Topological Optimization for Unequal Area Facility Layout Planning in Shipyard Using Heuristic Algorithms

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Abstract: In this paper, optimizing the layout of production facilities in shipyards is aimed at minimizing material handling (MHC) costs with two constraints, namely, several departments that must be close together and several that must be far apart. In other words, the constraints are adjacency and nonadjacent. The main work of this paper is to carry out topological optimization in an unequal area of production facilities at the shipyard using heuristic algorithms. Departments will be placed into several horizontal layers, and the number of departments in each layer may vary based on the minimum standard deviation in layer length. The fitness value is used to minimize the material handling costs within the production area. The performance of algorithm shows the genetic algorithm (GA) and simulated annealing (SA) can produce an efficiency of 14.592% and simulated annealing of 23.473%. Both of algorithms considering a same initial solutions, hence SA shows a better performance than GA.

Keywords: shipyard; layout optimization; unequal area; heuristic algorithm

1. Introduction

Facility layout planning (FLP) is a process for finding the best configuration of several things related to production facilities: tools, buildings, machines, and so on. There are many industries and examples of problems with applying FLP, such as the heavy equipment manufacturing industry, hospital layout, and so on. A complete description of the layout problem can be found in the study that Kusiak and Heragu conducted[1]. One of the indicators to determine the quality of a production facility layout design is based on material handling costs, namely the total costs incurred to carry out the production flow in a certain period or cycle. However, the definition of costs in material handling costs can be in many ways: time, cost, effort, and so on. Material handling costs contribute around 30-40 percent of the total production costs and can increase to 70 percent for some industries[2].

In the shipbuilding process, large steel components and intermediate products are commonly moved around the production area, with their handling costs accounting for a considerable portion of overall production expenses. This proportion increases particularly with the size of newly constructed ships. Hence, it is crucial to devise an efficient production system layout that facilitates smooth material flow between workshops and departments within the shipyard. Research on optimizing shipyard layouts using a heuristic approach represents a novel methodology that allows the problem to be discretized, despite ship production workshops typically presenting a continuous layout. This study focuses on a topological strategy tailored to varying workshop sizes within the shipyard optimization process. In contrast, prior research utilizing a topological approach assumed uniform workshop sizes during optimization. Consequently, this paper aims to bridge this research gap by introducing a topological approach suitable for workshops of varying sizes.

1.1 Literature review

Several researchers have researched facility layout planning, both in general and specifically for production facilities in shipyards. Wang et al. used a genetic algorithm to solve the unequal area problem with an objective TLC (total layout cost) function[3]. TLC is a combination of material flow factor cost (MFFC) or material handling cost, shape ratio factor (SRF), and area utilization factor (AUF). In this study, each department was in the form of a square with a uniform size. Each department is attached to the other departments to form a square or rectangular topological arrangement.

Among the methods that can be used to solve FLP problems is using metaheuristic methods, such as genetic algorithms, simulated annealing, ant colony optimization, etc. Several reviews and general techniques regarding genetic algorithms have been discussed by several researchers, such as Kumar et al.[4], McCall[5], Katoch et al.[6], and Alam et al.[7]. Aiello et al. used a genetic algorithm to solve multi-objective cases in FLP, namely minimizing material handling costs and maximizing adjacency, distance, and aspect ratio aspects[8]. Besbes et al. place several facilities or machines into specific points based on a genetic algorithm and then define locations where the path cannot be passed. After that, the shortest distance from one machine to another machine is determined using the A* algorithm[9]. Some time ago, Besbes et al. continued work with a combination of GA and A* algorithms by considering the department's directional orientation with input and output points as constraints[10]. Deep presents a solution approach using genetic algorithms for the Quadratic Assignment Model of the Facility Layout Problem (FLP). The study develops a mathematical model to assess the flow of materials within a facility layout, considering constraints arising from production processes[11]. Romero et al. improved how genetic algorithms work to solve FLP cases with Island Model GA (IMGA). The evolution of several populations is carried out in parallel with population diversity, resulting in better quality in several generations. This is done to avoid premature convergence and lack of diversity[12]. Kumar et al. divide the entities of facilities into four groups by using the topological constraints. The Multi-Population Genetic Algorithm (MPGA) is next employed to find topological relations between layout entities[13]. Paes et al. use a Genetic Algorithm (GA) and a GA combined with a decomposition strategy via partial solution deconstructions and reconstructions to address the Unequal-Area Facility Layout Problem (UAFLP) in an unlimited floor space without overlap[14].

Other researchers who use other algorithms to solve the FLP problem include Allahyari and Ahzab[15], Turgay[16], and Palubeckis[17], which use a simulated annealing algorithm. Liu et al.[18] and Guan et al.[19] solved the multi-objective FLP case using MOPSO (Multi-Objective Particle Swarm Optimization). Liu and Liu used multi-objective ant colony optimization to solve the UAFLP problem to minimize material handling costs while maximizing the closeness rating (CR) score[20]. Anjos and Vieira used two optimization steps to solve the facility layout on several rows problem. The first step used new mixed integer linear programming, and this step then became the initial input in the second step[21].

