International Journal of Marine Engineering Innovation and Research, Vol. 9(3), Sept. 2024. 476-485
(pISSN: 2541-5972, eISSN: 2548-1479)

Multi-Objective Optimization for Topological Shipyard Facility Layout using NSGA-II

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(Received: 12 July 2024 / Revised: 30 July 2024 /Accepted: 07 August 2024)

***Abstract*— The increasing complexity in ship construction due to larger vessel sizes has placed significant pressure on the shipbuilding industry to enhance efficiency and reduce costs. This paper focuses on optimizing shipyard facility layouts by minimizing material handling costs (MHC) and area costs (AC) using a topological approach for unequal areas. The objective is to develop a layout that reduces these costs while addressing gaps in previous research, which often assumed uniform department sizes. The proposed method employs the Non-Dominated Sorting Genetic Algorithm-II (NSGA-II), a heuristic algorithm designed for multi-objective optimization. Unlike previous models, this approach allows for variability in department sizes, aligning more closely with real-world conditions. The layout optimization is conducted by considering adjacency and non-adjacency constraints, ensuring an effective arrangement of shipyard departments. The results demonstrate that the proposed method significantly reduces both MHC and AC, leading to a more efficient and cost-effective shipyard layout. The dual-objective approach not only narrows the gap between topological and geometric models but also optimizes space utilization within the shipyard, making it a practical solution for modern shipbuilding challenges.**

Keywords— Shipyard Facility Layout; Optimization; Heuristic Algorithm; Ship Production.

I. Introduction

Due to the growing demand for maritime logistics, ship sizes have increased significantly, leading to greater complexity in ship construction [1]–[3]. As a result, the shipbuilding industry faces increased pressure to improve efficiency, reduce production costs, and shorten delivery times. Among the various factors affecting production efficiency, material handling cost (MHC) plays a crucial role, accounting for approximately 20-50% of the total operating cost in a manufacturing environment In shipbuilding, where heavy steel and large intermediate products dominate the material flow, MHC constitutes a significant portion of overall production costs [5].

The trend of increasing ship size continues to rise, especially with newly built vessels. A study by the International Transport Forum [6] found that the average size of container ships has doubled over the last decade, with the largest container ship capable of carrying 19,200 containers. The study highlighted that new containership orders persist despite economic stagnation, with the ITF reporting that container ship capacity has doubled in a decade, driven by the need for efficient goods transportation and economies of scale. Therefore, it is vital to design the optimal layout of a production system that enables the workshop and department in the shipyard to run smoothly for the material flow process. However, rather than using a systematic design approach, the layouts of shipyards that are currently in use were created using the expertise and experience of specialists [7]. In the last decades, many researchers have studied facility layout planning (FLP), and most of them have been trying to reduce the MHC by using their assumption approach or improving algorithms and methods [8]. The most popular methods for solving the FLP are heuristic algorithms such as genetic algorithm, simulated annealing, ant colony optimization, particle swarm optimization, and tabu search [9]. Some of the variables that are commonly used in the model assumption of FLP include pick and delivery points, production routing, aisle design, and workshop orientation [8], [10]–[12].

Commonly, most FLP studies focus on a general case of a manufacturing environment instead of a specific case of a particular manufacturing environment such as a shipyard and aircraft [13]. In recent years, research in shipyard facility layout optimization through the heuristic algorithm pioneered by Choi *et al.* [14]. Considering the adjacency and alignment of departments inside the shipyard, that study seeks to minimize the MHC during ship construction. First, a genetic algorithm is used to establish the ideal topological of departments, while the objective function of this step is MHC. Second, by applying a stochastic growth algorithm, the departments can progressively expand and develop geometries that meet predetermined criteria for area, form, adjacency, and alignment. However, the final MHC will be recalculated in the second step, while the departments arranged in the first step will still be considered the same size. Hence, the MHC generated in the first step will have a massive value gap. In the next few years, Junior *et al.* [5] conducted the improvement based on the study carried out by Choi *et al.* [14]. In that study, a partial mapping technique and a recursive algorithm were applied to the genetic procedure during the initial optimization step, which is topological optimization. The proposed procedure achieved the minimum cost in 100 iterations, whereas the earlier

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method required 3740 iterations to reach the exact cost. Another improvement of this study is the algorithm of the transition procedure, which changes the department's centroid coordinates from the topological grid (discrete representation) to the geometric (continuous representation) domain. The Transition Procedure Algorithm (TPA) helps to shorten the computational time needed to solve the second stage. Lastly, improving the geometrical optimization step involves adding electric methods and a local search method for a stochastic growth algorithm. Overall, compared with Choi *et al.* [14], mainly the improvements conducted in this study focused on the algorithm and method extension instead of the new approach to model assumptions.

