Optimization of Multi-Objective Unequal Area Facility Layout

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ABSTRACT The unequal area facility layout problem (UA-FLP) refers to the reasonable arrangement of a certain number of facilities in a given layout area. The facility layout should satisfy given layout constraints and optimize given optimization objectives as far as possible. In this paper, a method combining improved lowest horizontal line method and particle swarm optimization algorithm is proposed to solve UA-FLP, which achieves multi-objective optimization of material handling cost, the adjacent value and the utilization rate of floor shop. On the one hand, the algorithm formulates facility packing rules through the improved lowest horizontal line method, which simplifies the legalization of facility layout. On the other hand, a modified particle swarm optimization (PSO) algorithm combining objective space division method (OSD) and niche technology is used for multi-objective optimization. The proposed algorithm overcomes the shortcomings of previous facility layout methods such as complex overlapping interference process, large amount of calculation and long time for multi-objective optimization. Compared with the comparison methods, the results show that material handling cost is reduced by 1%-6% and the utilization ratio of floor shop is increased by 2%-7%.

INDEX TERMS Facility layout, lowest horizontal line, particle swarm optimization algorithm, niche technology.

I. INTRODUCTION Facility layout is one of the most important factors of enterprise production system. The facility layout will directly affect the performance of manufacturing system, such as logistics, information flow, production capacity, efficiency of equipment and works, production cost and safety, etc [1]. The unequal area facility layout problem (UA-FLP), which contains multi-objective optimization, has attracted much attention from scholars, due to its applicability to the actual facility layout situation. The multi-objective UA-FLP problem can be solved from the following two aspects: 1) Generate the legitimate facility layouts; 2) Deal with the conflict multi-objective optimization problem.

Legitimate facility layout means that there is no overlapping interference between any facilities in the layout and all facilities are arranged within the given workshop boundary. To generate legitimate facility layouts, Liu et al. [2], [3], [11] used elastic potential energy to evaluate overlapping interference of the facility layout, and legalized layout by alternately executing local search and heuristic deformation strategies; Huang et al. [4] and Conclaves [5] regarded UA-FLP as a binary mixed integer problem, and set binary variables and linear constraints to regulate the shape and location of facilities. Li et al. [6] proposed a variant of the QAP-based facility layout problem and designed the modified ant algorithm for solving the problem. Rectangle packing problem refers to a group of rectangles arranged on the material without overlapping, so as to improve the utilization of material [7]. When using the rectangle packing strategy to solve the rectangle packing problem, the two-dimensional rectangle packing problem can be transformed into a discrete combinatorial optimization problem. Luo et al. [8] proposed a rectangle packing method combing wolf pack algorithm and lowest horizontal line method; Zeng et al. [9] proposed a method combing adaptive multi-island genetic algorithm and lowest horizontal line method to improve the utilization of the material. The UA-FLP problem is similar to rectangle packing problem in mathematical model and application background. Zhao [10] took petrochemical plant layout as the research background and combined rectangle
packing strategy and genetic algorithm to optimize facility layout.

To deal with the conflict multi-objective optimization, the Pareto-based heuristic algorithm is widely used to solve the multi-objective UA-FLP. Liu et al. [11] proposed a discrete colony optimization algorithm combining Pareto optimization of local pheromone communication and global search based on niche technology; Zhou et al. [12] proposed a modified particle swarm optimization algorithm with variety inertia weights to solve the UA-FLP, and proved the effectiveness of the proposed method through simulation experiments; Hou [13] used the slice tree to divide the facility layout space into multiple regions, and applied the hierarchical coding genetic algorithm to represent the hierarchical process; Phanden et al. [14] proposed a combination of variable neighborhood search (VNS) method and genetic algorithm to solve the facility layout problem, which enhances the local search capability of the proposed algorithm; and Asl et al. [15] proposed an modified particle swarm optimization algorithm, which applied two local search methods and facility switching methods to improve the quality of facility layout solutions.

When using Particle Swarm Optimization (PSO) algorithm to solve the multi-objective UA-FLP, the general problems of multi-objective optimization should be overcome, and the pertinence of PSO should also be considered [16]. A suitable optimal particle selection strategy enables the population to approach the Pareto frontier rapidly without losing particle diversity. Niche technology [17] enables individuals to evolve in different environments, and more optimal individuals can be searched in the solution space. Qu et al [18] introduced the speciation mechanism into niche technology and searched Pareto optimal solution in a parallel way; Deng et al. [19] proposed the niche technology based on the neighbor movement strategy, in which particles constantly move to the particle with the highest fitness value in the neighbor set. Due to the influence of optimal particles, individuals in PSO are prone to fall into local optimum. Adapt objective space division strategies such as mesh division method [20] and angle division method [21] could divide the objective space into multiple regions, which makes the particles maintain the diversity and guide the individuals to accelerate convergence to a certain region.

In this paper, a combination of rectangle packing strategy and heuristic algorithm is proposed to solve the multi-objective UA-FLP, which transforms the two-dimensional facility layout problem into a discrete combinatorial optimization problem. To generate legitimate facility layouts, the proposed improved lowest horizontal line method could simplify the legalization of facility layout and reduce unnecessary layout space waste by constantly adjusting the facility layout sequence, facility shape and facility direction in layout process. To deal with the conflict multi-objective optimization, this paper proposes an modified PSO algorithm by combining objective space division method and niche technology, which avoids the algorithm falling into local optimum and improves the solution accuracy.