In a more specific case, namely in the design of ships, Nick conducted a design optimization of the ship's general arrangement using a two-step method[22]. First, a genetic algorithm is used to determine the topological design of the rooms on the ship. Then the stochastic growth algorithm is used to determine the geometric design of the rooms from the final topological design results. In the case of ship production system, Choi et al. did the same thing: the two-step method in optimizing shipyard facility planning[23]. First, a genetic algorithm is used to determine the topological design of the facilities in the shipyard. Then the stochastic growth algorithm is used to convert the topological shape into the optimum geometric shape while considering each facility's alignment and shape ratio. Several years later, this study was continued by Junior et al. with a fine-tuning of the solution achieved using the Electre Method and a Local Search Method in the step of geometrical optimization with a Stochastic Growth Algorithm[24]. In connection with this research, Turk et al. conducted a study with 13 different operators on genetic algorithms to solve topological design optimization cases in shipyard layouts[25]. Also, Gunawan et al. Optimizing the topology design of the shipyard layout using a genetic algorithm with a more significant number of buildings, namely 25 buildings, including free space[26]. Recently, Tamer et al. took an approach using systematic layout planning (SLP) and graph theory to optimize the layout of a shipyard in Yalova, Turkey, based on proximity[27].

However, before that, several researchers in the field of naval architecture have researched shipyard layout procedures and designs. Song et al. carried out a simulation-based shipyard layout design[28-30]. Shin et al. used the system engineering approach by utilizing data acquired from the shipbuilding system, conducting analysis, and implementing structural realizations[31]. Song and Woo carried out design procedures on the layout of a shipyard in Venezuela, South America (greenfield project), and focused on the preliminary phase[32]. The estimation of the necessary area utilizing factual product data from the designated ship and actual operational data from shipbuilding processes is used in that study to be more valid than several design procedures that have previously been made. Recently, Dixit et al. use a two-step approach to select shipyard layouts based on the fuzzy similarity index (FSI) and the fuzzy goal programming model (FGPM) by utilizing alternative layouts produced by field practitioners[33].

1.2 Related approaches

Considering that the case in this paper is an unequal area problem, in which the size of all departments is considered differently, a specific approach is needed to arrange the existing departments after the configuration based on the algorithm has been obtained. Azadivar and Wang used the slicing structure method to arrange several workstations in the case of unequal areas[34]. Slicing cuts a rectangular region into two smaller rectangular regions by either a horizontal or a vertical line segment. A slicing structure is constructed by recursively partitioning a rectangle R (i.e., the floor plan) so that each rectangular partition in the slicing structure corresponds to the space allocated to a workstation. Liu et al. used a flexible bay to place several workstations in the case of facility layout optimization[35]. The term bay here refers to vertical layers that separate the facilities into several areas. In a different case from FLP, namely in the case of the container loading problem (CLP), Bortfeldt and Gehring inspects the goods in the container from the front view first, then separate these goods into several vertical layers[36]. Based on several related literature, this paper will conduct topological optimization in an unequal area by separating departments through horizontal layers. Adjacency constraints and nonadjacent constraints were implemented in the equal area design process, then the value of material handling costs is calculated at the unequal area design process stage. In some previous research in respect of topological optimization for shipyard layout, the number of departments in each layer was always the same. However, this is not suitable for this paper because there may be a high standard deviation in layer length in the case of unequal area facility layout. Therefore, to address this gap, this paper allows each layer to have a different number of departments.

2. Problem Description

This paper has 25 departments or buildings, most of which are production facilities in shipyards. Each building has a different size, which has a length and width of each. The buildings are also categorized into "Free" and "Fix." Buildings in the "Free" category are buildings whose sequence can be changed during optimization. In contrast, buildings in the "Fixed" category are permanently fixed during the optimization process, which means that the order number of the building cannot be changed to another one. The data and all the characteristics of these buildings can be seen in Table 1.

Table 1. Building and facilities information.

No.	Name	Size (m)	Category
1	Profile stockyard	8 x 4	Free
2	Straightening area	15 x 3	Free
3	Cutting area	7 x 9	Free
4	Bending area	4 x 4	Free
5	Paint workshop	8 x 5	Free
6	Part assembly	7 x 6	Free
7	Sub-assembly	10 x 7	Free
8	Block assembly	8 x 8	Free
9	Panel production area	5 x 6	Free
10	Mechanical workshop	6 x 6	Free
11	Piping workshop	7 x 5	Free
12	Warehouse	7 x 7	Free
13	Electrical workshop	4 x 4	Free
14	First pre-erection	8 x 5	Free
15	Pre-outfitting	5 x 4	Free
16	Second pre-erection	17 x 9	Free
17	Waste material area	7 x 6	Free
18	Fire protection facilities	6 x 6	Free
19	Stock space (second quay)	4 x 16	Fix
20	Free space area	6 x 6	Fix
21	Stock space (first quay)	4 x 16	Fix
22	Office	5 x 6	Fix
23	Refreshing room & Toilet	5 x 4	Fix
24	Parking area	6 x 6	Fix
25	Entrance area	5 x 5	Fix

Material flows are the process of sending materials from one department to another. These materials consist of iron and other materials, which are the primary materials in shipbuilding. Table 2 provides information on material flows from one department to another in the shipyard simulated in this paper, and all of these flows are in units of "t" or tonnes.