Other studies have been carried out specifically to solve the topological layout optimization problem in the shipyard case. In 2019, Azzolini [15] conducted a study of these issues by using the partially matched crossover (PMX) genetic operator and also using a recursive expression in addition to implementing the biased random-key genetic algorithm (BRKGA). The purpose of those two different approaches is to compare the results. In the following few periods, in 2021, Türk *et al.* [16] carried out experiments using 13 different operators to achieve the most optimal solution of topological layout for the shipyard and then compared those operators.

Research on the shipyard layout optimization using a heuristic approach is the new methodology that enables a discretization of the problem. In contrast, the actual layout of the ship production workshop is a continuous case. This paper works on a topological approach for unequal areas in a shipyard, which considers a workshop in its size through optimization. Meanwhile, the workshop was considered the same size through the optimization process in the previous research, which also covered a topological approach. Therefore, in this paper, a topological approach for unequal areas will address the study gap. Another extension of this paper is an added objective function, which considers an area cost (AC) as an objective, namely a total area of the workshop layout arrangements. This step will apply a multi-objective optimization algorithm, Non-Dominated Sorting Genetic Algorithm – II (NSGA-II), to minimize MHC and AC. While calculating an MHC, the distance between departments will be rectilinear. Besides that, in previous similar research, all layers had the same number of departments. Meanwhile, in this paper, the number of departments in each layer can be different because it involves an adjustment that decreases the possibility of some layers being exceptionally longer or shorter.

A motivation for developing a topological model in the unequal area is to reduce the gap of MHC between the optimal MHC results of the equal area model towards the geometric model as a continuous representation of shipyard layout and also optimizing space utilization in the shipyard by minimizing an AC as the initial total area on the shipyard. However, the geometric model approach needs to be covered in this paper. The focus is to arrange the optimal sequence of the departments, while the unequal area approach will bring it closer to the realistic model. This paper introduces a novel approach to shipyard layout optimization by focusing on a topological model for unequal areas, thereby addressing the gap left by previous research. Unlike earlier studies that assumed uniform department sizes, this work incorporates the variability in department sizes, aligning the model more closely with real-world conditions. Additionally, this study introduces an area cost (AC) as a secondary objective, using a multi-objective optimization algorithm, Non-Dominated Sorting Genetic Algorithm-II (NSGA-II), to minimize both MHC and AC. This dual-objective approach not only reduces the gap between topological and geometric models but also optimizes space utilization within the shipyard. Furthermore, unlike previous models where all layers had the same number of departments, this paper allows for variation in department numbers across layers, enhancing the model's flexibility and realism.

II. METHOD

This chapter delves into the methodologies employed to optimize the shipyard layout. It involves a detailed examination of the materials used, the problem statement that frames the objectives, and the specific methodology adopted to achieve these goals. The primary focus is to ensure that the layout effectively meets both adjacency and nonadjacent constraints, optimizing for material handling and area costs through a systematic approach. The process leverages the Non-dominated Sorting genetic algorithm-II (NSGA-II), a robust heuristic algorithm known for solving complex layout problems.

A. *Materials*

The simulated shipyard information includes building information, materials flow, adjacency constraint, and nonadjacent constraint. The number of buildings, including a free space area, is 25, and the detailed information is divided into length, width, and category. The length and width of the workshop are measured by a unit of meter (m), and a category refers to the location of a sequence. In contrast, a “Free” workshop can be in a free order of sequence, and a “Fixed” workshop must be located in a particular order. All of the building information is presented in Table 1.

TABLE 1.
BUILDINGS INFORMATION

No.	Name.	Length	Width	Category
1	Profile stockyard	8	4	Free
2	Straightening area	15	3	Free
3	Cutting area	7	9	Free
4	Bending area	4	4	Free
5	Paint workshop	8	5	Free
6	Part assembly	7	6	Free
7	Sub-assembly	10	7	Free

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

Transporting materials from one department to another is known as material flow. Iron and other materials make up these materials; they are the primary materials used in shipbuilding. The material flows at the shipyard that this study simulates are shown in Table 2, and all these flows are expressed in terms of "t" or ton.

According to the adjacency and nonadjacency constraints applied in this study, some departments must be positioned close to each other, while others must be kept apart. Table 3 details the adjacency constraints, specifying which departments must be near each other. Table 4 outlines the nonadjacency constraints, indicating which departments should be separated.