### II. PROBLEM STATEMENT AND FORMULATION

Assume that facilities and workshop are rectangle. $l_i$ and $w_i$ are the length and width of facility $a_i$, respectively, and the length and width of the workshop are $L$ and $W$ respectively. Set $n$ be the number of facilities, $(x_i, y_i)$ represents the center coordinate of facility $a_i$, $(x_{left}, y_{bottom})$ represents the lower left coordinate of facility $a_i$, and $(x_{right}, y_{top})$ represents the upper right coordinate of facility $a_i$. Set $\vartheta_i$ as 0-1 variable, $\vartheta_i = 0$ means facility $a_i$ is placed horizontally, that is, the facility wide edge is parallel to the bottom edge of the workshop, and $\vartheta_i = 1$ means facility $a_i$ is placed vertically.

The coordinate system of UA-FLP in this paper is shown in Figure 1:

According to non-logistic factors such as product process constraints, equipment particularity, noise, workshop topography, and human preferences, some facilities should be arranged near or far from each other to satisfy the actual layout requirements. Therefore, it is necessary to evaluate the adjacency relation between facilities in the layout process.

The adjacency factor [22] $\varphi_{ij}(\varphi_{ij} \in [0, 1])$ is introduced to define the adjacency relation between facilities. Set $r^* = \max$ be the maximum allowed distance of facility $a_i$ and $r_{ij}$ be the Euclidean distance between facility $a_i$ and facility $a_j$. Here, $r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$.

**TABLE 1. The value of the adjacency factor $\varphi_{ij}$.**

| $\varphi_{ij}$ | Value of $\varphi_{ij}$ |
|---------------|-------------------------|
| $0 \leq r_{ij} < 1/5r^*$ | 1 |
| $1/5r^* \leq r_{ij} < 2/5r^*$ | 0.8 |
| $2/5r^* \leq r_{ij} < 3/5r^*$ | 0.6 |
| $3/5r^* \leq r_{ij} < 4/5r^*$ | 0.4 |
| $4/5r^* \leq r_{ij} < r^*$ | 0.2 |
| $r_{ij} \geq r^*$ | 0 |

The adjacency relation between facilities:
1) If the Euclidean distance $r_{ij}$ of two facilities exceeds the maximum allowable distance $r^*$, which means the two facilities are not adjacent at all ($\varphi_{ij} = 0$);
2) When the Euclidean distance $r_{ij}$ of two facilities within the maximum allowable distance $r^*$, then the adjacency relation is determined.
factor $\varphi_{ij}$ between facilities is negatively correlated with the Euclidean distance $r_{ij}$, as shown in Table 1.

As shown in Figure 1, the adjacent circular regions are constructed with $(x_i, y_i)$ as the center and $3/5r_i$, $4/5r_i$ and $r_i$ as radii respectively. The facility $a_j$ is outside the adjacent circular region constructed with radius $r_i$, so $\varphi_{ij} = 0$, which means the facility $a_j$ is not adjacent to facility $a_i$. The facility $a_k$ intersects the adjacent circular region constructed with radius of $4/5r_i$ and fails to intersect with the adjacent circular region constructed with radius of $3/5r_i$. According to Table 1, $3/5r_i \leq r_{ik} < 4/5r_i$, and $\varphi_{ik} = 0.4$.

In this paper, the multi-objective UA-FLP can be described as follows: The facilities with different areas and adjustable shapes are arranged within a given workshop. The facility layout should satisfy the layout constraints such as no embedding interference between facilities, no embedding interference between facility and the boundary of workshop, and orthogonal layout of facilities, so as to achieve the objectives optimization of minimizing material handling cost, maximizing the adjacency value and maximizing the utilization rate of workshop area.

Objective functions:

$$
\begin{align*}
\text{min} f_1 (x) & = \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} \left( C_{ij} * f_{ij} * d_{ij} \right) \\
\text{max} f_2 (x) & = \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} \left( AV_{ij} * \varphi_{ij} \right) \\
\text{max} f_3 (x) & = \sum_{i=1}^{n} (l_i * w_i) / (L * \max \{y_{i, top}\})
\end{align*}
$$

Subject to:

$$
\begin{align*}
D_i \cap D_j & = \emptyset, \quad i, j = 1, 2, \ldots, n, \quad i \neq j \\
0 \leq x_{i, left} & \leq L, \quad i = 1, 2, \ldots, n \\
0 \leq y_{i, bottom} & \leq W, \quad i = 1, 2, \ldots, n \\
0 \leq x_{i, right} & \leq L, \quad i = 1, 2, \ldots, n \\
0 \leq y_{i, top} & \leq W, \quad i = 1, 2, \ldots, n \\
\min \{l_i, w_i\} & \geq a, \quad i = 1, 2, \ldots, n \\
0 \leq \max \{l_i, w_i\} & \leq b, \quad i = 1, 2, \ldots, n
\end{align*}
$$

Formula (1) represents the minimum of material handling cost. Where, $C_{ij}$ represents the cost of a unit material handling per unit distance between facilities, $f_{ij}$ represents the frequency of material flow between facilities and $d_{ij}$ represents the Manhattan distance between facilities. Here $d_{ij} = |x_i - x_j| + |y_i - y_j|$. Formula (2) represents the maximum of the adjacency value. Where, $AV_{ij}$ represents the adjacent value between facilities. According to the adjacency degree between facilities, it can be divided into AEIOUX level, which are assigned from 5 to 0. And $\varphi_{ij}$ is the adjacency factor between facilities, the value of $\varphi_{ij}$ can be queried in Table 1. Formula (3) represents the maximum of floor shop utilization ratio. Where, $\max \{y_{i, top}\}$ is the maximum height of facility and $L * \max \{y_{i, top}\}$ is the rectangular area formed by the maximum height of facility and the bottom edge of floor shop.

