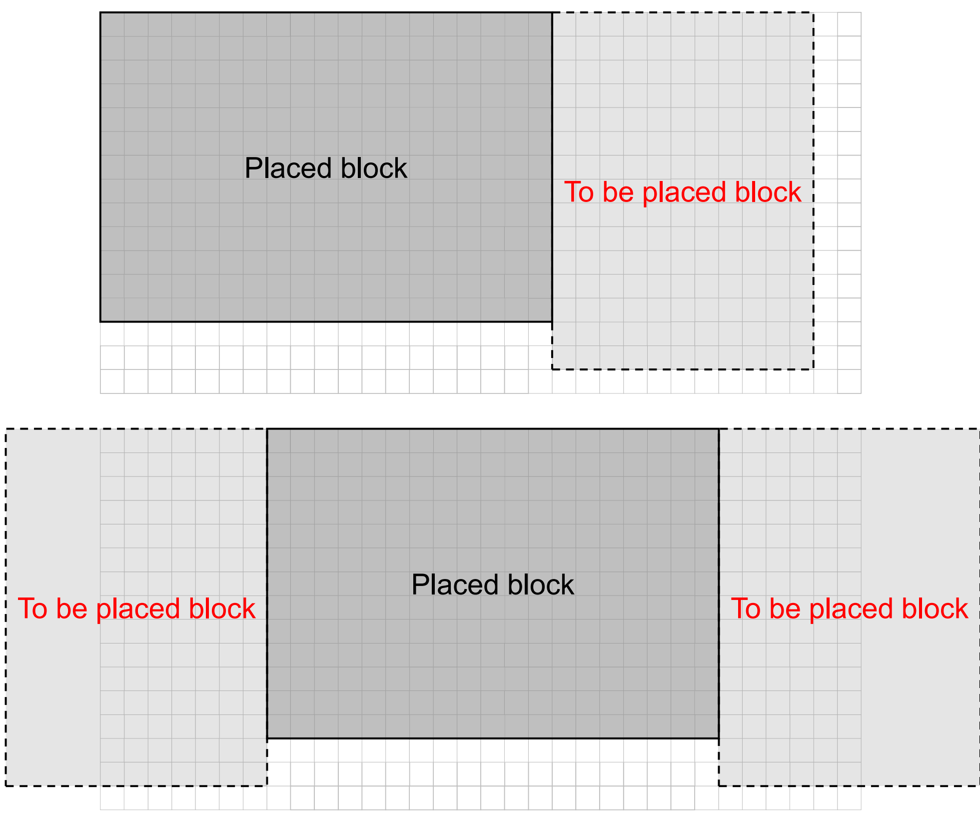


Fig. 4 Arrangement possibility of unplaced block according to the shape of free space

3 Definition of shipyard spatial arrangement planning problems

In this section, variables are defined to specifically express shipyard spatial arrangement planning problems, and the problems are modeled based on such variables. As mentioned earlier, this study focuses on large-block arrangement problems, such as P.E. area arrangement problems. Members made by cutting steel plates have various shapes, but as the assembly process proceeds, the projected shapes become closer to that of a rectangle. The P.E. area is usually located close to the dock of a shipyard, and it has a simple shape according to the shape of the dock. Therefore, in this study, the problems are defined by simplifying the arrangement items and arrangement area as rectangular shapes.

The arrangement area was defined with L unit cells in the horizontal direction and W unit cells in the vertical direction, and the unit cell is a square with a side length s. The variable β_{ijt} was defined to indicate whether the unit cell c_{ij} located in the i-th horizontal direction and in the j-th vertical direction is occupied by an arrangement item at a specific time t. β_{ijt} is 1 if c_{ij} is occupied, or 0 if not (Eq. 1).

$$\beta_{ijt} = \begin{cases} 1 & \textit{if unit cell } c_{ij} \textit{ is occupied} \text{ at } t \\ 0 & \textit{otherwise} \end{cases} \tag{1}$$

The item placed in the unit cell c_{ij} occupies the unit cell for a predetermined period and releases the occupation on the outgoing date. c_{ijt} was defined as a variable indicating the occupancy period remaining in a unit cell at a specific time t (Eq. 2), and the set of variables c_{ijt} for all unit cells at a specific time t was defined as $\mathbf{C_t}$ as shown in Fig. 5. In addition, the variable β_{ijt} can be computed as 1 if c_{ijt} is positive at a given time t, or 0 if c_{ijt} equals 0 (Eq. 3).

$$c_{ijt} = \textit{remaining placement period of the current unit cell } c_{ij} \text{ at } t \tag{2}$$

$$\beta_{ijt} = \begin{cases} 1 & c_{ijt} > 0 \\ 0 & c_{ijt} = 0 \end{cases} \tag{3}$$

Next, the set of arrangement items to be placed in the arrangement area was defined as $\mathbf{B}$, and the set $\mathbf{B}$ includes N arrangement items b_k. To express the geometrical characteristics of the arrangement item b_k, a variable l_k representing the length and another variable w_k representing the width were defined, and α_{kt} was defined to indicate whether b_k was placed at the present time. α_{kt} is 1 if b_k is placed in the arrangement area at the present time, or 0 if not (Eq. 4).

$$\alpha_{kt} = \begin{cases} 1 & \textit{if } b_k \textit{ is placed} \text{ at } t \\ 0 & \textit{otherwise} \end{cases} \tag{4}$$

The variable f_k was defined to distinguish the case where the item b_k belonging to the set $\mathbf{B}$ has already been placed and released. f_k is 0 if the arrangement of b_k is completed, or 1 if not (Eq. 5).

$$f_k = \begin{cases} 0 & \textit{if } b_k \textit{ have finished arrangement process} \\ 1 & \textit{otherwise} \end{cases} \tag{5}$$

The planned arrival and departure dates of b_k were defined as d_{1k} and d_{2k}, respectively. The variable b_k shows its planned arrangement period using these variables as indicated in Eq. 6.

$$p_k = d_{2k} - d_{1k} \quad \textit{scheduled arrangement period of } b_k \tag{6}$$

When the arrangement item b_k is placed in the arrangement area, the placed location can be expressed as (x_k, y_k), which indicates the location where the upper left unit cell of b_k is arranged in the arrangement area. The variables related to the arrangement item b_k are shown in Fig. 6.

The factors for evaluating the spatial arrangement results can be expressed using the variables defined above. In general, the area utilization u_t is used to evaluate the arrangement results at a specific time t. This can be calculated by dividing the sum of the projected areas of the arrangement item placed at the current time t by the area of the arrangement area as indicated in Eq. 7.

$$u_t = \frac{\textit{Total area of placed items}}{\textit{Total area}} = \frac{\sum_k a_{kt} f_k (area_k)}{LW} = \frac{\sum_k a_{kt} f_k l_k w_k}{LW} \tag{7}$$

As shown in Eq. 7, the area utilization evaluates the arrangement results at a specific time. A high area utilization indicates a small wasted arrangement area. However, it is also important to efficiently operate the arrangement area in the long term in spatial arrangement planning. Therefore, how uniformly the entire arrangement area has been utilized can be an important evaluation factor. This can be compared by using the cumulative occupation date of each unit cell, and the degree of uniform utilization can be quantitatively calculated using the standard deviation of this value. The cumulative occupation date of each unit cell was defined as COD_{ij} as indicated in Eq. 8, and the average value calculated for all cells was defined as indicated in Eq. 9. Using this, the standard deviation of the cumulative occupation date of each unit cell can be calculated as indicated in Eq. 10.

$$COD_{ij} = \sum_t \beta_{ijt} \tag{8}$$

$$\overline{COD_{ij}} = \frac{COD_{ij}}{LW} \tag{9}$$

$$\sigma = \sqrt{\frac{\sum_i \sum_j \left(COD_{ij} - \overline{COD_{ij}} \right)^2}{LW}} \tag{10}$$

In this study, the area utilization and the standard deviation of the cumulative occupation date of each unit cell defined by