Table 2. Material flows between departments.

No.	From	To	Quantity
1	1	2	1300t
2	2	3	1100t
3	2	4	200t
4	3	4	1020t
5	4	6	850t
6	4	7	180t
7	5	16	1180t
8	6	7	680t
9	6	8	130t
10	8	5	1350t
11	8	15	550t
12	8	14	700t
13	11	15	550t
14	15	16	620t

Given that the constraints used in this paper are adjacency and nonadjacent, there will be several departments that must be close together, and there will also be several departments that must be far apart. Table 3 provides information regarding adjacency constraints, namely, departments that must be close together. Table 4 provides information regarding nonadjacent constraints, namely, departments that must be far apart.

Table 3. Adjacency constraint between departments.

Dept 1	Dept 2	Adjacency
2	3	Yes
3	4	Yes
6	7	Yes
7	8	Yes
6	17	Yes

Table 4. Nonadjacent constraint between departments.

Dept 1	Dept 2	Nonadjacent
5	22	Yes
5	23	Yes
8	23	Yes

3. Methodology

Choi et al. used the two-stage method to solve the problem of optimizing the layout of facilities in shipyards. First, a genetic algorithm is used to find the optimum topology design solution for existing departments, namely

20 departments (17 are production facilities, and the remaining three are considered inaccessible areas). The topology optimization process is carried out on an equal area basis, which all departments are considered to have the same size. When the optimum topology design has been obtained, the topological shape is converted to the optimum geometric shape using the stochastic growth algorithm. The calculation of material handling costs is applied only during the topology optimization process. In the geometry optimization process, the things that are reviewed are shape ratio and alignment[23].

Related to the paper presented by Choi et al., this paper focuses on unequal area topology design optimization, while that carried out by Choi et al. was worked in an equal area. In this paper, first of all, a genetic algorithm (GA) and simulated annealing (SA) are used to form a equal area design through the individuals in those two heuristic algorithms. Then the equal area design is converted into unequal area design with horizontal layer approach. After that, modifications will be made for some department positions to minimize standard deviation in layer length. This makes it possible for the number of departments at each layer to be different. Finally, the material handling cost is calculated using the manhattan distance. The result of the total material handling cost will become the fitness value of the individual of algorithm. At the end of this paper, the performance of the genetic algorithm and simulated annealing in solving this case will be compared. Figure 1 displays the method flow in this research.

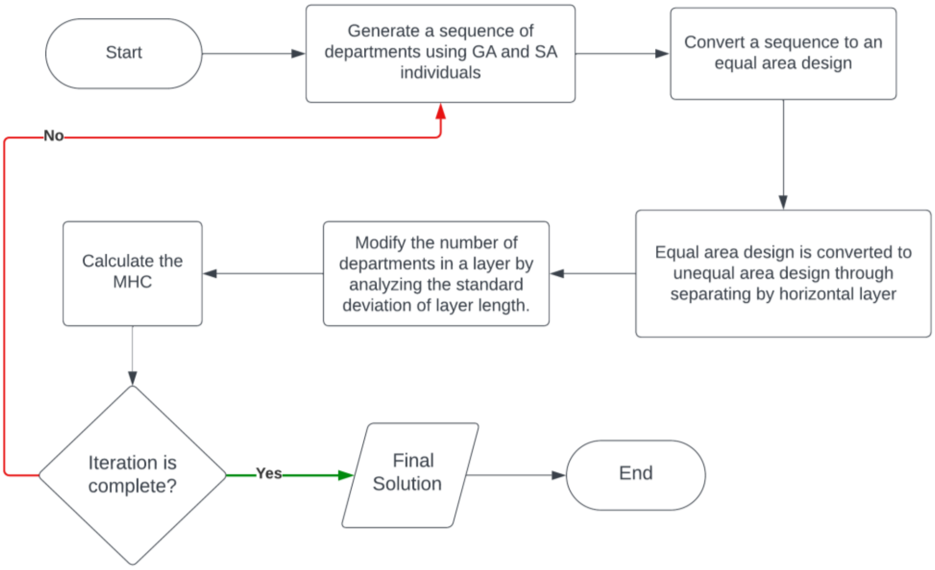


Fig. 1: Methods of This Paper.

3.1 Equal area design stage

There are 25 departments and buildings contained in this paper. Each of these buildings will be placed into a square which is considered to have the same length and width, which is 1 unit length. Some buildings that have a "Fix" category need to be regulated so that they are always located in a particular square; the details are as follows: Department 19 in Square 22, department 20 in Square 21, department 21 in Square 16, department 22 in square 6, department 23 in square 3, department 24 in square 2, and department 25 in square 1. An initial description of the equal area design and algorithm configuration can be seen in Fig. 2.

Furthermore, the squares that are still empty will be filled by buildings that are categorized as "Free" so that later the entire square will be filled, and an individual from GA and SA will be formed. The items that fill the individual will follow the order of the squares that have been filled in, from square 1 to square 25. For example, if department 11 is in square 14, then 11 will be in the individual at number 14, and so forth.