$D_i$ and $D_j$ represent the internal space of facility $a_i$ and facility $a_j$ respectively. Constraint (4) ensures that there is no overlapping interference between any facilities in the facility layout. Constraints (5) - (8) ensure that all facilities are arranged within the given workshop boundary. The deformation of the facility needs to be carried out within certain limits. The constraint (9) ensures that the facility shape should satisfy the minimum side length limit, and constraint (10) ensures that the facility shape should satisfy the maximum aspect ratio limit.

### III. A HEURISTIC ALGORITHM FOR UA-FLP

This paper transformed the two-dimensional facility layout problem into a discrete combinatorial optimization problem, and proposed a heuristic algorithm combining the lowest horizontal line method and particle swarm optimization algorithm to solve the problem. The proposed algorithm focuses on the application of the lowest horizontal line method in the legalization of facility layout, the improvement of particle swarm optimization algorithm to solve the multi-objective problems, and the effective combination of this two algorithms.

#### A. THE ALGORITHM FRAMEWORK

The lowest horizontal line method is simple to operate, and numerous research results [23] show that the packing results are better than other rectangle packing strategies. Among the heuristic algorithms, particle swarm optimization (PSO) algorithm has good generality, fewer parameters, and strong search ability, and can efficiently deal with multi-objective and multi-constraint problems.

This paper combines the lowest horizontal line method and PSO algorithm to solve the multi-objective UA-FLP. The algorithm framework takes PSO algorithm as the main line and supplements the lowest horizontal line algorithm to legalize facility layout, which can be divided into two modules:

1) The lowest horizontal line method is used to formulate the facility packing rules, so as to legalize facility layouts.

2) PSO algorithm is used to generate facility layout sequence randomly to obtain diversified facility layout.

On the other hand, it is used to evaluate the fitness value of facility layout to get satisfactory solutions.

The algorithm framework as shown in Figure 2.

#### B. DISCRETE PARTICLE RENEWAL DESIGN

PSO is a global search algorithm that simulates the activities of natural biological groups. In particle swarm optimization algorithm, each individual of the population is called particle and represents a solution. The particles evolve to the global optimum position based on the historical particle optimum position and the global optimum position of current population.

The facility layout sequence is a discrete sequence within a certain range, so update the particles by discrete PSO
algorithm. Set $n$ as the number of facilities. Define the particle position as a sequence of integers: $X = (x_1, x_2, \ldots, x_n)$, $i = 1, 2, \ldots, n$. The $x_i$ represents the facility number and $i$ represents the layout sequence of the facility. $x_2 = 4$ means that the facility 4 is arranged in sequence 2. Define the particle velocity as a sequence of integers: $V = (v_1, v_2, \ldots, v_n)$, $i = 1, 2, \ldots, n$. The value of $v_i$ indicates the exchange of facility number. $v_1 = 3$ means the exchange of $x_1$ and $x_3$.

1) The addition of the velocity and position of the particle gives a new particle position: $X' = X + V$.

Assume that $X = (4, 3, 2, 5, 1, 6)$ and $V = (2, 4, 1, 3, 5, 6)$. Then $X' = X + V = (2, 5, 4, 3, 1, 6)$. The additive process of particle velocity and position is shown in Figure 3.

2) The subtraction of the positions of the two particles gives a velocity: $V = X' - X$.

Assume that $X' = (4, 3, 2, 5, 1, 6)$ and $X = (2, 4, 1, 3, 5, 6)$. Then $V = X' - X = (2, 4, 1, 3, 5, 6)$. The subtractive process of particle positions is shown in Figure 4.

3) The addition of particle velocities is analogous to the addition of particle velocities and positions.

4) Combined with the above definition, the particle updating formula of discrete PSO algorithm is as follows:

$$V' = V + C_1 \times (X_{pbest} - X) + C_2 \times (X_{gbest} - X)$$  \hspace{1cm} (11)

$X_{pbest}$ represents the historical optimal position of the particles, and $X_{gbest}$ represents the global optimal position of the current population. $C_1$ and $C_2$ are learning factors, which respectively represent the dependence of the PSO algorithm on local and global populations. Refer to reference [24], set $C_1 = C_2 = 2$.

C. THE IMPROVED LOWEST HORIZONTAL LINE METHOD

Jia et al. [25] proposed the lowest horizontal line method, which aims to pack rectangles on the lowest horizontal line of the highest contour. If the lowest horizontal line fails to satisfy the discharge requirements of the arranged rectangle, raise the lowest horizontal line to be flush with the adjacent section with the lowest height difference, then continue to judge whether the lowest horizontal line satisfies the discharge requirements of this rectangle until it can be discharged.

In order to improve the utilization of layout space, the improvement of the lowest horizontal line method mainly considers the height, width, area and other factors of rectangle, and proposes a comprehensive evaluation factor [8], [9] to select the appropriate rectangle for discharge.