TABLE 2.
MATERIALS FLOW

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

TABLE 3.
ADJACENCY OF DEPARTMENTS

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

TABLE 4.
NONADJACENT OF DEPARTMENTS

Dept	Dept	Nonadjacent
5	22	Yes
5	23	Yes
8	23	Yes

B. Problem Statement

Constraints that must be fulfilled are adjacency and nonadjacent. As explained by Choi *et al.* [14], the adjacency constraint was adjusted at the step of equal area of topological layout. Meanwhile, in this paper, adjacency and nonadjacent constraints will be adjusted at an equal area of topological layout. The representation model of equal area layout can be seen in Figure 1, which must satisfy the following formula:

$cx_i = centroid\ x\ of\ department\ i\ in\ equal\ area$
$cy_i = centroid\ y\ of\ department\ i\ in\ equal\ area$
$dc_{p,q} = euclidean\ distance\ between\ department\ p\ and\ q$
$adj_{p,q} = 1\ if\ dept\ p\ and\ q\ have\ an\ adjacency\ constraint\ (table\ 3), otherwise\ is\ 0$
$ndj_{p,q} = 1\ if\ dept\ p\ and\ q\ have\ a\ nonadjacent\ constraint\ (table\ 4), otherwise\ is\ 0$

Model:

$$dc_{p,q} = \sqrt{\left(cx_p - cx_q\right)^2 + \left(cy_p - cy_q\right)^2} \quad (1)$$

$$dc_{p,q} \leq \sqrt{2},\ if\ adj_{p,q} = 1 \quad (2)$$

$$dc_{p,q} \geq 4,\ if\ ndj_{p,q} = 1 \quad (3)$$

This study aims to minimize both MHC and AC of unequal area layout through the NSGA-II. There will be five horizontal bays, or they can be called layers. By default, there are five departments or buildings in each layer, but this can be changed lately by the added adjustment method. This paper will not cover the department orientation as a variable or constraint. Hence, the representation of departments and bays is a default model that becomes fixed. The essential representation of departments and bays can be seen in Figure 1.