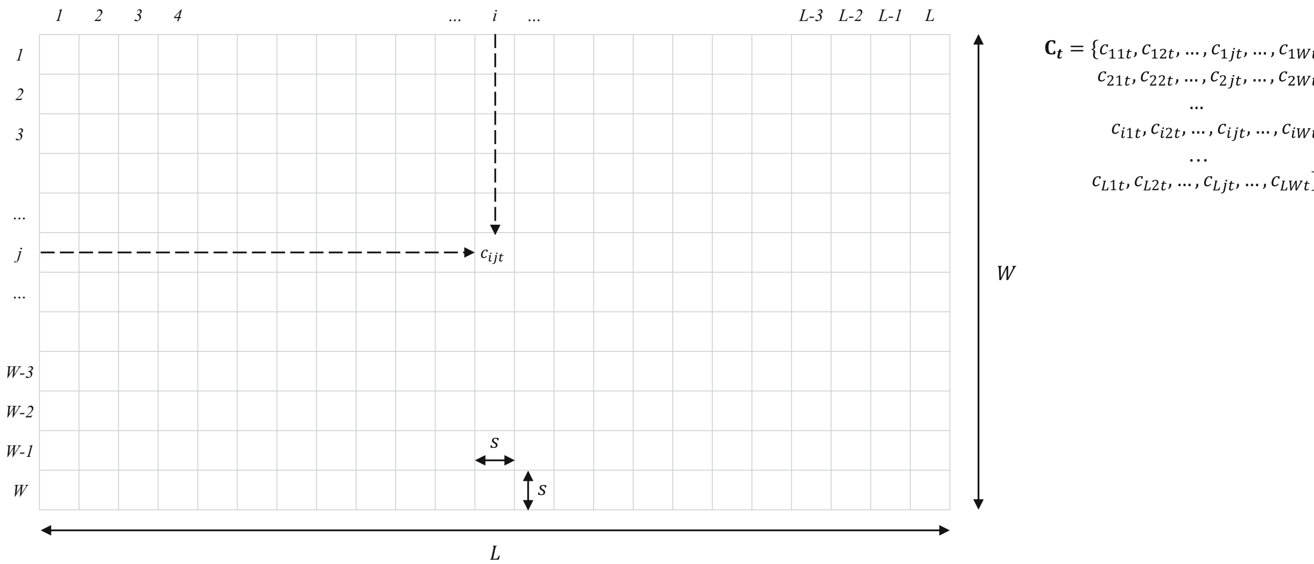


Fig. 5 Variables related with an arrangement area and unit cells

Eq. 7 and Eq. 10 were used as basic evaluation factors for evaluating the spatial arrangement results. In the next section, the evaluation factors used in applying the spatial arrangement algorithm will be discussed.

4 Evaluation factors for spatial arrangement results taking free space and unplaced blocks into consideration

As mentioned in Section 2, in the case where the size of the arrangement item is relatively larger than the arrangement area, the shape of the free space has a significant influence on the arrangement of a new arrangement item. Therefore, in this study, in addition to the basic evaluation factors, the evaluation factors that can quantitatively evaluate the shape of the free space were additionally considered when the location of the arrangement item was determined.

First, the number of twist shapes (n_t) was used as an evaluation factor to express the shape of the space that is not occupied by the arrangement item as a quantitative value. The number of twist shapes indicates the smallest number of rectangles that can divide an arbitrary polygonal space [23]. The more complicated the shape of the free space becomes, the larger the value of n_t. In this case, the possibility of placing a new block is low even when the sum of the areas of the free space is larger than the area of the new block. Therefore, when the location of the arrangement item is determined, a smaller value of n_t can increase the possibility of the item being placed. The value of n_t can be calculated using various methods for the same arrangement results as shown in Fig. 7. As the value of n_t is the same if it is calculated by any proper method, this factor is considered appropriate as an evaluation factor.

When the spatial arrangement results are evaluated only by the number of twist shapes, the same value is frequently calculated for various arrangement results. Therefore,

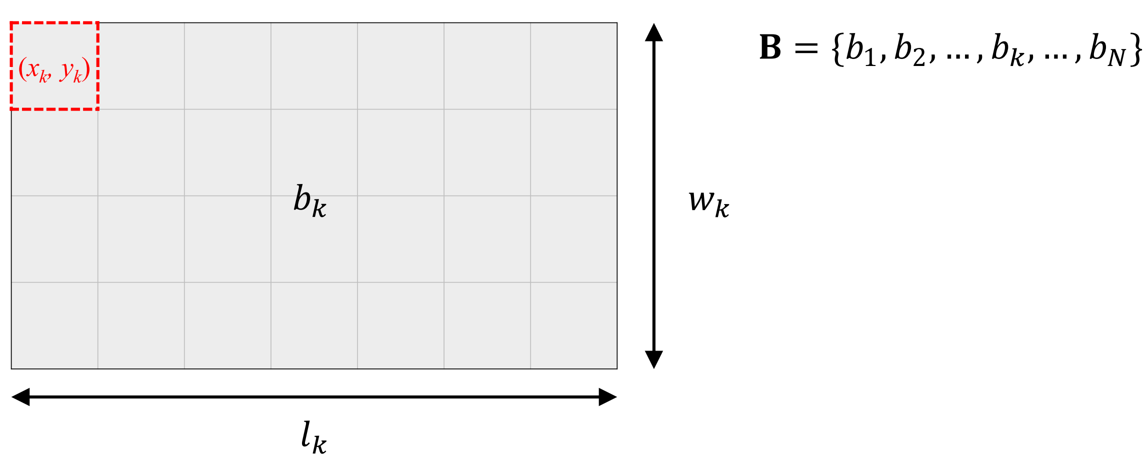


Fig. 6 Variables related with an arrangement item

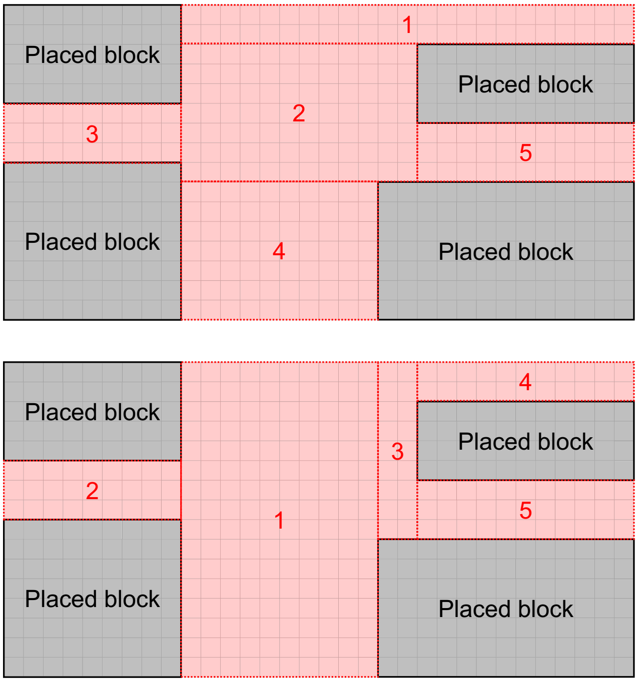


Fig. 7 Number of twist shapes according to calculation method

evaluating the spatial arrangement results only by the number of twist shapes is not appropriate for finding an alternative with the best quantitative evaluation results among various arrangement alternatives. To supplement this, the evaluation factor used in existing spatial arrangement problems was used as an auxiliary evaluation factor in this study. Lee et al. studied algorithms and evaluation factors for arranging rectangular polygonal modules in the process of designing the layout of a leisure boat production factory [25]. To derive the layout in which the modules were arranged densely, the number and length of the sides contacting the placed module and the location of the center of the layout were taken into account when the location of the new module was determined. For the module to be densely arranged, the number and length of the sides contacting the placed modules must be high and long, and the location of the newly made layout center must be close to the specific location, such as the origin. In this study, these concepts were utilized, and the number and length of the sides of the arrangement items contacting each other, as well as the distance between the origin and the layout center, were used as evaluation factors. A higher number and length of the sides contacting the placed items yield excellent evaluation. A shorter distance between the origin and the layout center yields better evaluation by considering that a shorter distance produces denser arrangement results. This concept may help to derive the arrangement results taking the locations of the entrance and the exit of the storage yard or workshop into consideration in shipyard spatial arrangement problems. Although the origin is currently the reference point, it is possible to derive the arrangement results concentrated near the entrance and the exit when their locations are set as the reference point.