When applying the lowest horizontal line method to legalize facility layout, in addition to considering the impact of facility characteristics, it is necessary to consider the facility layout factors such as the logistics relationship, the adjacent relation between facilities, and the adjustable shape of facilities.

This paper proposes an improved lowest horizontal line method to achieve the legalization of facility layouts. On the basis of facility discharge at the lowest horizontal contour line, the method constantly adjusts the layout direction and the facility shape to reduce unnecessary layout space waste in the layout process, and embeds PSO algorithm to randomly generate facility discharge sequence, so as to generate diversified facility layouts. The legalization process of facility layout is shown in Figure 5.
随机生成对应参数的初始种群$M$：

1) Set the facility layout sequence as particles, and randomly generate particles to form the initial population $M$;
2) Randomly generate the initial facility layout direction of each facility as 0 or 1;
3) Set the minimum side length of each facility to $a$ and the maximum transverse ratio of each facility to $b$. The transverse ratio of facility is randomly generated by $b^{*}$rand$(0,1)$ function, and discard the facilities that do not conform the deformation constraints.

2) THE LEGALIZATION OF THE FACILITY LAYOUT

Among the traditional facility layout legalization methods, the heuristic algorithm of facility layout legalization is easy to fall into local optimum and needs repeated deformation and local search to solve the overlapping interference of facilities; and the linear programming model for facility layout legalization requires a large number of binary variables and linear constraints to standardize the shape and location of facilities. The improved lowest horizontal line method overcomes the disadvantages of traditional facilities legalization methods, such as complex solution process and large amount of calculation.

Assume that the facility layout sequence is {2,1,3,4}, and randomly generate the length, width and initial layout direction of the facility. Refer to the improved lowest horizontal line method in Section III.C, and the realization process is shown in Figure 6.

The steps are as follows:
1) By scanning the horizontal contour of floor shop, the vertex set $O$ of contour line is generated by considering the horizontal contour line and floor shop boundary.
2) Facility 2 is arranged as shown in Figure 6(a). The vertex set is $O[(x_1, y_1), (x_2, y_2), (x_3, y_3)]$, the lowest horizontal width is $(x_3 - x_2)$, and the available height of floor shop is $(y_3 - y_2)$.
3) As shown in Figure 6(b), when facility 1 is arranged in the initial facility layout direction, the width of the lowest horizontal line $(x_4 - x_3)$ does not satisfy the layout requirements. Switch the layout direction of facility 1 so that the lowest horizontal width satisfies the layout requirements. Arrange facility 1 to the left of the lowest horizontal line and update the contour vertex set $O$.
4) As shown in Figure 6(c), when facility 3 is arranged in the initial facility layout direction or changed facility layout direction, the lowest horizontal width $(x_4 - x_3)$ does not satisfy the layout requirements. Set the new width of Facility 3 as the lowest horizontal width $(x_4 - x_3)$ and the new length of facility as $h_3 = S_3/(x_4 - x_3)$. Facility 3 still satisfies the minimum side length and maximum aspect ratio constraints after deformation. Arrange facility 3 to the left of the lowest horizontal line and update the contour vertex set $O$.
5) As shown in Figure 6(d), the lowest horizontal line width $(x_2 - x_1)$ satisfies the layout requirements of facility 4. Arrange facility 4 to the left of the lowest horizontal line and update the contour vertex set $O$.
5) FINDING PARTICLE BEST

In biology, the niche is a specific environment in which an organism consistently chooses to live with its own species [19].

By using the niche technology in PSO algorithm, the population can be divided into several small populations, which can avoid the mass reproduction of particles with higher fitness and keep the diversity of particles, so that the algorithm can find more optimal individuals.

In order to generate reasonable niches to improve the performance of PSO algorithm, this paper introduces niches technology based on nearest neighbor movement strategy. In this niche technology, L particles with similar Euclidian distance in the population form the neighborhood sets respectively. Particle $i$ continuously moves to the optimal particle direction of the neighborhood set and updates the historical optimal position $X_{pbest}$.

Algorithm 1 shows the general steps of generating niches based on the nearest neighbor movement strategy.

The formula of the grid position $h_i$ of particle $s$ is as follows:

$$ h_i = \text{mod} (s_i, d_i) + 1 \quad (14) $$

3) Health index $H(s, k)$ represents the number of other particles dominated by particle $s$ in the $k$-th iteration. The larger the health index is, the more representative particle $s$ is and the higher the fitness value is. Crowding index $\text{density}(s, k)$ represents the number of particles in the grid where particle $s$ resides in the $k$-th iteration. The smaller the crowding index is, the more representative the particle $s$ is and the higher the fitness value is.