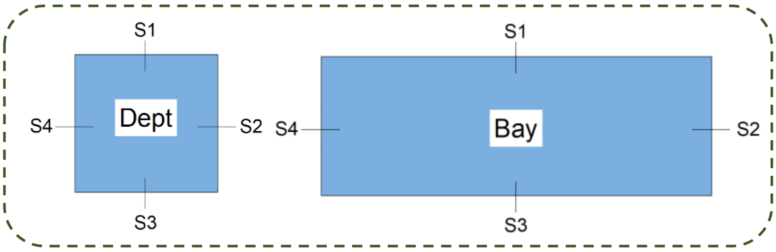

Figure 1. Equal area model representation

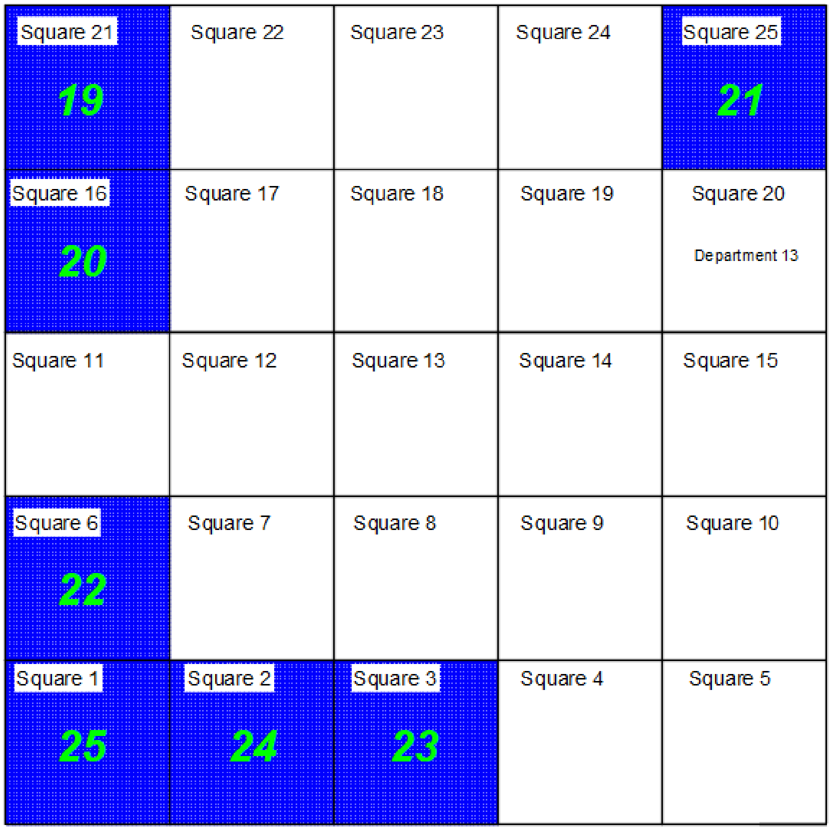

Figure 2. Equal area model representation

The placement process of departments into bays, in an unequal area layout, exactly as done by (Gunawan *et al.*, 2024), which must satisfy some requirements expressed in a mathematical model:

Parameter and variable:

$k = Total\ number\ of\ departments = 25$

$m = Total\ number\ of\ bays = 5$

$m_j = Number\ of\ department\ in\ bay\ j$

$n_{mf} = Total\ number\ of\ rows\ in\ table\ 2$
$d_{p,q} = rectilinear\ distance\ between\ department\ p\ to\ department\ q$
$f_{p,q} = material\ flow\ quantity\ from\ department\ p\ to\ department\ q$
$c_{p,q} = Unit\ cost\ for\ transportation\ between\ two\ departments$
$S_{NSGA-II} = x_1, x_2, x_3, x_4, \ldots\ldots, x_k$
$K_j = Set\ of\ departments\ located\ at\ bay\ j$

$Ybj_{S1} = The\ y - coordinate\ of\ bay\ j'S1$
$Xbj_{S2} = The\ x - coordinate\ of\ bay\ j'S2$
$Ybj_{S3} = The\ y - coordinate\ of\ bay\ j'S3$
$Xbj_{S4} = The\ x - coordinate\ of\ bay\ j'\ S4$
$Ydi_{S1} = The\ y - coordinate\ of\ department\ i'S1$
$Xdi_{S2} = The\ x - coordinate\ of\ department\ i'S2$
$Ydi_{S3} = The\ y - coordinate\ of\ department\ i'S3$
$Xdi_{S4} = The\ x - coordinate\ of\ department\ i'S4$

$rx = The\ closest\ distance\ between\ 2\ departments\ horizontally\ in\ same\ bay = 1$
$ry\ (j, j+1) = The\ distance\ between\ neighboring\ bays = 1$
$D_{j,z} = The\ department\ in\ bay\ j, ranked\ zth$
$Wb_j = Width\ of\ bay\ j = Length\ of\ its\ S4\ or\ S2$
$Lb_j = Length\ of\ bay\ j = Length\ of\ its\ S1\ or\ S3$
$Wd_i = Width\ of\ department\ i$
$Ld_i = Length\ of\ department\ i$

Fitness Function:

$$F(1) = MHC = Minimize\left[\sum_{from=1}^{n_{mf}} \sum_{to=1}^{n_{mf}} d_{from,to} \cdot c_{from,to} \cdot f_{from,to}\right]$$

$$F(2) = AC = Minimize\left[\left(max_j\left(Lb_j\right)\right) \cdot \left(\sum_{j=1}^{m} Wb_j\right)\right]$$

Model:

$$k = \textstyle\sum_{j=1}^{m} n\left(K_j\right) \tag{4}$$

$$Xbj_{S4} = 0, \quad \forall j = 1 \ldots m \tag{5}$$

$$ry\ (j, j+1) = Yb(j+1)_{S3} - Ybj_{S1}, \quad \forall j = 1 \ldots m-1 \tag{6}$$

$$Wb_j = max_{i \in K_j}(Wd_i), \quad \forall j = 1 \ldots m, \forall i = 1 \ldots m_j \tag{7}$$

$$Lb_j = max_{i \in K_j}(Xdi_{S2}), \quad \forall j = 1 \ldots m, \forall i = 1 \ldots m_j \tag{8}$$

$$Ybj_{S1} = Ydi_{S1}, \quad \forall j = 1, \forall i = 1 \ldots m_j \tag{9}$$

$$Ybj_{S3} = Ydi_{S3}, \quad \forall j = 2 \ldots m, \forall i = 1 \ldots m_j \tag{10}$$

$$Xbj_{S4} = Xdi_{S4}, \quad \forall j = 1 \ldots m, \forall i = 1 \tag{11}$$

$$rx\ (i, i+1) = Xd(i+1)_{S4} - Xdi_{S2}, \quad \forall i = 1 \ldots m_j - 1 \tag{12}$$