The evaluation factors defined for evaluating the spatial arrangement results at a specific time t include the number of twist shapes n_t, the length of the contacting sides cl_t, the number of the contacting sides cs_t, and the distance between the origin and the layout center d_t as shown in Fig. 8. As it is difficult to compare each evaluation factor from the same perspective, the values of all evaluation factors were normalized to values between 0.0 and 1.0 in this study. The evaluation factors were used to calculate and compare values for all possible candidate locations at a specific time t. To compensate these values, the evaluation factors were calculated for all candidate locations and normalized by dividing each value by the maximum value.

In this study, all arrangement alternatives were quantitatively compared using a greedy algorithm, and an item was placed in the location that has the largest objective function value at the present time. The objective function value was calculated by normalizing the values of n_t, cl_t, cs_t, and d_t as mentioned earlier. If the objective function using the four evaluation factors is defined as z_t, it can be calculated as indicated in Eq. 11. ω_n, ω_{cl}, ω_{cs}, and ω_d are the weights of the evaluation functions n_t, cl_t, cs_t, and d_t, respectively. The importance of each evaluation factor can be adjusted by changing its weight value.

$$z_t = \omega_n\left(1-\frac{n_t}{\max(n_t)}\right) + \omega_{cl}\frac{cl_t}{\max(cl_t)} + \omega_{cs}\frac{cs_t}{\max(cs_t)} + \omega_d\left(1-\frac{d_t}{\max(d_t)}\right) \tag{11}$$

In order to consider the free space of the workshop, this section defined four evaluation factors that can evaluate the shape of the free space (Eq. 11). These evaluation factors are used to determine the possibility and arrangement position of the arrival block for a case in which the order and the date of the block is determined. The evaluation factors are determining and evaluating the appropriate arrangement location for cases in which the order and the arrival date of blocks are determined. In addition, the following three factors are used to evaluate the spatial arrangement results for the entire arrangement period. The change of the area utilization rate, the number of unplaced blocks and the number of cumulative unplaced days were analyzed as evaluating indicators for the entire period. These evaluation factors are not used in the process of performing spatial arrangement algorithm but are used to evaluate the results of the application of the long-term spatial arrangement algorithm.

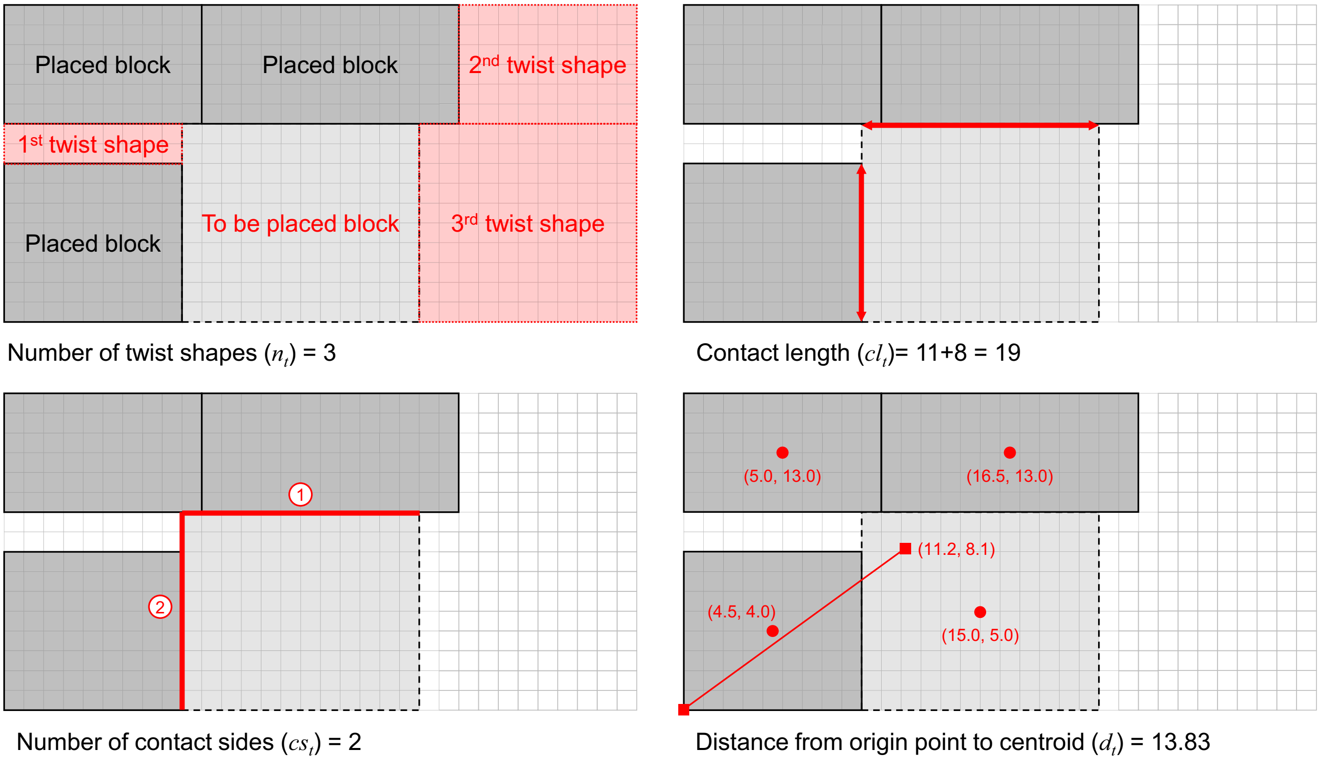


Fig. 8 Arrangement evaluation factors and examples

5 Spatial arrangement planning algorithm using a greedy algorithm

In shipyards, keeping the ship's delivery date is the most important factor. Therefore, the start dates and end dates of the processes are determined in consideration of the delivery date at the time of establishing the production plan. If a process is not performed as planned, various related processes may be delayed. Therefore, the start dates and end dates of the processes determined at the production planning stage must be observed. However, in reality, the processes may be delayed depending on the situation at the production site. This can be confirmed by carrying out a simulation. In this study, a simulation was conducted to determine the influence of spatial arrangement results on subsequent processes in the situation where the start dates of the processes and work priorities have been determined.

Spatial arrangement algorithms utilized in various industries aim to derive the result when the objective function is minimized by changing the arrangement item combination, arrangement order, and arrangement locations to efficiently utilize space. In particular, for the nesting problem of Fig. 2, many studies have been conducted to determine the optimal arrangement order and locations using various algorithms. In the case of spatial arrangement planning problems, however, as the arrival and departure of arrangement items in the arrangement area are repeated, the arrangement status continuously varies over time. For such cases where the arrangement status varies over time, there are many variables to be considered to find the optimal spatial arrangement solution and it is difficult to derive the optimal solution if all variables are considered. Therefore, in this study, problems were simplified by simplifying the shapes of the arrangement item and arrangement area, and limiting the variables to be considered. Furthermore, spatial arrangement was performed using a greedy algorithm, which selects the best alternative at the present time, rather than algorithms for finding a strict optimal solution. To improve the performance of the algorithm, candidate arrangement locations were selected through reasonable assumptions and the objective function values defined in Section 4 were calculated for each candidate location. The arrangement item was placed at a position having the best evaluation result among multiple candidate locations, and this process was repeated until all the arrangement items were placed.