In the $k$-th iteration, the formula of the fitness value $\text{fit}(s, k)$ of particle $s$ is as follows:

$$ \text{fit}(s, k) = \frac{H(s, k)}{\text{density}(s, k)} \quad (15) $$

6) FINDING GLOBAL BEST

Based on the particle fitness value obtained by OSD method, the global optimal position $X_{gbest}$ is selected by roulette method. Roulette is a common method of probabilistic
Algorithm 1 Niche Technology Based on Nearest Neighbor Movement Strategy

1. **Input:** The whole Pareto population
2. Set the upper limit of particle number in Pareto solution as \( P \), and set the number of neighbors of each particle as \( L \).
3. **for** each particle \( i \) \( \in \) Pareto **do**
   4. **for** each particle \( j \) \( \in \) Pareto (\( i \neq j \)) **do**
   5. \( \text{result}[j] = \text{distance}(i, j) \)
   6. **end for**
7. Sort \( \text{result}[j] \) set in ascending order of Euclidean distance
8. Find the particle with the largest fitness value among the current \( L \) particles as the \( X_{pbest} \) of particle \( i \)
9. **end for**
10. **Output:** The \( X_{gbest} \) of all particles

selection [27]. For the particle in Pareto solution set, the greater the fitness value of the particle, the greater the probability of the particle being selected as the global optimal position.

Set the fitness value of particle \( i \) in the \( k \)-th iteration as \( \text{fit}(i, k) (i = 1, 2, \ldots, n) \), the total fitness value of particles in the \( k \)-th iteration as \( \text{fit}_k = \sum_{i=1}^{n} \text{fit}(i, k) \), and the probability of selecting particle \( i \) as the global optimal position is \( \text{fit}(i, k)/\text{fit}_k \). When the fitness value of particle \( i \) satisfies the inequality: \( \frac{\sum_{j=1}^{n} \text{fit}(j, k)}{\sum_{j=1}^{n} \text{fit}(j, k)} \leq \text{random}(0, 1) \leq \frac{\sum_{j=1}^{n+1} \text{fit}(j, k)}{\sum_{j=1}^{n+1} \text{fit}(j, k)} \), which means the particle \( i \) is selected as the global optimal position \( X_{gbest} \) in the \( k \)-th iteration.

Compare the historical optimal position \( X_{pbest} \) by niche technology with the global optimal position \( X_{gbest} \) selected by random probability, then the particle with high fitness value is confirmed to update the \( X_{gbest} \).

7) DESCRIPTION OF THE PROPOSED ALGORITHM

1. Define multi-objective function and fitness value function;
2. Randomly generate facility layout sequence, facility layout direction and facility shape. Set \( t = 1 \), and the maximum number of iterations as \( T \);
3. Legalize facility layouts through the improved lowest horizontal line method and calculate the multi-objective values of particles;
4. Calculate the fitness value of particles through OSD method;
5. The Pareto solution set is updated with the non-dominant relation and fitness value of the particles until satisfies the upper limit \( p \) of the number of particles in the Pareto solution set.
6. Initialize the position and velocity of particles in the Pareto solution set. The historical optimal position of particle is set as \( X_{pbest} \), and the global optimal position of population is set as \( X_{gbest} \).
7. The velocity and position of particles are updated by discrete PSO formula (11) - (12).
8. Update the Pareto solution set. If the number of particles in Pareto solution set does not reach the upper limit \( p \), then return to step (2) to regenerate the particles to supplement the Pareto solution set. If the number of particles exceeds the upper limit \( p \), the first \( p \) non-dominated solutions with large fitness value are retained.
9. Update the particle historical optimal position \( X_{pbest} \) by niche technology based on the nearest neighbor strategy.
10. Update the global optimal position \( X_{gbest} \) with random probability.
11. Confirm and update the global optimal position \( X_{gbest} \).
12. Let \( t = t + 1 \). If \( t \leq T \), go to step (7) to continue iteration. Otherwise, output the Pareto solution set and \( X_{gbest} \), and end the algorithm.

The overall flow of the proposed algorithm is shown in Figure 7. In order to facilitate readers to understand the algorithm evolution process, population optimization of PSO in this paper is shown in Figure 8.

IV. EXPERIMENT RESULTS AND ANALYSIS

A. INSTANCES RESULTS AND ANALYSIS

The instances SC30, SC35 and Du62 from reference [28] are given to verify the performance of the proposed algorithm. The floor shop size and facility quantity of each instance are shown in Table 2. Refer to reference [28] to obtain the basic data of facility layout such as material flow, facility area, maximum transverse ratio constraint and minimum side length constraint. Set the cost of a unit material handling per unit distance between facilities as 1. The instances only consider the optimization of material handling cost, so this paper randomly generate the facility adjacency matrix of each instance.

In order to verify the superiority of combining the improved lowest horizontal line method and PSO algorithm (the proposed PSO) in solving multi-objective UA-FLP, the proposed PSO is compared with OSD-based PSO (PSO-OSD) and NSGA-II proposed by Zhang et al [27].

| Instances | Facility | Workshop length/m | Workshop width/m | Total area of facilities/m² |
|-----------|----------|-------------------|------------------|---------------------------|
| SC30      | 30       | 15                | 12               | 163                       |
| SC35      | 35       | 16                | 15               | 192                       |
| Du62      | 62       | 140               | 100              | 13718                     |

The instances SC30, SC35 and Du62 from reference [28] are shown in Table 2. Refer to reference [28] to obtain the basic data of facility layout such as material flow, facility area, maximum transverse ratio constraint and minimum side length constraint. Set the cost of a unit material handling per unit distance between facilities as 1. The instances only consider the optimization of material handling cost, so this paper randomly generate the facility adjacency matrix of each instance.
**FIGURE 7.** The algorithm flow chart combined with improved lowest horizontal line method and PSO.