All departments will be ordered in a sequence of algorithms, namely non-dominated sorting genetic algorithm – II (NSGA-II). Constraint gives the information that the summation of all departments in each bay will equal the number of all departments, which is 25, even though the number of departments in each bay might differ. Constraints (5) and (6) inform that the y-coordinate of bay is always equal to 0, while the distance between bay j and bay j+1 is 1. As explained in equations (7) and (8), the bay's length and width depend on the departments in the bay itself. The length of the layer will be the same as the last department side in its bay, while the width of the bay will be the same as the maximum width of the department located there. Constraints (9) and (10) verify that in bay 1, its S1 will follow the same line as the S1 of its departments.

Meanwhile, in the other bay, its S3 will be through the same line as the S3 of its departments. Constraint (11) adjusts that the first department's S4 will be through the same line as the bay' S4 in each bay. Lastly, the adjacent departments in each bay will be separated by 1, as explained in constraint (12).

III. Methodology

This section will present a proposed methodology in which multi-objective GA, namely NSGA-II, will be the solution to solve an FLP in the shipyard. GA is one of the most popular heuristic algorithms to solve an FLP, and many researchers have used it [17], [18]. Therefore, this paper uses NSGA-II to solve the problem by generating various configurations.

A. *Non-Dominated Sorting Genetic Algorithm – II*

NSGA-II was first introduced by [19], and the illustration of its process can be seen in Figure 3.

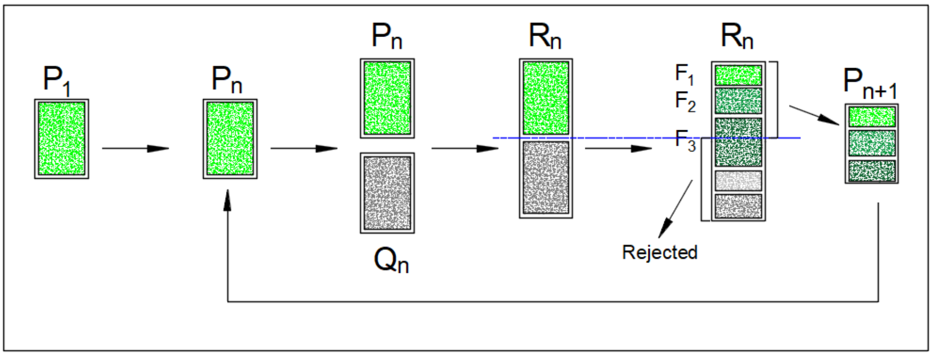

Figure 3. Illustration of NSGA-II process

The explanation of the process in the image above is as follows:

1. Initially, the population in the first generation (P1) is randomly generated with x individuals.
2. Pn produces offspring (Qn) through a crossover and mutation process. The resulting Qn must consist of the same number of individuals as Pn, namely x.
3. Pn and Qn are combined into a population labeled Rn.
4. Rn is then classified into several parts (F) using a non-dominated sorting process. Individuals in F1 represent the best individuals, and so forth.
5. Next, the best x individuals from Rn are selected to form the population in the next generation (Pn+1).

B. Non-Dominated Sorting Genetic Algorithm – II

The main idea of implementing NSGA-II in this case is to generate various configurations. Hence, the shipyard facility layout arrangement can be made in various models immediately. Firstly, the constraints of adjacency and nonadjacent must be fully satisfied before generating an algorithm. These arrangements will be conducted randomly if they satisfy the Euclidean distance requirements stated in (1) and (2).