Regarding adjacency constraints and nonadjacent constraints, it is necessary to set them in this equal area design stage. Each department listed in Table 3, which has an adjacency relationship, must be placed close together. Each department listed in Table 4, which has a nonadjacent relationship, must be placed far apart. Two departments, namely department i and department j, will be considered adjacent if they have a closeness value, namely Adji,j, equal to 1. Moreover, it will be considered far apart if Adji,j equals 2. These rules can be displayed in the following formula:

$$Adj_{i,j} = 1 \quad \text{if } d_{i,j} \leq \sqrt{2},$$
$$Adj_{i,j} = 2 \quad \text{if } d_{i,j} \geq 4,$$
$$\text{otherwise} \quad Adj_{i,j} = 0. \tag{1}$$

$$d_{i,j} = \sqrt{(C_{i,x} - C_{j,x})^2 + (C_{i,y} - C_{j,y})^2} \tag{2}$$

With:

Ci = Centroid of department i in equal area design

Cj = Centroid of department j in equal area design

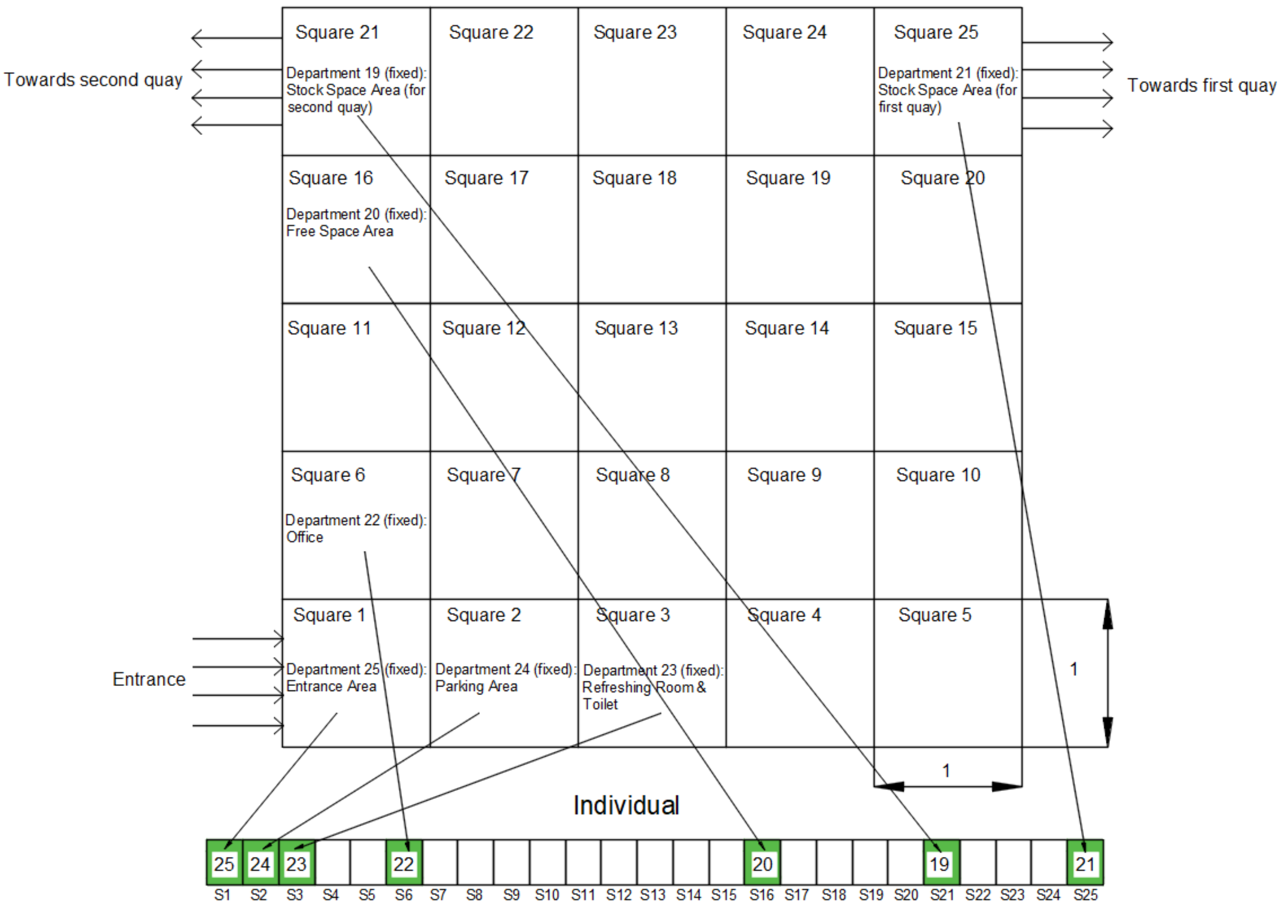


Fig. 2: Initial equal area design and configuration of algorithm's individual.