**FIGURE 8.** The population optimization process of multi-objective PSO.
Genetic algorithm (GA) is an evolutionary algorithm with global optimization ability, which is suitable for solving large-scale combinatorial optimization problems. In order to further verify the superiority of improved lowest horizontal line method for legalized facility layout, this paper combined the improved lowest horizontal line method and GA (The proposed GA) to solve the multi-objective UA-FLP.

Design of the proposed GA [27], [29]: The facility layout sequence is a set of discrete sequences, so chromosomes are encoded by decimal integers. Set the population size as $M = 200$ and the maximum number of iterations as $T = 10000$. In genetic algorithm, individual variation and population evolution direction are mainly affected by crossover operators The proposed GA uses double-point crossover to select gene fragments to obtain new generations, and the crossover probability is set to 0.8. The mutation operator can generate new genes, the proposed GA set the mutation probability as 0.2 to randomly exchanges the facility layout sequence.

The proposed PSO and the proposed GA are implemented in Python and independently run for 50 times of each instance.

The experimental statistics of each instance obtained by the proposed algorithm and comparison algorithm are shown in Table 3. Analysis of Table 3 shows that:

(1) The optimal value and average value of each objective of the proposed PSO are superior to other comparison algorithms, which fully indicates that the proposed algorithm is conducive to solve multi-objective UA-FLP.

(2) Compared with PSO-OSD method, the proposed PSO results show that the material handling cost is reduced by 1%-5.9%, and the utilization ratio of floor shop is increased by 1.7%-6.5%, which demonstrates the superiority of the lowest horizontal line method in overall facility layout optimization to a certain extend.

(3) In instance SC35 and Du62, the worst value of material handling cost of PSO-OSD algorithm is better than the proposed PSO and GA. When using the improved lowest horizontal line method to legalize the facility layout, it may limit the possibility of other facility layout, making some layouts inferior to the PSO-OSD algorithm.

(4) In these instances, the results of the proposed PSO are better than the proposed GA, which indicates the excellence of improved PSO based on OSD and niche technology in solving the multi-objective UA-FLP. The effective combination of GA and lowest horizontal line method will be further studied.

The Pareto distribution of the instances obtained by the proposed PSO is shown in Figure 9-11, where the black star points represent the Pareto optimal solutions and the red solid points represent the dominated solutions. It can be seen from Figure 9-11 that the Pareto solution set of each instances are evenly distributed, forming the good Pareto frontiers.

Each particle of Pareto optimal solution set is the candidate facility layout scheme. Decision makers can choose the satisfactory facility layout according to the actual facility layout demands and personal preference. In Pareto solution set, the non-dominated solution biased to single objective optimization is taken as one of the optimal solutions. Figure 12-18 show the optimal layouts of SC30, SC35 and Du62 instances by the proposed PSO.

**B. ACTUAL CASE RESULTS AND ANALYSIS**

Taking a boiler manufacturing workshop (50m*30m) as the actual case, and the facility area and size constraints are shown in Table 4. Set the minimize side length of facility as 3 and the maximum aspect ratio of facility...
TABLE 3. The algorithm result statistics of each instance.

| Instance | Contrast algorithm | Material handling cost (min) | Best | Worst | Average | The adjacency value (max) | Best | Worst | Average | The utilization ratio of floor shop (max) | Best | Worst | Average |
|----------|--------------------|------------------------------|------|-------|---------|--------------------------|------|-------|---------|------------------------------------------|------|-------|---------|
| SC30     | The proposed GA    | 3685.55                      | 4065.89 | 3980.88 |         | 407.0                    | 356.6 | 390.6 |         | 94.23%                                   | 90.56% | 92.76% |         |
|          | The proposed PSO   | 3604.67                      | 4010.64 | 3888.08 |         | 459.8                    | 408.8 | 436.7 |         | 95.92%                                   | 90.56% | 93.94% |         |
|          | PSO-OSD [22]      | 3649.73                      | 4079.24 | 3928.17 |         | 387.2                    | 348.7 | 369.3 |         | 92.64%                                   | 87.52% | 88.96% |         |
|          | NSGA-II [22]      | 4193.25                      | 4598.02 | 4378.26 |         | 349.2                    | 307.3 | 325.2 |         | 86.32%                                   | 82.84% | 84.95% |         |
| SC35     | The proposed GA    | 3696.46                      | 4101.84 | 3960.60 |         | 477.8                    | 411.4 | 455.1 |         | 92.10%                                   | 84.55% | 88.36% |         |
|          | The proposed PSO   | 3686.91                      | 4077.38 | 3894.31 |         | 550.2                    | 550.4 | 521.4 |         | 94.37%                                   | 88.50% | 91.36% |         |
|          | PSO-OSD [22]      | 3712.82                      | 3998.18 | 3897.26 |         | 343.3                    | 308.8 | 327.8 |         | 92.64%                                   | 87.52% | 88.96% |         |
|          | NSGA-II [22]      | 4173.28                      | 4637.39 | 4387.12 |         | 298.3                    | 278.4 | 279.9 |         | 89.32%                                   | 85.69% | 86.17% |         |
| Du62     | The proposed GA    | 3822538.51                   | 4371986.09 | 4088279.50 |         | 661.8                    | 416.8 | 569.4 |         | 97.20%                                   | 90.97% | 94.93% |         |
|          | The proposed PSO   | 3728303.97                   | 4331053.72 | 3844058.27 |         | 691.0                    | 507.0 | 617.6 |         | 98.8%                                    | 95.59% | 96.42% |         |
|          | PSO-OSD [22]      | 3965209.71                   | 4219293.22 | 4210301.35 |         | 322.6                    | 256.2 | 278.3 |         | 92.35%                                   | 84.88% | 86.28% |         |
|          | NSGA-II [22]      | 3997512.96                   | 4353847.93 | 4220214.64 |         | 264.2                    | 102.5 | 168.2 |         | 87.90%                                   | 80.15% | 82.93% |         |

In actual cases, the optimization objective of facility layout remains unchanged, but other actual layout constraints need to be satisfied as follows:

As 3. The material flow between facilities as shown in Table 5, and randomly generate the adjacency matrix between facilities.