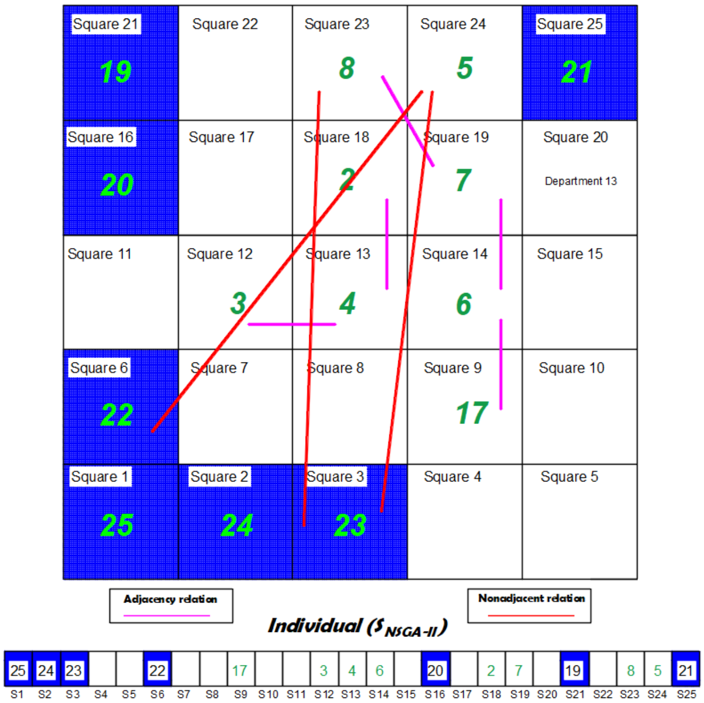

Figure 4. Possible initial layout arrangement

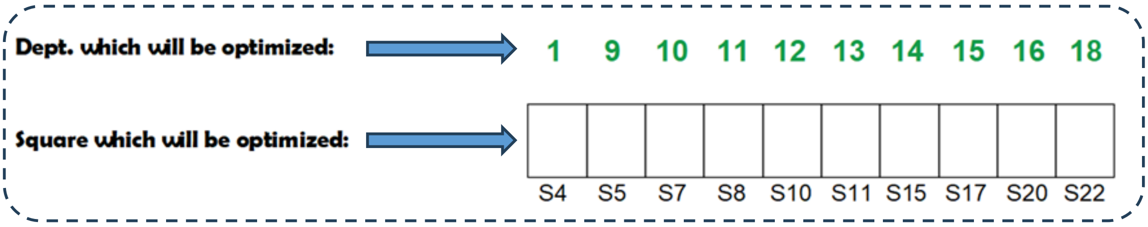

Figure 5. Arrangement to be optimized

As shown in Figures 4 and 5, some departments and squares will be optimized. In other words, those departments will be randomized at the available squares by following the procedure of NSGA-II, as discussed in a previous section. Figure 6 shows the overall process of these methods.

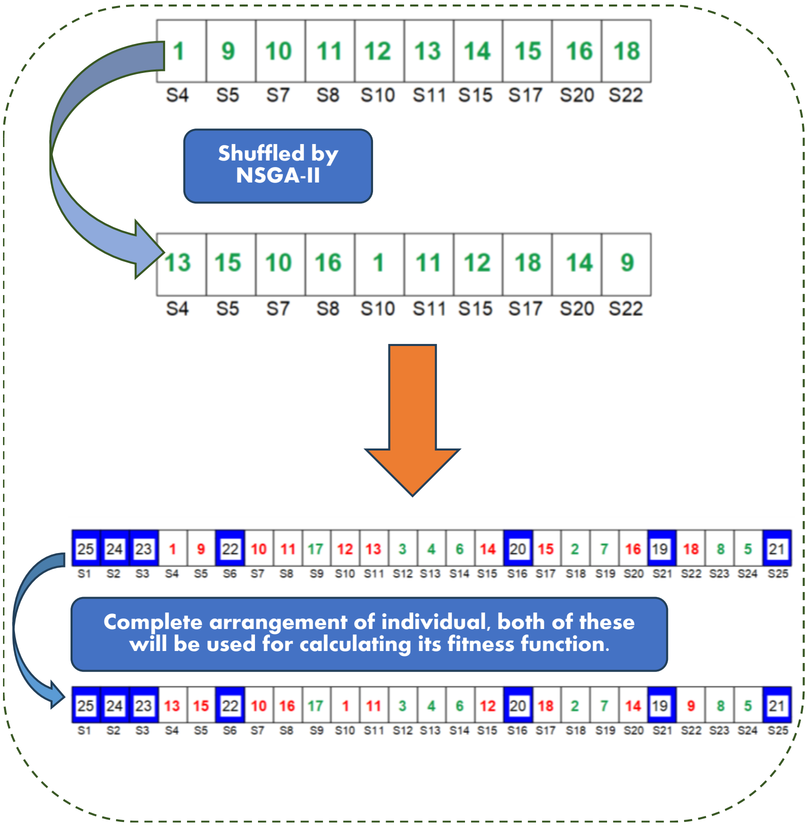

Figure 6. Arrangement to be optimized by NSGA II

IV. Result and Discussion

The computational process was executed using Python 3 over 200 iterations, leveraging the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) to address the multi-objective nature of the shipyard layout optimization problem. As this is a multi-objective optimization, the algorithm generates a set of Pareto-optimal solutions, from which the best solution is selected using the crowding distance procedure. Figures 7 and 8 demonstrate the evolution of the solution quality throughout the iterative process. Initially, the solutions were dispersed randomly across the objective space, as shown in Figure 7. This randomness is typical in the early stages of genetic algorithms, where solutions explore the solution space broadly. Over successive iterations, however, the solutions converge towards the lower-left region of the objective space, as depicted in Figure 8. This region represents the simultaneous minimization of both Material Handling Cost (MHC) and Area Cost (AC), the two objectives of the optimization process. The convergence towards this region illustrates the effectiveness of the NSGA-II algorithm in guiding the solution set towards optimal trade-offs between the objectives.