In other words, $d_{i,j}$ is the Euclidian distance between department i and department j in the equal area layout. So, in the equal area layout, departments with an adjacency relationship must have a maximum distance of $\sqrt{2}$ unit of length. The departments that have a nonadjacent relationship must be separated by a minimum of 4 unit of length.

3.2 Conversion from equal area to unequal area

After all the squares in the equal area layout are filled, GA and SA already have a complete individual. An example of a possible equal area layout and its individual can be seen in Fig. 3. Then the sequence of departments in the equal area layout will be converted into unequal area using horizontal layer approach. All buildings will follow a predetermined size in this unequal area design stage, as seen in Table 1. Following are some general rules for constructing unequal area designs with horizontal layer approaches:

- Firstly, there are five departments in each layer.
- The distance between the nearest sides of 2 departments in the same layer must be 1 meter.
- In a layer, if a department has the largest width of all the departments in that layer, then the width of that department will be the width of that layer.
- The distance between layers must be equal to 1 meter.

Based on the abovementioned unequal area design rules, the following is a conversion of the equal area shape in Fig. 3 into an unequal area shape. The results of the conversion can be seen in Fig. 4.

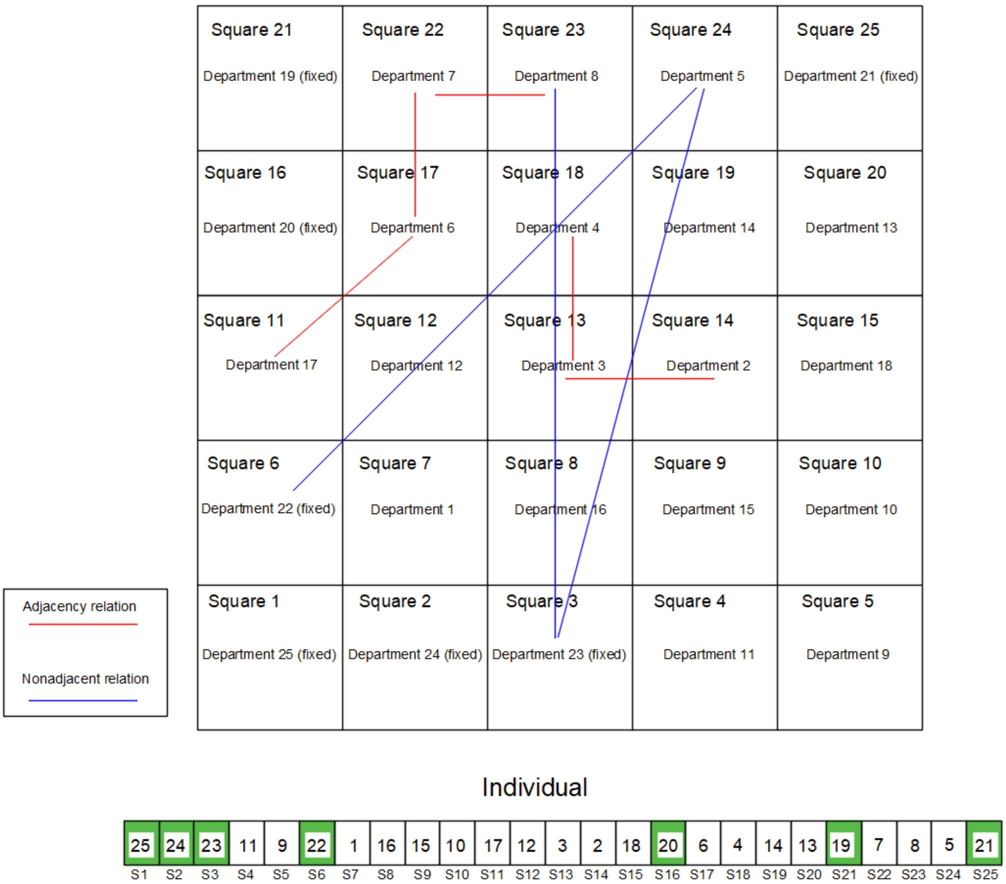


Fig. 3: Possible equal area layout and its individual configuration (algorithm).