The spatial arrangement planning algorithm based on a greedy algorithm, which is proposed in this study, considered the flow of time and it consists of two stages. For the entire planning period, the first stage was to eliminate the arrangement items that were departing on the corresponding date from the arrangement area, and the second stage was to determine the locations of the arrangement items that were arriving on the date. This process is shown in Fig. 9 using a flowchart and defined variables. As the proposed algorithm is based on a greedy algorithm, it selects the solution with the best evaluation result in a situation where decision-making is required rather than finding the optimal solution for the entire planning period. If there is no arrangement location available, the

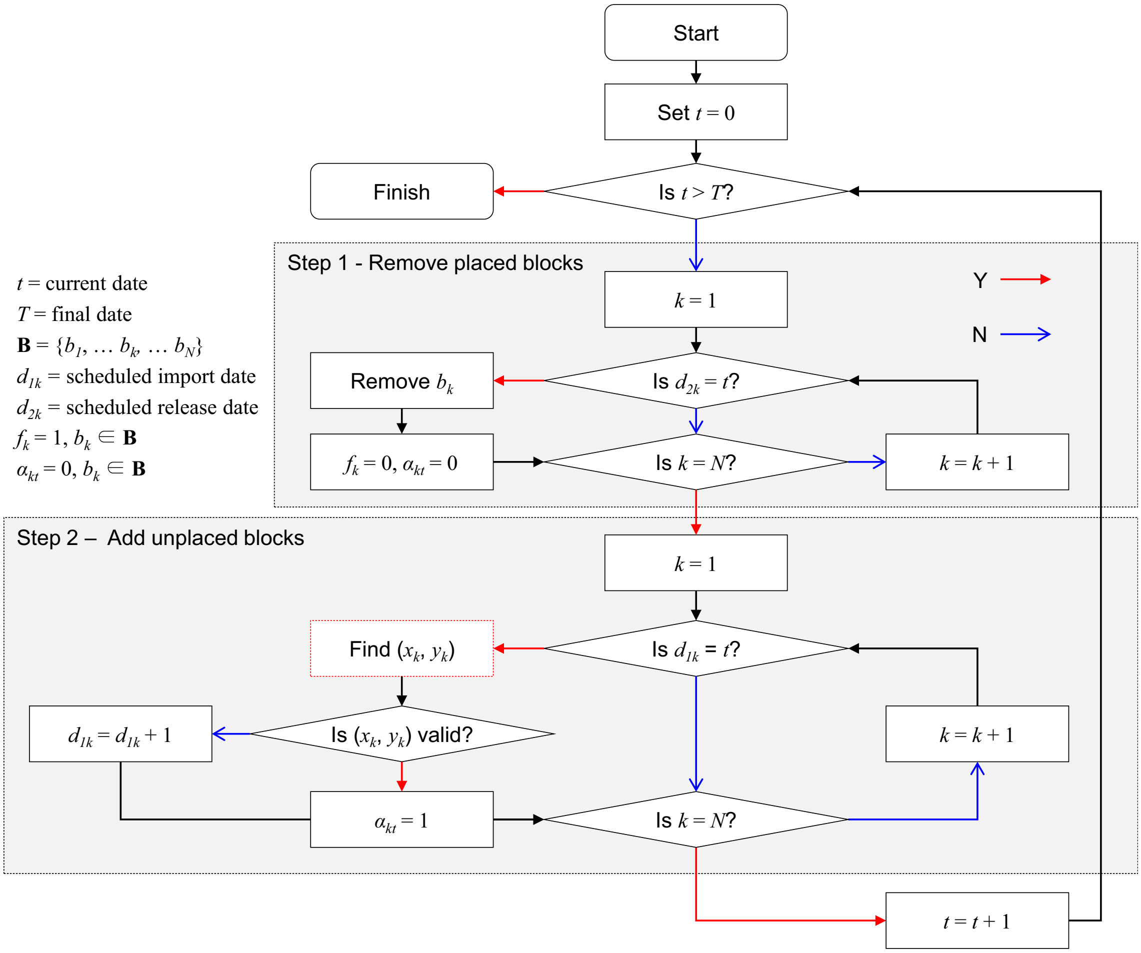


Fig. 9 Flow chart of spatial arrangement planning algorithm based on the greedy algorithm (Greedy-TW)

planned arrival data is changed to the following date and the search is performed again as shown in Fig. 9.

In the second stage, the vertex-edge-based candidate location searching algorithm was applied to search for the candidate locations of arrangement items. The basic heuristic algorithm for placing a rectangular polygonal item, such as a large block in a shipyard is the BL algorithm [26]. This algorithm densely places arrangement items to the bottom left of the arrangement area. Later, a BLF algorithm was proposed [27], which compensates for the shortcomings that the space surrounded by arrangement items cannot be considered. While these algorithms produce reasonable results, they fail to accurately reflect the situation at the worksite. In this study, the vertex-edge-based candidate location searching algorithm was proposed to reasonably reflect the situation at the worksite and to keep the shape of the free space simple. A new arrangement item can be placed with its vertex or edge contacting those of the placed items. The detailed method is shown in Fig. 10a.

The candidate location for arrangement was selected through four steps. First, all vertices of the placed items were selected as candidate locations, and then all vertices of the arrangement area were selected as candidate locations. Next, all crossing points between the extension lines of the placed items' edges and all edges of other placed items were selected as candidate locations. Finally, all crossing points between the extension lines of the placed items' edges and the outlines of the arrangement area were selected as candidate locations. If the candidate locations overlapped, they were merged into one candidate location, and the objective function was calculated for all candidate locations when they were not overlapped with the placed items and were placed within the arrangement area as shown in Fig. 10b. If a new item was placed at the candidate location selected based on the vertices and edges of the placed items, the shape of the free space was simplified, to assist in the arrangement of a new item. The objective function values were calculated for multiple candidate locations and a location with the largest value was selected.

6 Analysis of shipyard spatial arrangement planning data

To verify the spatial arrangement evaluation factors and algorithms proposed earlier, appropriate data for the products and

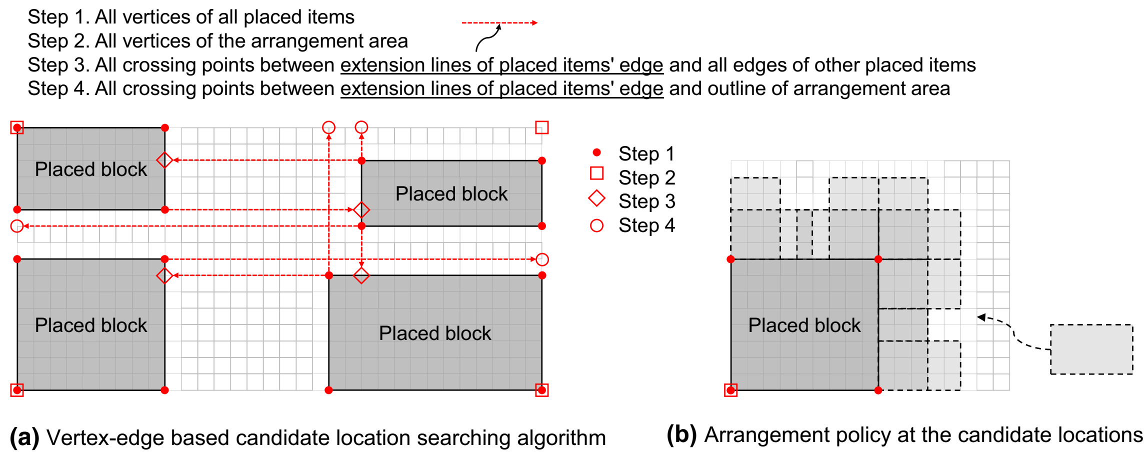


Fig. 10 **a**, **b** Candidate location searching algorithm and arrangement policy

space are required. For this purpose, data on two medium-sized shipyards in South Korea was collected and analyzed in this study. The product information was classified into members, subassembly blocks, assembly blocks, first P.E. blocks, and second P.E. blocks for analysis according to the assembly status of the products. The geometric shape information of blocks plays an important role in verifying the effectiveness and performance of evaluation factors and algorithms. Therefore, the results were analyzed based on geometric shape information, such as length and area. In addition, for the analysis results of this study to be utilized for cases where data on shipyard product information is insufficient, standard deviations and averages of the length and area according to the product status were calculated. These results can be used as data for experimenting with the spatial arrangement planning algorithm in various situations.