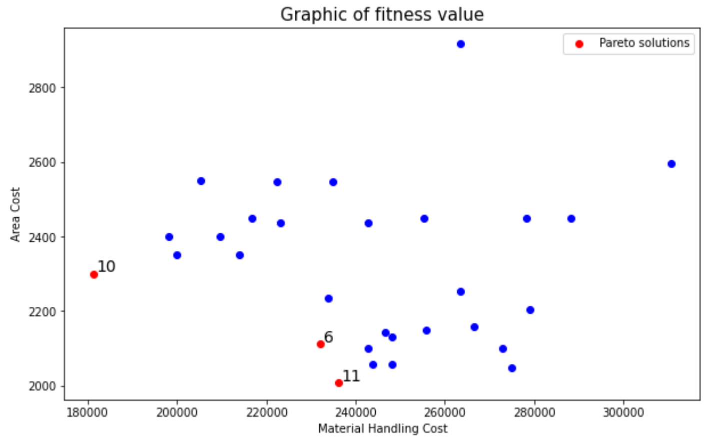

Figure 7. Results of first iteration

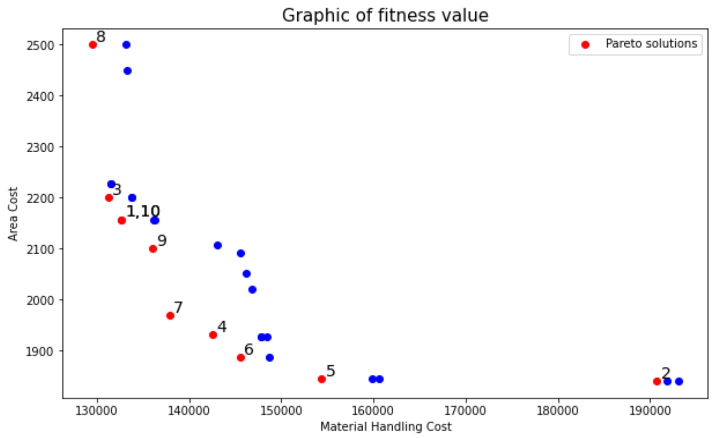

Figure 8. Results of final iteration

The Pareto front obtained, illustrated in Figure 9, showcases the set of non-dominated solutions, each representing a different compromise between MHC and AC. The final solution selected from this set was based on the crowding distance metric, a technique used in NSGA-II to ensure diversity among the Pareto-optimal solutions. The crowding distance evaluates the proximity of a solution to its neighbors in the objective space, prioritizing solutions that are less crowded and thus offer a better exploration of the trade-off surface.

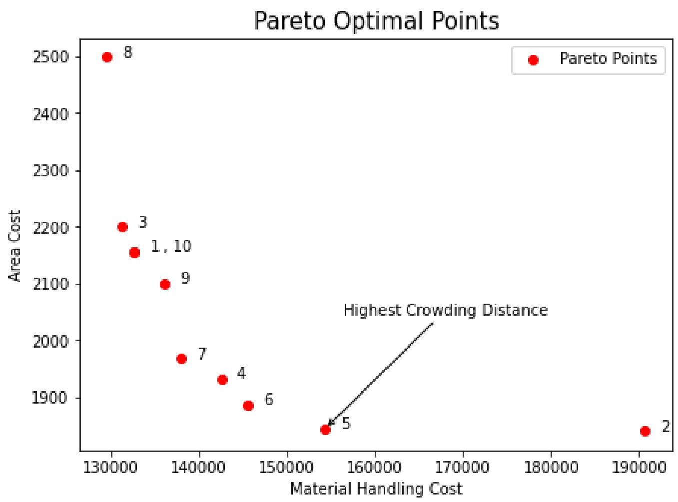

Figure 9. Pareto optimal points

TABLE 5.
SELECTED SOLUTION

Configuration	MHC	AC
[25, 24, 23, 14, 10, 22, 8, 12, 7, 17, 11, 5, 1, 2, 15, 20, 9, 6, 4, 18, 19, 16, 3, 13, 21]	154345	1845