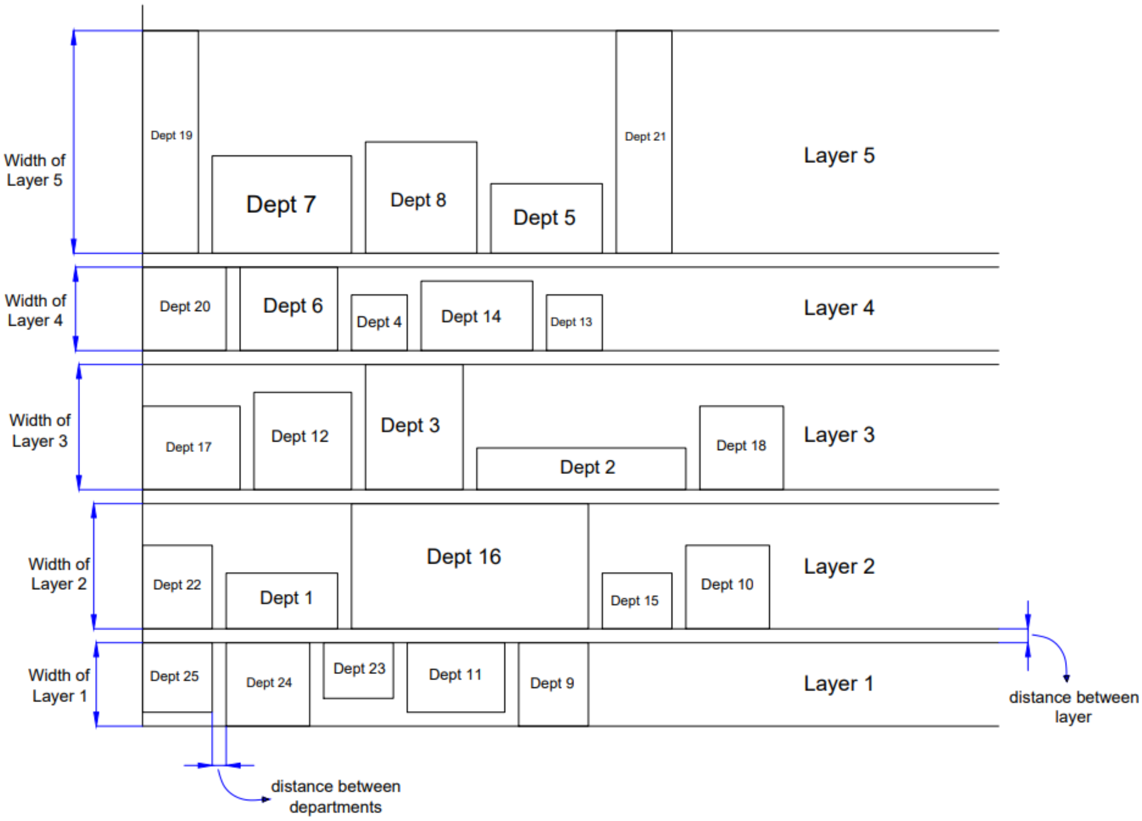


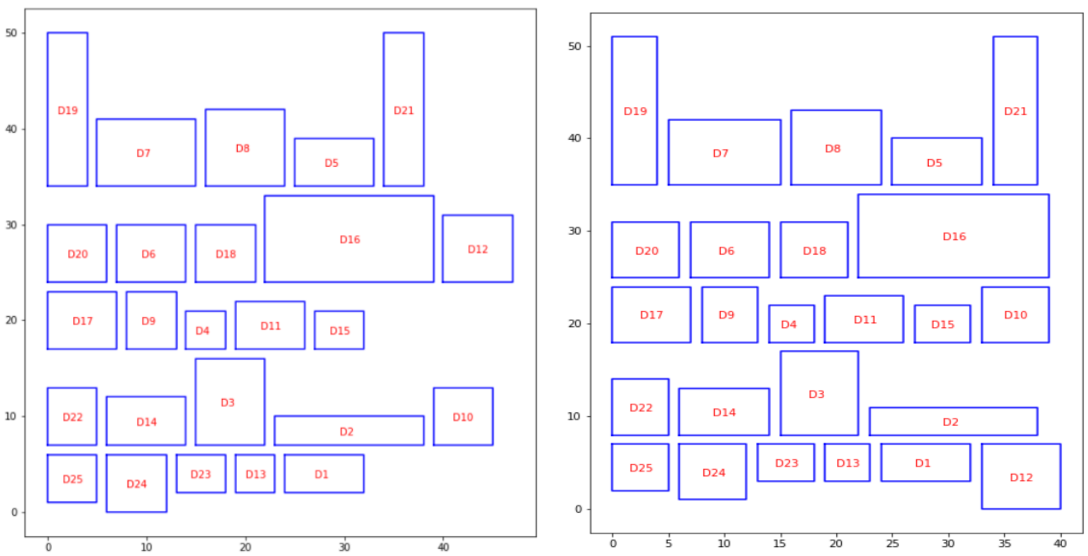
Fig. 4: Geometry design based on topology layout in Fig. 4.

3.3 Adjusting the layer's department count

The layout form produced at the unequal area design stage may produce layers of varying lengths. The higher range of differences in layer lengths, the higher standard deviation of lengths, and it will also make the department's arrangement unbalanced. Therefore, at this stage, the number of departments in the layer will be modified to minimize the range of differences in layer lengths. As for the layer, length is measured from the left side of the first department in the layer to the right side of the last department. The following is the pseudocode of this modification method and “free_dept” is defined as a "free" department not within the constraints in neither table 3 nor table 4.

Pseudocode for adjustment process

```
1. Identify departments belonging to "free_dept".
2. Perform a trial relocation of departments:
   a. Calculate the total length of all layers.
   b. Determine the longest layer (LH).
   c. Determine the shortest layer (LS).
   d. Calculate the standard deviation of layer lengths (SD0).
   e. Define the last department on LH as DM.
   f. If DM is a "free_dept":
      i. If LS is equal to 5:
         - Attempt to move DM to LS in the 4th position.
      ii. If LS is not equal to 5:
         - Attempt to move DM to LS in the last position.
      iii. Calculate the updated standard deviation of layer lengths (SDN).
      iv. If SDN < SD0:
            - Proceed with the relocation.
            - SDN now becomes SD0.
            - REPEAT
         v. If SDN >= SD0:
            - Relocation is not carried out.
            - BREAK
   g. If DM is not a "free_dept":
      - BREAK
3. BREAK
4. END
```



(a) (b)

Fig. 5: Comparison of layout results between a). Before adjustment, b). After adjustment.