In actual cases, the optimization objective of facility layout remains unchanged, but other actual layout constraints need to be satisfied as follows:
FIGURE 16. Instance SC35 prefers optimal facility layout of the shop floor area utilization objective.

FIGURE 17. Instance SC35 prefers optimal facility layout of the adjacency value objective.

(1) Considering the product process constraints and material flow between facilities, some facilities should be arranged near or far away from other facilities. In this actual case, M1-M2-M3 and M12-M13-M15 are set adjacent, and M3-M6 and M12-M14 are set far away;

(2) Considering the internal structure design of the facility, some facilities should not be deformed arbitrarily. As shown in Table 4, some facilities have fixed areas and dimensions;

(3) Considering the production safety of workshop and the convenience of the material transportation, the distance between adjacent facilities should satisfy the minimum safe distance. Set the safe distance between facilities as 2;

(4) To facilitate material handling and operator activities, facilities should also be kept at a distance from the workshop boundary. Set the minimum distance between facility and workshop boundary as 2.

(5) Considering the topographic features of workshop and special functions of the facility, some facilities should be arranged in the fixed area of the workshop.

On the basis of the basic constraints (4) – (10), the UA-FLP mathematical model is improved according to the actual layout requirements.

Parameters

- $l_0$: Minimum distance between facility and workshop boundary in $X$ direction
- $w_0$: Minimum distance between facility and workshop boundary in $Y$ direction
- $d_s$: Minimum safe distance between facilities
- $D_0$: A fixed area of the workshop

Subject to:

$$l_i/2 + l_0 - x_i \leq 0 \quad (16)$$
$$w_i/2 + w_0 - y_i \leq 0 \quad (17)$$
$$x_i - (L - l_i/2 - l_0) \leq 0 \quad (18)$$
$$y_i - (w - w_i/2 - w_0) \leq 0 \quad (19)$$
$$|x_i - x_j| \geq (l_i + l_j) / 2 + d_s \quad (20)$$
$$|y_i - y_j| \geq (w_i + w_j) / 2 + d_s \quad (21)$$
$$(x_i - l_i/2, x_i + l_i/2, y_i - w_i/2, y_i + w_i/2) \notin D_0 \quad (22)$$

Constrains (16) - (19) indicate that each facility should keep a certain distance from the given workshop boundary. Constrains (20) - (21) indicate that the distance between any adjacent facilities in the $X$ and $Y$ directions should satisfy the minimum safety distance. Constrain (22) represents that a certain facility is fixed in this layout area, and other facilities cannot be arranged in this workshop area.

Independently run for 10 times of the actual case and preserve the Pareto optimal solutions in Table 6. The optimal value, the worst value and the average value of each objective in actual case are preserved in Table 7.

Analysis the results in Table 7 show that the material handling cost data is large, so the standard deviation is large, but the standard deviations of the other two objectives are small, which to some extent indicates that the results obtained by the proposed algorithm are convergent.

The Pareto distribution of the actual case obtained by the proposed algorithm is shown in Figure 19, where the blue star points represent the Pareto optimal solutions and the red solid points represent the dominated ones.
FIGURE 18. Instance Du62 prefers optimal facility layout of (a) the material handling cost objective, (b) the shop area utilization objective and (c) the adjacency value objective.

TABLE 5. Material flows between facilities in actual case.

|     | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 | M10 | M11 | M12 | M13 | M14 | M15 |
|-----|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|-----|
| M1  | 0  | 16.05 | 6.55 | 0.75 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M2  | 0  | 12.75 | 0.9  | 0.75 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M3  | 0  | 9   | 4.75 | 5.55 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M4  | 0  | 0.75 | 4.1  | 0.7  | 5.1 | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M5  | 0  | 3.1 | 2.4  | 0   | 0.7 | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M6  | 0  | 12.6 | 0    | 6.05 | 7.5 | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M7  | 0  | 8.85 | 1.45 | 1.45 | 3.9 | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M8  | 0  | 0   | 6    | 7.95 | 0  | 0  | 0  | 0  | 0  | 2.4 | 0   | 0   | 0   | 0   | 0   |
| M9  | 0  | 2.4 | 0    | 0.75 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M10 | 0  | 6.3 | 5.7  | 4.8  | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M11 | 0  | 5.8 | 0    | 5.55 | 3.1 | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M12 | 0  | 8.15 | 0  | 16.7 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M13 | 0  | 0   | 10.45 | 0  | 0   | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M14 | 0  | 5.55 | 0  | 0   | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| M15 | 0  | 0   | 0   | 0   | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   |

solutions. It can be seen from Figure 19 that the Pareto solution set is evenly distributed, forming a good Pareto frontier.