6.1 Analysis of geometric characteristics according to product assembly stages

In this study, the product information of two medium-sized shipyards in South Korea was analyzed. Shipyard A used information on 15,106 products of 39 ships and shipyard B used information on 3080 products of 11 ships. The total area of blocks in shipyard A was 2,511,274 m^2 and that in shipyard B was 1,222,623 m^2. Although the area may vary according to the size of the final product, shipbuilding method, and product assembly state, it was confirmed that on the average, shipyard B had larger products compared with shipyard A. The fact that the average product size was larger indicates that shipyard B had a larger space or maximum facility capacity than shipyard A.

In shipyards, products are classified according to the product assembly stages, and each shipyard may have different standards. In general, products are classified into steel plates, members, assembly blocks, and P.E. blocks. In this study, assembly blocks and P.E. blocks were further classified into sub-assembly blocks, assembly blocks, first P.E. blocks, and second P.E. blocks for the analysis of shipyard product information.

As mentioned above, product information of shipyard A and shipyard B was divided into four types according to the product assembly stages, and the averages and standard deviations of the long-axis length, the short-axis length, and the area were calculated. The averages of the long-axis length, the short-axis length, and the area according to the product assembly stages are summarized in Fig. 11. Figure 11d compares the average sizes of the products in shipyards A and B according to the assembly stages. Table 1 presents the results, including standard deviations. As the shipyards assemble low-level products to make high-level products, the long-axis length and the short-axis length increased as the product assembly stage progressed. It is possible to estimate the minimum required area and maximum capacity of space or facility by analyzing the average size of each assembly stage of the product. In this study, these results were used to randomly generate blocks by product assembly stages.

6.2 Definition of experiment cases

The algorithm proposed in this study is characterized by considering the free space and unplaced blocks with arrangement evaluation factors, including the number of twist shapes as described above. Such characteristics were considered to be effective in large-block arrangement problems among various shipyard spatial arrangement problems, where the area of the arrangement item occupies more than a certain ratio of the area of the arrangement area. When the area of the arrangement item is small, a sufficient number of unplaced blocks can be placed in the free space without considering the number of twist shapes. However, when the area of the arrangement item is large, even if the area of the free space remains the same, the shape of the unplaced block may influence the possibility of its placement. In this section, to verify the effectiveness of the algorithm proposed in this study, experiment cases for the spatial arrangement algorithm were developed according to the composition ratios of different arrangement items. Data

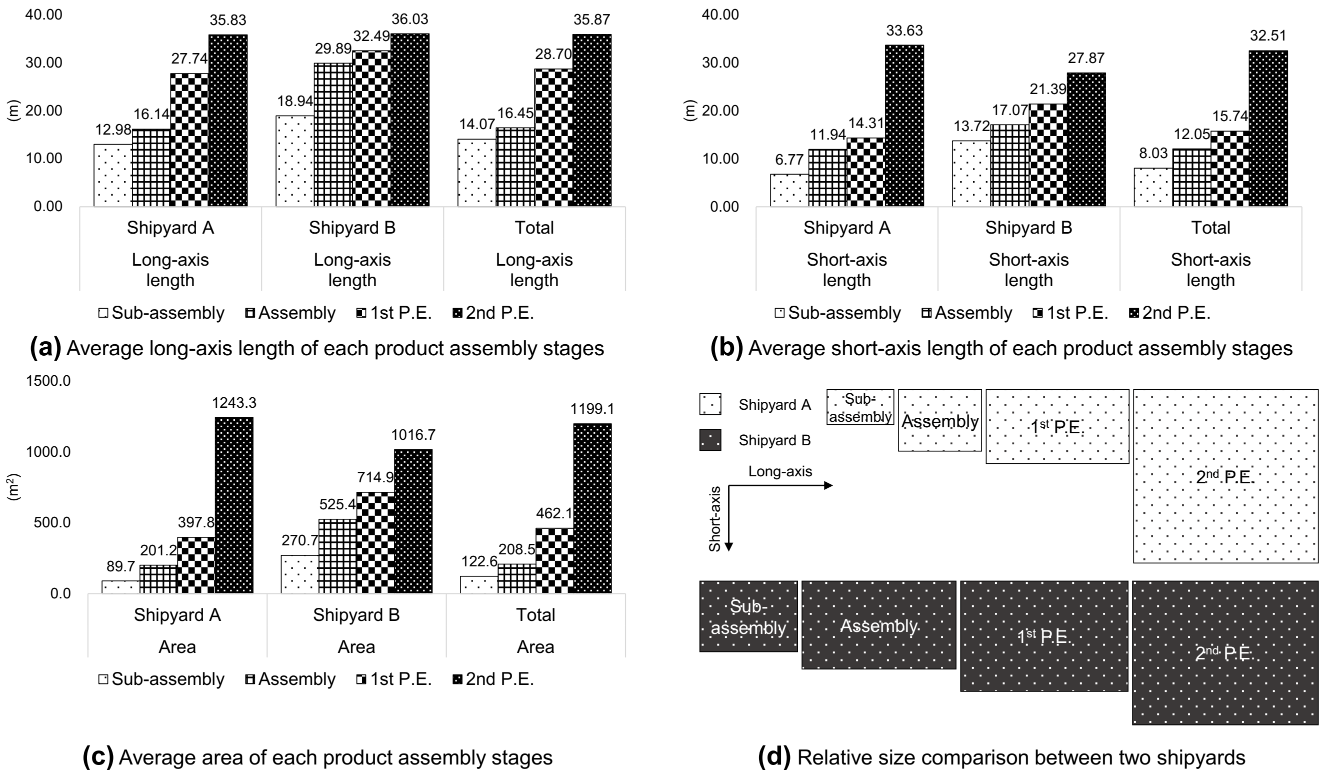


Fig. 11 **a**–**d** Analysis results of geometric characteristics according to product assembly stages

collected from shipyards can be directly used in the experiments. However, as insufficient data was collected and to identify the performance of the algorithm by variously changing the composition of the products according to the assembly stages, virtual product information was created based on data analysis presented in Section 6.1. The long-axis length and short-axis length of the virtually created product were arbitrarily generated within the range of the standard deviation based on the average value.

Essentially, experiment cases for the spatial arrangement algorithm were developed based on the spatial arrangement problems determined by the combination of the arrangement area and arrangement item. Shipyard spatial arrangement problems can be divided into two cases: the first case has a workshop as the arrangement area and the second has a stock area as the arrangement area. In the first case, generally one type of arrangement item arrives, but in the second case, various types of arrangement items arrive. Reflecting this, the

Table 1 Analysis results data of geometric characteristics according to product assembly stages

Variables	Source	Product assembly stages							
		Sub-assembly		Assembly		1st P.E.		2nd P.E.	
		Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev
Long-axis length (m)	Shipyard A	12.98	3.36	16.14	5.39	27.74	4.06	35.83	6.69
	Shipyard B	18.94	4.71	29.89	5.89	32.49	8.55	36.03	2.35
	Total	14.07	4.31	16.45	5.77	28.70	5.62	35.87	6.09
Short-axis length (m)	Shipyard A	6.77	3.33	11.94	3.41	14.31	4.54	33.63	7.15
	Shipyard B	13.72	4.49	17.07	4.43	21.39	5.47	27.87	8.90
	Total	8.03	4.46	12.05	3.52	15.74	5.53	32.51	7.86
Area (m^2)	Shipyard A	89.66	51.99	201.16	89.50	397.79	145.56	1243.32	479.19
	Shipyard B	270.68	120.62	525.39	172.84	714.91	332.51	1016.73	347.73
	Total	122.58	98.65	208.45	103.99	462.11	235.75	1199.11	465.27

spatial arrangement problems of the sub-assembly block workshops, assembly block workshops, 1st P.E. block workshops, and 2nd P.E. block workshops had arrangement items limited to the blocks of the corresponding workshops. Stock areas were classified into small-block stock areas and large-block stock areas, and the spatial arrangement problems were defined using different combinations of various types of arriving blocks. For example, the spatial arrangement problems for a small-block stock area are composed of 50% of sub-assembly blocks, 30% of assembly blocks, and 20% of 1st P.E. blocks, and the spatial arrangement problems for a large-block stock area are composed of 20% of 1st P.E. blocks and 80% of 2nd P.E. blocks (Table 2). The BLF algorithm and the algorithm proposed in this study (Greedy-TW) were applied to all spatial arrangement problems and compared. The detailed results will be discussed in the next section.