3.4 Calculation of Material Handling Costs

After the adjusted unequal area design is obtained, as shown in Fig. 5(b), the next step is calculating the fitness value, which in this case is material handling costs. The following is a mathematical formula from MHC that refers to the data in Table 2:

$$\text{MHC} = \left[\sum_{No.=1}^{14}(Q^{No.}\ x\ R_{From,To}^{No.})\right] \quad (3)$$

$$R_{From,To}^{No.} = |Cg_{i,x} - Cg_{j,x}| + |Cg_{i,y} - Cg_{j,y}| \quad (4)$$

$$\text{Objective} = minimize\ (MHC) \quad (5)$$

With:
Q = Quantity of material (ton)
$R_{From,To}$ = Manhattan distance between department "From" to department "To" (meter)
Cg_i = Centroid of department *i* in geometry layout
Cg_j = Centroid of department *j* in geometry layout

For example, based on the layout in Fig. 5(b), the MHC value is 191365.0 tons-meter.

4. Results

As explained in the previous section, the configuration search will use genetic algorithms and simulated annealing. Given that simulated annealing is not a population-based algorithm like the genetic algorithm, in this paper, the best individual from the initial population of the genetic algorithm will be used as the initial individual for simulated annealing. A comparison graph between the performance of the genetic algorithm and simulated annealing algorithms can be seen in Fig. 6.

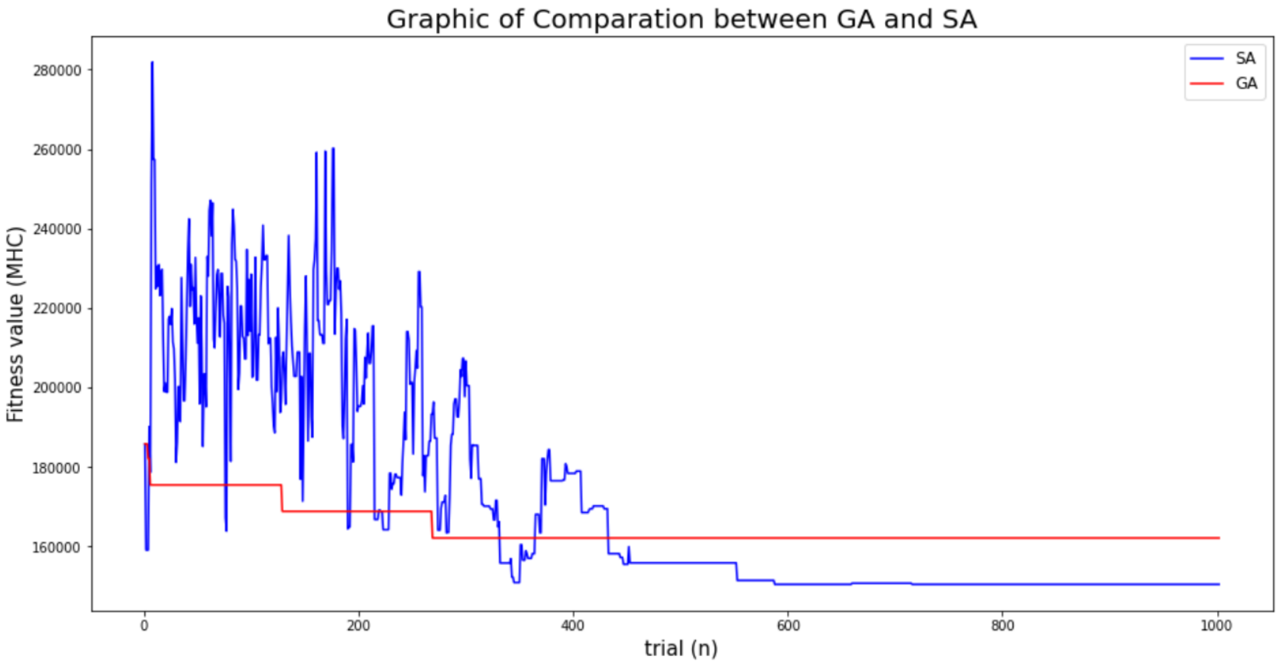


Fig. 6: Comparation performance between GA and SA

Figure 6 shows that the fitness value of GA is based on the best individual from each generation, considering that GA is a population-based algorithm with many individuals in each trial or generation. Based on the computational results, after 1000 iterations, the performance of the GA is 14.592% better than its initial solution. The performance results from SA is 23.473 % better than its initial solution. Table 5 shows the final results of the best individuals. The final layout of the best solution is shown in Fig. 7 and Fig. 8.