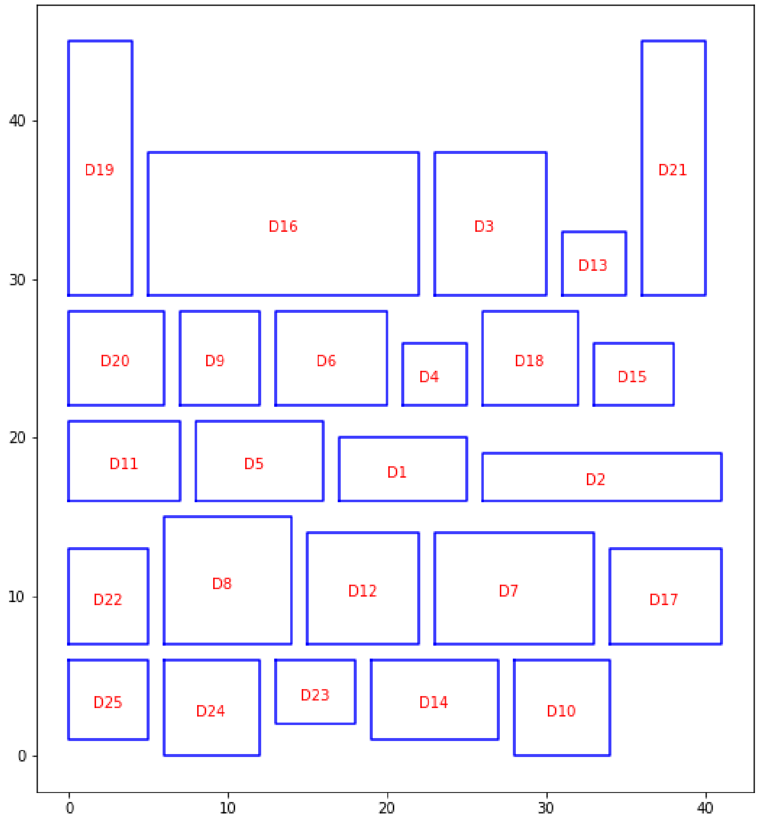

Figure 10. Selected layout

Table 5 highlights the characteristics of the selected solution, revealing a configuration that achieves an MHC of 154,345 and an AC of 1,845. The layout corresponding to this configuration, depicted in Figure 10, reflects a departure from the initial equal distribution of workshops across layers. Unlike the initial condition where each layer contained exactly five workshops, the final layout exhibits variability in the number of workshops per layer. This flexibility in the layout design is a direct result of the unequal area approach, which allows for adjustments in workshop placement to better satisfy the optimization objectives and constraints. The adjustments made to the department configurations were guided by the methodology outlined in Gunawan *et al.* [20], ensuring that all model constraints were satisfied. The final layout not only meets these constraints but also demonstrates the robustness of the NSGA-II algorithm in handling the complexity of the shipyard layout problem. By enabling the optimization of both MHC and AC while allowing for non-uniform department distribution, the algorithm has produced a layout that is both efficient and practical, moving closer to a realistic representation of shipyard operations.

This result underscores the efficacy of NSGA-II in solving multi-objective optimization problems in the context of shipyard layout design. The ability to balance multiple objectives while adhering to real-world constraints makes NSGA-II a powerful tool in industrial optimization scenarios, where trade-offs between conflicting goals are often necessary. The selected layout, with its optimized configuration, represents a significant improvement over traditional approaches that often assume equal area allocations, demonstrating the value of incorporating more sophisticated and flexible optimization techniques in shipyard design.

V. Conclusion

The study successfully achieved its objective of optimizing shipyard facility layouts by minimizing material handling costs (MHC) and area costs (AC) through a topological approach for unequal areas. By employing the NSGA-II algorithm, the research addressed the gaps in previous studies that assumed uniform department sizes, offering a more realistic and practical solution. The results demonstrate that the proposed method effectively reduces both MHC and AC, optimizing space utilization and enhancing overall efficiency in shipyard operations. This approach provides a valuable framework for improving shipyard layouts, contributing to cost savings and operational efficiency in the shipbuilding industry.

Acknowledgements

The authors would like to thank the Department of Mechanical Engineering for their invaluable support in providing lessons on academic writing and design of experiment. The guidance received has been instrumental in the successful completion of this manuscript.

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