The shape and size of the arrangement area were determined by referring to the actual workshops and storage areas in shipyards. Most of the workshops in shipyards had a rectangular shape with the ratio of the short axis to the long axis ranging from 1:3 to 1:5, while stock areas had a square shape or a rectangular shape. Taking this into consideration, different arrangement areas were applied to each experiment case as presented in Table 2. The arrival date and departure date of virtually block data were applied to all cases in the same manner by referring to the production plan of shipyard A. When there was insufficient space on the date of block arrival, the block was considered as a delayed block and the arrangement location for a delayed block was preferentially searched on the next date.

7 Algorithm application and simulation result analysis

In Section 6, a total of five experiment cases were defined. They had different combinations of arrangement areas and arrangement items. The BLF algorithm and the Greedy-TW algorithm proposed in this study were applied to each experiment case under the same conditions. The number of arrangement items was 200 for all the experiment cases, and the arrival dates and orders were applied in the same manner. The arrangement simulation was conducted from December 10, 2014, which is the day when the arrangement items arrived for the first time, to July 22, 2015.

First, the difference between the arrangement results due to the application of the BLF algorithm and the Greedy-TW algorithm was investigated. As arrangement items were placed in accumulation if the arrangement simulation was conducted for more than a certain period of time, it is difficult to identify the difference between the results of the different algorithms. Therefore, the arrangement results of December 23, 2014, when seven blocks were placed in the arrangement area, were compared. As the free space was large enough in the initial period of the arrangement simulation, there was no difference in the area utilization, although the arrangement algorithms were different. However, as shown in Fig. 12, the locations of the respective arrangement items were different. In Fig. 12, the figure at the top shows the results of the BLF algorithm and the figure at the bottom shows the results of the Greedy-TW algorithm. In both cases, the area utilization was the same (26.11%), but in the case of the BLF algorithm, the free space was divided. In the case of the Greedy-TW algorithm, however, the free space was integrated and it was observed that 10A block and 10B block were placed in close contact with the upper and lower ends of the arrangement area, respectively. Through these results, the Greedy-TW algorithm shows that arrangement items were placed in a direction favorable for inputting the next arrangement item as compared with the conventional heuristic arrangement algorithm.

The area utilizations for the five experiment cases were compared for the entire simulation period. Area utilization is an evaluation factor that focuses on the efficient use of the arrangement area at a specific time rather than the efficient use of the arrangement area during the entire period. However, it can be utilized to confirm whether the arrangement area was efficiently used during the entire period through the overall trends and changes of the area utilization. Figure 13 shows the trends of the area utilization for each experiment case during the arrangement simulation period. At the beginning of the simulation, there was no difference between the algorithms in all cases. This means that there was

Table 2 Experiment case list and conditions

Test case	Arrangement problem type		Composition ratio of arrangement items				Arrangement area
			Sub-assembly block	Assembly block	1st P.E. block	2nd P.E. block	
Case 1	Workstage	Sub-assembly	100%	–	–	–	20 × 100
Case 2		Assembly	–	100%	–	–	30 × 150
Case 3	Stock area	Small-size block set no. 1	50%	30%	20%	–	200 × 200
Case 4		Large-size block set no. 1	–	20%	30%	50%	100 × 300
Case 5		Large-size block set no. 2	–	–	20%	80%	100 × 300

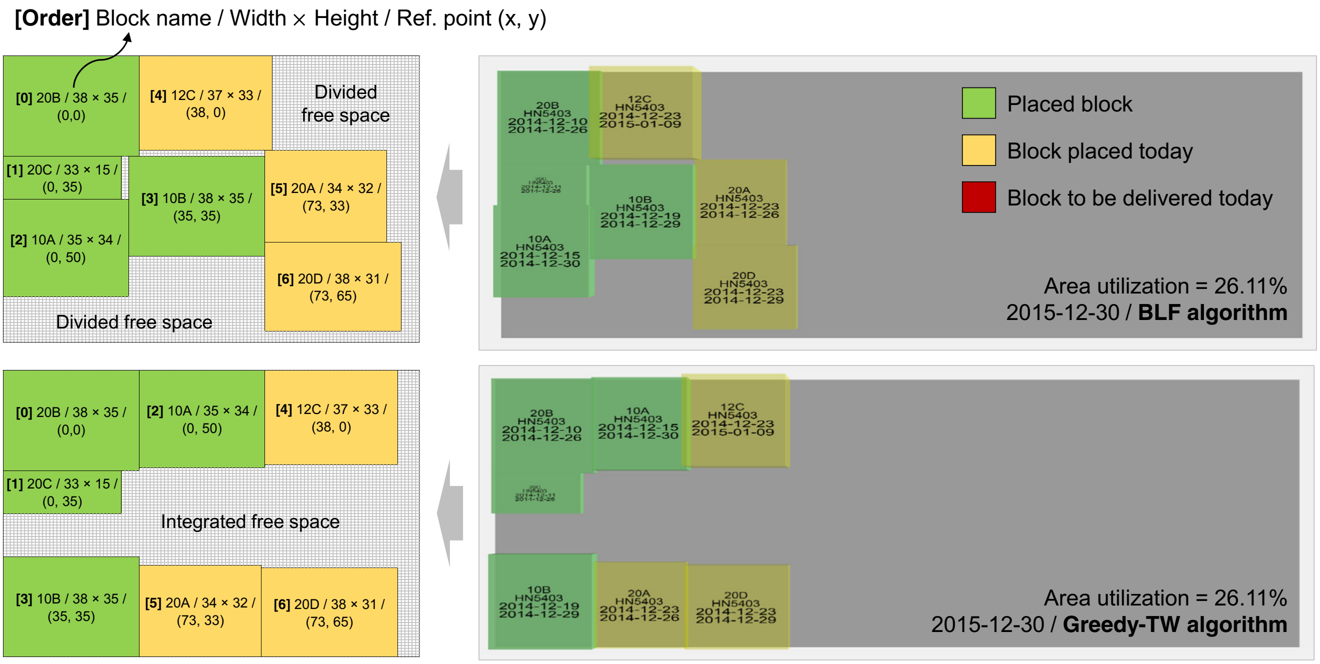


Fig. 12 Comparison of BLF algorithm and Greedy-TW algorithm

no difference between the algorithms when the free space was large enough. In addition, in case 3, there was no significant difference in the area utilization between the algorithms compared with other experiment cases. This is because the arrangement item having a small size can be placed at any location without being significantly influenced by the shape of the free space. Case 3 had a higher mixing ratio of the relatively small arrangement items than the other experiment cases. Case 5 had the most similar characteristics to large-block spatial arrangement planning problems, which is the subject of this study. It was confirmed that the Greedy-TW algorithm proposed in this study showed higher area utilization than the BLF algorithm during most periods of the simulation. Through these results, it can be seen that the algorithm