Table 5. Best solution of GA and SA

	Layout Configuration	**Fitness Value (MHC)**
Best of GA	[25, 24, 23, 2, 3, 22, 15, 18, 9, 4, 6, 17, 12, 1, 13, 20, 7, 10, 16, 14, 19, 11, 8, 5, 21]	162180.0
Best of SA	[25, 24, 23, 2, 3, 22, 12, 11, 1, 4, 6, 17, 15, 10, 9, 20, 7, 18, 16, 13, 19, 14, 8, 5, 21]	150515.0

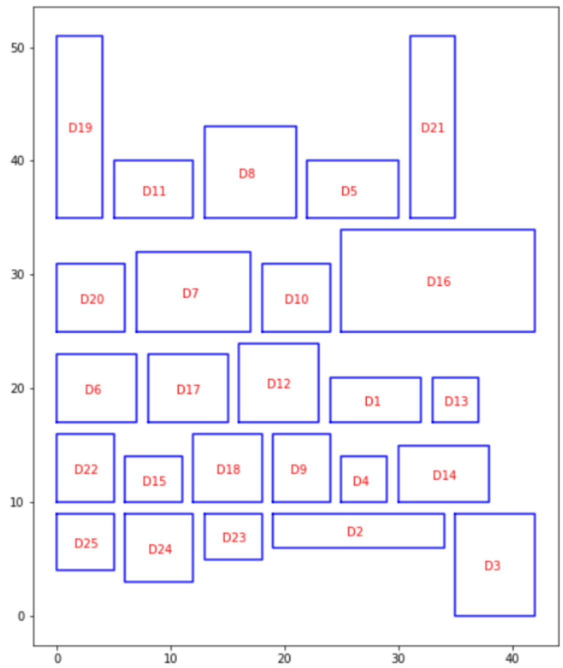


Fig. 7: Final layout of GA's model.

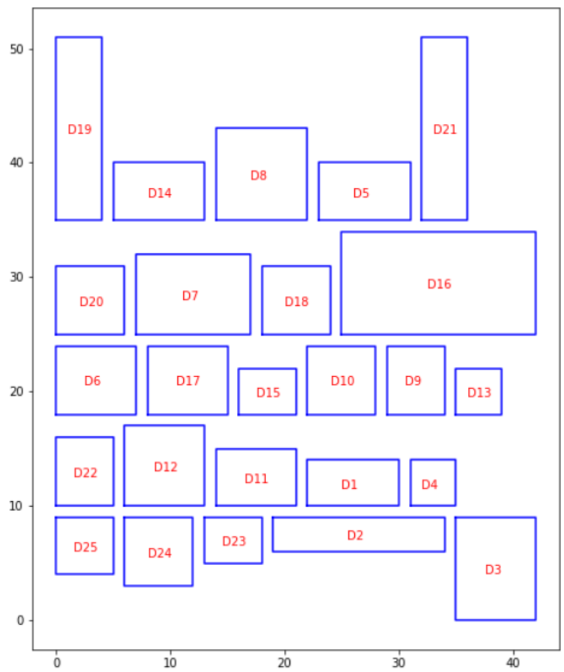


Fig. 8: Final layout of SA's model.

4.1 Discussion

Layer 4 in the optimum configuration obtained from GA has departments moved to layer 2. Meanwhile, layer 4 in the optimum configuration obtained from SA has departments moved to layer 3. This makes the resulting total area more space-efficient and the transfer of departments does not affect the algorithm configuration.

In an existing similar study, the final MHC will be recalculated on the second step because the departments arranged in first step still considering the same size in all of them. Hence, they will have a massive enough of value gap. Meanwhile the results of this paper give a more realistic topological layout in a shipyard because the size of workshops has been considered. Therefore, it has addressing the gap to the existing research of similar study which designs a shipyard facility layout through the topological approach into the geometrical layout, while still considering a same size of a workshops.

5. Conclusions

The configuration of facility layout design in shipyard can be formed unequally area using the proposed method. First, the equal area layout is formed, and its configuration is made by the genetic algorithm and simulated annealing. The formation of the equal area layout has considered adjacency and nonadjacent constraints. Then the equal area layout is converted into unequal area layout using the horizontal layer method. After that, the standard deviation of layer lengths is minimized by moving the department from the most extended layer to the shortest layer. This is intended to ensure a balanced layout and reduce space between departments. Once the adjusted layout has been formed, the MHC will be calculated, and this MHC value is used as the fitness value of the individual of algorithms. Finally, GA and SA can solve this problem with good results. Namely, the efficiency of GA is 14.592%, and the efficiency of SA is 23.473%.

However, the final result of the layout in this paper tends to be arbitrary, considering that data on department size and material flow uses an analytical approach and is not actual data in the field. However, the methods and approaches used in this paper have proven effective based on the algorithm's efficiency, which reaches more than 10 and 20 percent. Future research expects that data on workstation size and material flow will use actual data from existing or planned shipyards. In addition, this study also shows that each final layout will produce a different total work area and remaining space. Even though adjusting the number of departments in the layer that has been carried out has minimized space between departments, this is still only an effect caused by the adjustment process and is still not considered an objective function. Therefore, future studies should also consider minimizing the total work area or remaining space through a multi-objective optimization scheme.

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