In this paper, the convergence of the proposed algorithm is further demonstrated by analyzing the evolution process of the optimal value and average value of each optimization objective in the actual case. As show in Figure 20-21, the evolution process of the optimal value and average value of each objective keeps gradually converging to the optimal value in the iterative process, which indicates that the proposed algorithm can simultaneously optimize the multi-objective problems. Around 20000 iterations, the adjacency value objective fluctuates greatly, indicating that the algorithm may sacrifice the optimal solution of some objectives to achieve the global optimization.

Figure 23-25 show the optimal facility layouts with three objectives in the actual case. In order to verify the facility layout satisfies the layout constraints of adjacent or distant layout, the center of M2, M13, M6 and M12 are taken as the center of the circles, and the sum of the long edge and safe
TABLE 6. The optimal solutions for the actual case.

| Index | Material handling cost (min) | The utilization ratio of floor shop (max) | The adjacency value (min) | Index | Material handling cost (min) | The utilization ratio of floor shop (max) | Adjacency value (min) |
|-------|-------------------------------|------------------------------------------|--------------------------|-------|-------------------------------|------------------------------------------|----------------------|
| 1     | 3557.16                       | 78.21%                                   | 138.60                   | 11    | 3289.64                       | 81.25%                                   | 134.80               |
| 2     | 2880.55                       | 68.94%                                   | 110.60                   | 12    | 3454.25                       | 84.69%                                   | 117.80               |
| 3     | 3208.17                       | 73.84%                                   | 132.20                   | 13    | 3436.96                       | 84.84%                                   | 116.20               |
| 4     | 3042.02                       | 71.20%                                   | 130.40                   | 14    | 3242.53                       | 82.91%                                   | 125.20               |
| 5     | 3942.62                       | 89.07%                                   | 87.40                    | 15    | 3600.42                       | 90.71%                                   | 81.80                |
| 6     | 3275.75                       | 76.90%                                   | 130.40                   | 16    | 2914.97                       | 79.02%                                   | 98.40                |
| 7     | 3949.55                       | 88.99%                                   | 105.60                   | 17    | 3549.44                       | 88.97%                                   | 120.40               |
| 8     | 3974.31                       | 89.54%                                   | 108.60                   | 18    | 3201.51                       | 84.47%                                   | 123.00               |
| 9     | 2782.62                       | 73.16%                                   | 108.80                   | 19    | 2956.52                       | 82.66%                                   | 127.20               |
| 10    | 3591.05                       | 86.39%                                   | 127.60                   | 20    | 2981.74                       | 87.43%                                   | 114.60               |

TABLE 7. The statistics of the optimal solutions of actual case.

| Objective                                      | Best     | Worst    | Average  | Standard deviation |
|------------------------------------------------|----------|----------|----------|--------------------|
| Material handling cost                         | 2782.62  | 3974.31  | 3341.59  | 362.78             |
| The utilization ratio of floor shop            | 90.71%   | 68.94%   | 82.16%   | 6.62%              |
| The adjacency value                            | 138.60   | 81.80    | 116.98   | 15.36              |

As shown in Figure 23-25:

1. M1 and M3 respectively intersect with the adjacent circular area of M2, and M12 and M15 respectively intersect with the adjacent circular area of M13, which indicates that the three facility layout schemes all satisfy the adjacent layout constraints of M1-M2-M3 and M12-M13-M15;

2. M3 does not intersect with the adjacent circular area of M6, and M14 does not intersect with the adjacent circular area of M12, which indicates that the three facility layout schemes all satisfy the distance layout of M3-M16 and M12-M14.
such as flexibility and configurability of facility layout should of facility layout by mathematical model, qualitative factors problem better.

On the one hand, the proposed algorithm formulates layout problem into a discrete combinatorial optimization (PSO) are combined to solve the multi-objective (OSD) and niche technology are combined to improve the layout. On the other hand, the objective space division method, which simplifies the legalization of facility facility packing rules through the improved lowest horizontal line method (and particle swarm optimization ratio of floor shop are considered comprehensively. In addition to satisfy the basic constraints of the facility layout, the actual layout requirements such as product process constraints, material flow between facilities, safe production and transportation are further considered, so as to obtain the suitable facility layout in actual production situation.

(2) The rectangle packing strategy (the improved lowest horizontal line method) and particle swarm optimization (PSO) are combined to solve the multi-objective UA-FLP, which transforms the two-dimensional facility layout problem into a discrete combinatorial optimization problem. On the one hand, the proposed algorithm formulates facility packing rules through the improved lowest horizontal line method, which simplifies the legalization of facility layout. On the other hand, the objective space division method (OSD) and niche technology are combined to improve the overall performance of PSO to solve the multi-objective problem better.

(3) The facility layout is a complex problem, which involves many layout factors. In the subsequent simplification of facility layout by mathematical model, qualitative factors such as flexibility and configurability of facility layout should be further considered to realize the overall optimization of the facility layout.

V. CONCLUSION

(1) In The paper, the optimization objectives such as material handling cost, the adjacency value and the utilization ratio of floor shop are considered comprehensively. In addition to satisfy the basic constraints of the facility layout, the actual layout requirements such as product process constraints, material flow between facilities, safe production and transportation are further considered, so as to obtain the suitable facility layout in actual production situation.

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