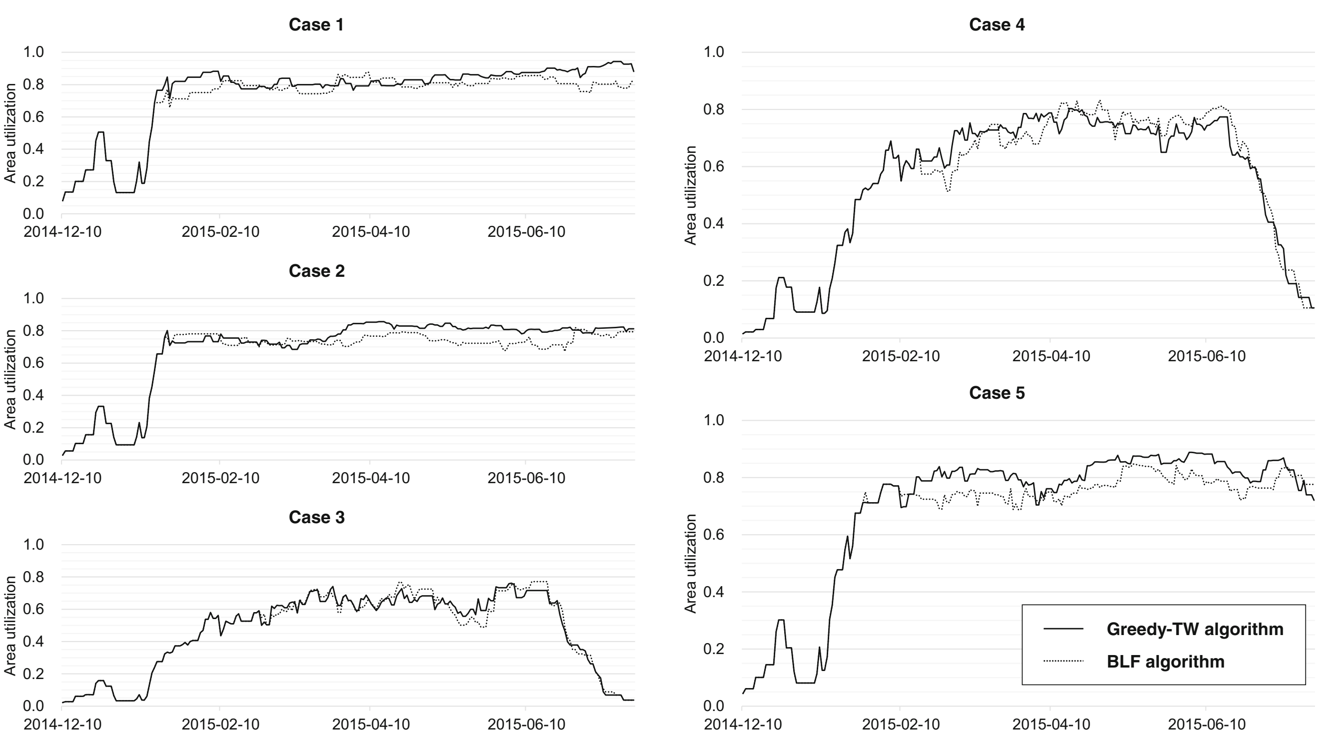


Fig. 13 Area utilization rate by experiment cases

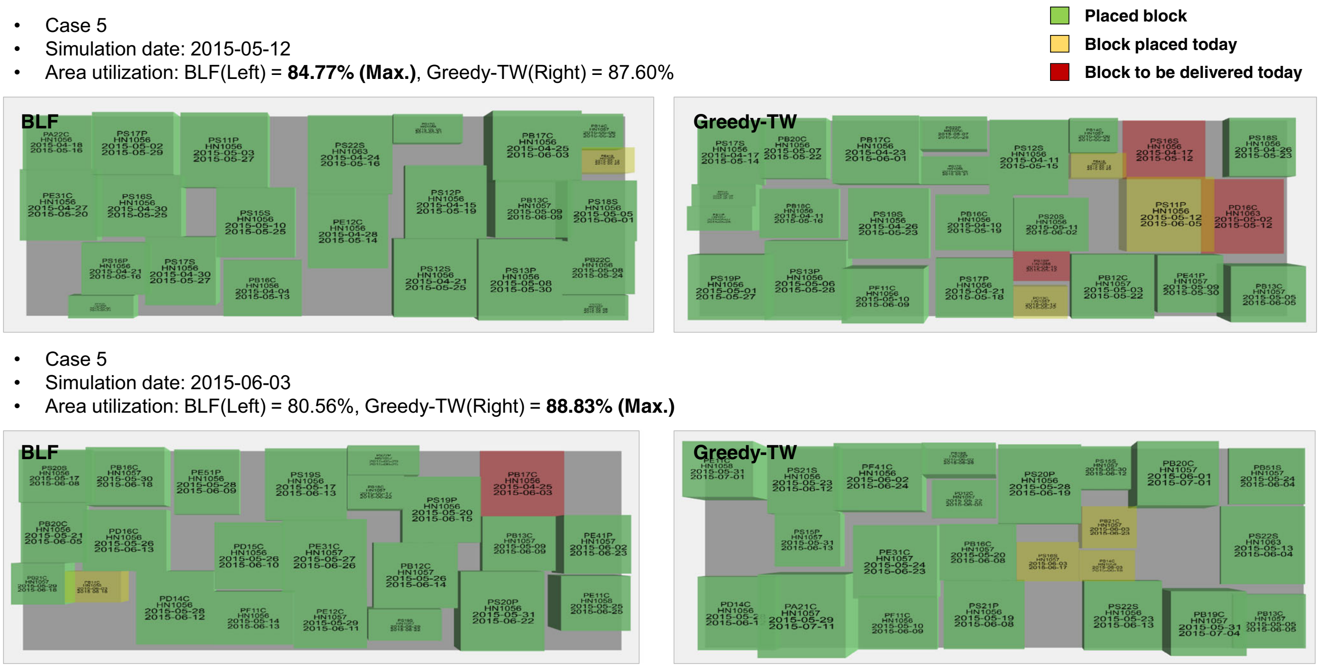


Fig. 14 Comparison of arrangement results when the area utilization rate is maximum

proposed in this research derives valid results regardless of the size of the arrangement item. Especially, when the arrangement item size is large, it shows that it performs better than the existing algorithm.

The arrangement status was investigated when the area utilization of the BLF algorithm and that of the Greedy-TW algorithm reached their peaks in case 5 where the algorithm application was most effective. When the BLF algorithm was applied, the area utilization reached its peak at 84.77% on May 12, 2015 (the area utilization of the Greedy-TW algorithm reached 87.60% on the same date). When the Greedy-TW algorithm was applied, the area utilization reached its peak at 88.83% on June 3, 2015 (the area utilization of the BLF algorithm was 80.56% on the same date). Figure 14 shows the arrangement status when the area utilization of each algorithm reached its peak. In the case of the BLF algorithm with a complicated free space shape, the space for a new arrangement item was insufficient even when the remaining area was large. The Greedy-TW algorithm, on the other hand, efficiently used the arrangement area by keeping the shape of the free space

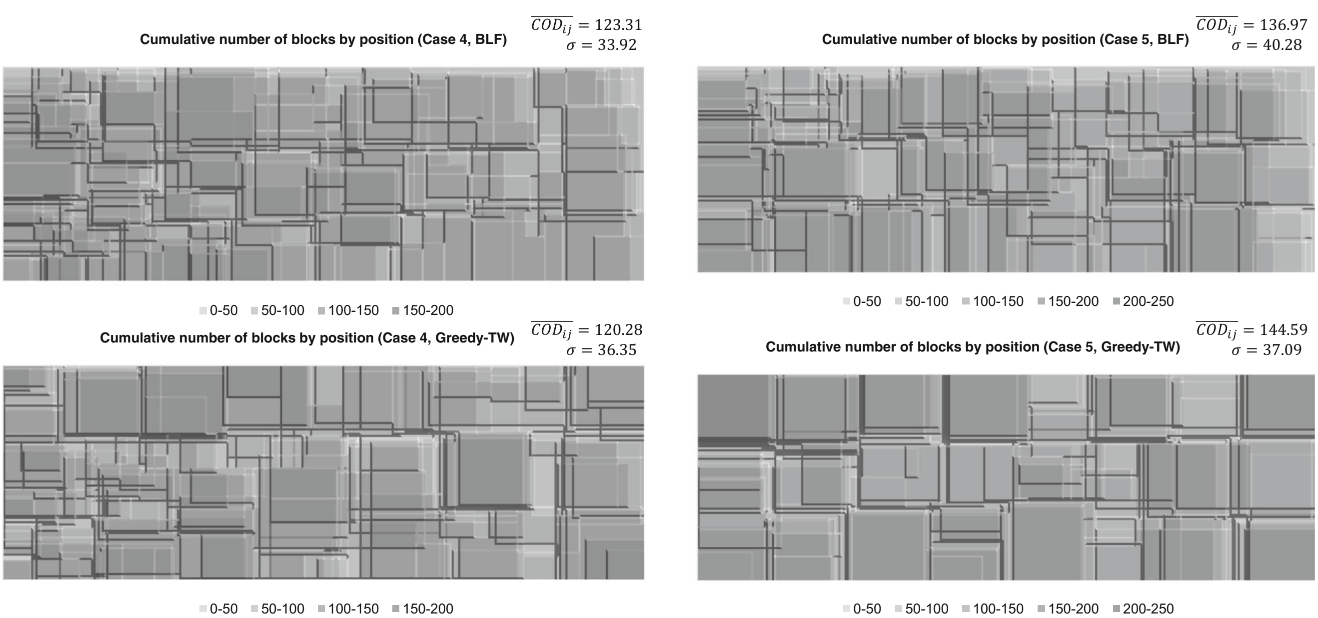


Fig. 15 Comparison of cumulative occupation date of each unit cell

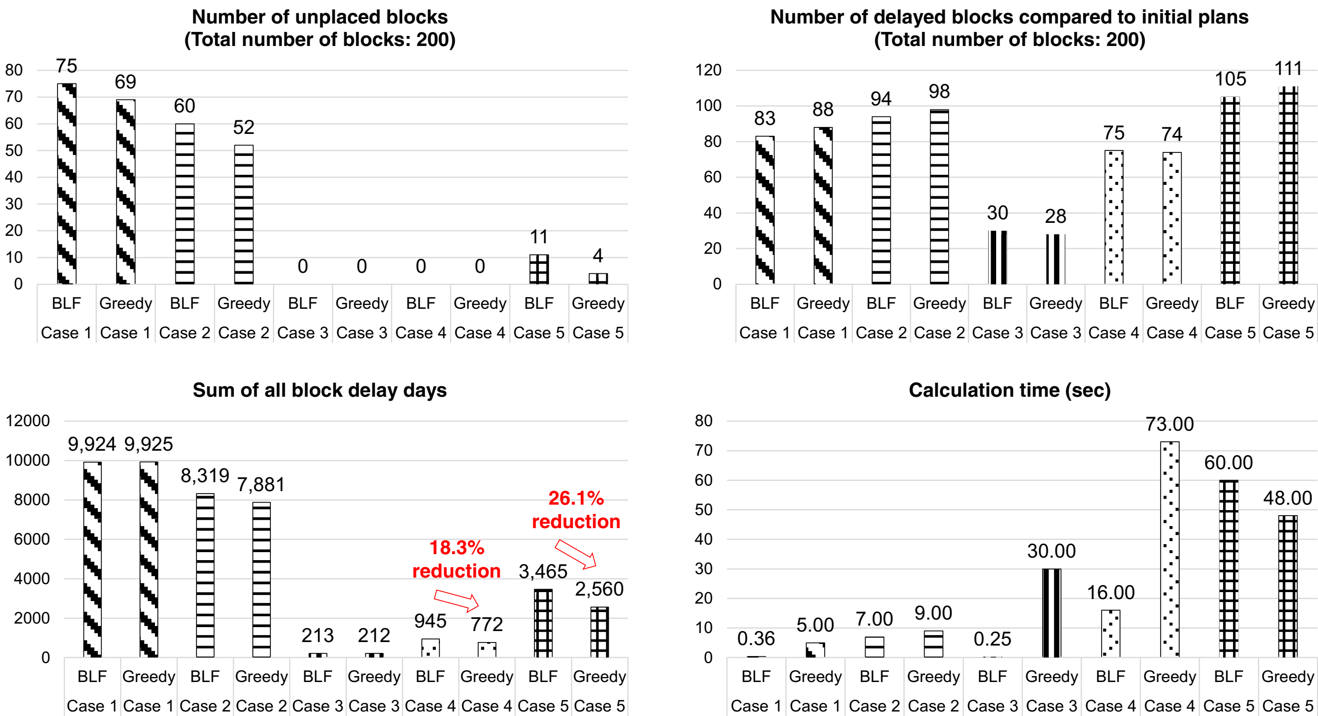


Fig. 16 Comparison of the evaluation values of the entire simulation period

similar to that of the unplaced block. The results of the Greedy-TW algorithm show that not only the area utilization value is high but also the space is effectively utilized.

To quantitatively verify whether the arrangement area was uniformly occupied during the entire period of the arrangement simulation, the number of occupancy of each grid constituting the arrangement area was analyzed on cumulative basis. Figure 15 shows the cumulative arrangement status for case 4 (left) and case 5 (right), which had high proportions of large blocks. The darker display represents a high cumulative number of occupancy, and the cumulative number of occupancy was displayed on a base of 50 times. In case 4, there was no significant difference in the $\overline{COD_{ij}}$ value (Eq. 9) that represents the average cumulative number of occupancy, and the standard deviation (Eq. 10) was higher when the Greedy-TW algorithm was applied. In case 5, however, the boundary of the cumulative number of occupancy was simpler compared with other results as can be seen from the figure when the Greedy-TW algorithm was applied. The standard deviation of the cumulative number of occupancy was 37.09, which was approximately 7.92% lower than the result for the BLF algorithm. This means that the arrangement items were placed relatively regular compared with other cases. Through this, it was confirmed that the Greedy-TW algorithm can keep the shape of the free space relatively simple and use the area evenly for large-block arrangement problems.

Finally, the number of unplaced blocks until the end of the arrangement simulation, the number of delayed blocks compared with initial plans, the sum of all block delay days, and the calculation time were analyzed for all the experiment cases. Figure 16 shows the analysis results. The Greedy-TW algorithm had fewer unplaced blocks in all cases than the BLF algorithm, but the number of delayed blocks compared with initial plans was higher in some cases. The sum of all block delay days confirmed that the Greedy-TW algorithm performed better in large-block spatial arrangement planning problems. In cases 1 and 2, where the proportions of small blocks were high, the sum of all block delay days of the Greedy-TW algorithm was similar to or slightly lower than that of the BLF algorithm. In cases 4 and 5 with high proportions of large blocks, however, the sum of all block delay days of the Greedy-TW algorithm was 18.3 and 26.1%, respectively lower than that of the BLF algorithm. As the calculation time with the Greedy-TW algorithm was higher in some cases, improvement is required.

8 Conclusion

Space is an important resource in shipyards that build large ships and various methods have been studied to efficiently utilize limited space. In this study, various shipyard spatial arrangement planning problems were classified and defined based on arrangement areas, arrangement items, algorithms, and evaluation factors. In particular, in consideration of the increasing sizes of shipyard blocks, evaluation factors and algorithms were proposed so that the shape of the free space and the characteristics of unplaced blocks can be considered for spatial arrangement planning problems of large blocks.

When the size of the arrangement item was relatively larger than the arrangement area, the shape of the free space had a significant influence on the placement of the new arrangement item. In this study, the number of twist shapes was used as an evaluation factor to enable the shape of the free space to maintain a rectangular shape as much as possible. In addition, a spatial arrangement planning algorithm, which is capable of finding the best alternative at a given time, was proposed using a greedy algorithm. The vertex-edge-based candidate location searching algorithm was used to efficiently search for candidate locations for arrangement.

To verify the performance of the spatial arrangement planning algorithm proposed in this study, various experiment cases were defined and conducted. For these experiment cases, arrangement items were classified into sub-assembly blocks, assembly blocks, first P.E. blocks, and second P.E. blocks according to the product assembly stages. As a result of applying the proposed algorithm to various experiment cases and comparing the results from various perspectives, it was confirmed that the proposed algorithm showed a better performance than the existing algorithm (BLF algorithm) for spatial arrangement planning problems of large blocks. This is because it is important for the shape of the free space to be regularly formed and maintained in a rectangular shape. The performance of the proposed algorithm, however, was not significantly different from the existing algorithm when the area utilization was low or when the size of the arrangement item was relatively small compared with the arrangement area. Furthermore, it was confirmed that improvement in terms of the calculation time is required because a greedy algorithm performs calculations for all alternatives based on its characteristics. The results from this study are useful for efficient utilization of space in shipyards and other applications where the size of the arrangement item is relatively larger than the arrangement area.

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