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RESEARCH ARTICLE

Facilities Layout Design Optimization of Production Workshop Based on the Improved PSO Algorithm

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ABSTRACT The facility layout of the production workshop primarily focuses on the layout planning of production equipment to reduce material handling costs within the workshop. With the development of the low-carbon economy, a scientifically rational facility layout planning contributes to improving overall operational efficiency and reducing carbon emissions in the production process. However, the design of a production workshop facility layout is a complex optimization problem involving multiple objectives, such as minimizing handling costs, maximizing total non-logistics relationships, and optimizing the utilization of workers' working hours. Additionally, it must adhere to various constraints, including area utilization rates and equipment utilization constraints. Existing layout methods often fall short of meeting the practical requirements of engineering practice. Therefore, to address the optimization challenges related to the facility layout of the production workshop, this paper establishes a comprehensive optimization model, targeting low-carbon logistics within the production workshop and optimizing the overall non-logistical relationships between operational units as the optimization objectives. Subsequently, this paper proposes an improved Particle Swarm Optimization (PSO) method, considering task collaboration, to solve the integrated optimization model of the facility layout for the valve component production workshop at Company A. Finally, the validity of the model and algorithm is confirmed through example calculations and result analysis. The analysis results demonstrate that, under the same conditions, the improved PSO algorithm outperforms PSO and SGA (Simple Genetic Algorithm) algorithms in terms of optimization results, iteration counts, and runtime. In conclusion, this study introduces task collaboration to enhance the traditional PSO algorithm. Simultaneously, we consider both logistics and non-logistics relationships in optimizing facility layout design. This provides theoretical references and new solving algorithms for low-carbon logistics.

INDEX TERMS Facilities layout design, low carbon logistics, integrated optimization, improved PSO, production workshop.

I. INTRODUCTION

The swift evolution of manufacturing technology, information technology, and the multifaceted requirements of customers have injected the market with vibrancy. However, this development has also engendered increased pressures and challenges for manufacturing enterprises in their production processes. In this context, enhancing the rationality of workshop layout design stands as a potent strategy for manufacturing enterprises to bolster their core competitiveness [1]. Research indicates that throughout the entire product processing and manufacturing cycle, spanning from the initial

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raw material to the final output of the finished product, only 5%-11% of the total production cycle time is dedicated to actual material processing. In contrast, the remaining 90%-95% of the time is predominantly spent on material handling or waiting [2], [3]. In summary, the limited proportion of value-added operation time significantly hampers the enhancement of economic benefits for enterprises. The purpose of facility layout design is to reasonably plan the logistics route of the production site and minimize the times and distance of material handling in the production process [4]. Rational layout design of workshop facilities can effectively reduce the handling cost, thus reduce the production and operation cost of the enterprise, and maintain the cost advantage position of the enterprise in the fierce market [5], [6]. From the perspective of production management, the optimization of workshop facility layout is the key factor to improve production efficiency and reduce production and operating costs [7].

The optimization of production workshop facility layout is a multi-objective and multi-constraint optimization problem [6], [8]. It has become a hot topic in academic circles to systematically determine and solve the optimization objectives of workshop facility layout [9], [10]. In the current environment, the combination of workshop facility layout optimization method and computer technology has become a major trend of production workshop management research [11], [12]. The rapid development of computer technology also provides strong support for the improvement of the production facility layouts.

At present, scholars mainly use modern design methods and technologies to conduct a more in-depth study on the facility layout from multiple angles. Balakrishnan et al. [13] used genetic algorithm to analyze the static facility layout of the workshop. McKendall et al. [14] proposed a hybrid ant colony algorithm to solve the optimization problem of static facility layout. Aiming at the common two-line equipment layout problem in semiconductor processing and manufacturing, Zuo et al. [15] proposed a two-line equipment layout method based on multi-objective immune algorithm and linear programming. Feo et al. [16] solved the optimal design of single machine scheduling by using greedy random adaptive search method. Chae and Peters [17] investigated the problem of equipment layout constraints in a single area by classifying all kinds of equipment. Prasad et al. [18] studied the optimal layout of single-line equipment in two regions by using the classical Computerized Relative Allocation of Facilities Technique (CRAFT) algorithm. Guan et al. [19] proposed a heuristic algorithm based on Complete 2-Opt (C2Opt) neighborhood search to solve a double-layer corridor allocation problem. With the goal of minimizing the material handling distance and the occupied area of facilities, Yu and Fang [20] established a double-objective optimization model for the layout of cell manufacturing system, and proposed a simulated annealing algorithm to solve the model. Derakhshan and Wong [21] formulated multi-objective models for unequal area static and dynamic facility layout problems; therefore, a modified PSO was suggested to solve them. Önüt, et al. [22] conceived a PSO to handle the multiple-level warehouse layout design problem, and the PSO can obtain near optimal results in a short time.

Based on the above literature analysis, it can be seen that due to the complexity of facility layout and the huge solution space, most literatures adopt heuristic optimization algorithm to solve the facility layout optimization problem. Therefore, the research objectives of this paper include:

a) Optimize factory layout design by constructing a multi-objective optimization model that takes into account both logistics and non-logistics relationships within the factory.

b) Introduce the concept of task collaboration to enhance the traditional PSO algorithm for addressing the multi-objective optimization problem of the static facility layout in the production workshop.

To address the aforementioned issues, this paper quantitatively considers both logistics and non-logistics factors in the facility layout process and proposes an improved particle swarm optimization (PSO) algorithm that takes task collaboration into account to optimize the layout of production workshop facilities. This approach aims to resolve the problem of inadequate consideration of requirements and elements in production workshop facility layout. In summary, the contributions of this paper are as follows: firstly, this paper proposes an improved PSO method considering task collaboration. In comparison to the traditional PSO method, the key advantage of this algorithm resides in its ability to dynamically adjust inertia weight and particle flight paths in real-time. This feature significantly reduces the inherent limitations of referenceless particle searching, effectively prevents the algorithm from getting trapped in local optima, addresses issues of low convergence accuracy, and enhances the likelihood of particles converging towards a global optimum solution [23], [24], [25]. Secondly, in this study, a quantitative analysis has been undertaken to incorporate both logistics and non-logistics factors into the facility layout process. As a result, the entire logistics system operates more seamlessly, leading to reduced logistics costs, enhanced production efficiency, and consequently, an overall improvement in the competitiveness of the enterprise.

Finally, the structure of this paper is as follows. Section II provides a literature review, where previous studies related to workspace facility layout and literature on the PSO algorithm are reviewed. In Section III, a multi-objective optimization model for the facility layout of production workshop and associated assumptions are proposed. Section IV presents the improvements made to the particle swarm optimization algorithm based on task collaboration. Section V includes a research case in which the proposed optimization model and enhanced particle swarm optimization algorithm are applied, and the relevant parameters are designed and subjected to simulation experiments. In Section VI, the paper concludes the study while highlighting certain limitations and suggesting future research directions.

II. LITERATURE REVIEW

A. RESEARCH RELATED TO FACILITY LAYOUT

Facility layout problems (FLPs) are typically NP-hard issues and find many practical applications in the industrial field [26]. Şahin et al. [27] extended the classical single-row facility layout problem to its dynamic type, considering multiple planning periods. Lamba et al. [28] formulated a dynamic cellular facility layout problem, accounting for the minimization of net electric energy consumption, as well as material handling and rearrangement costs. Gao et al. [29] introduced a framework that combines systematic layout planning (SLP) and simulation to design and assess facility layouts for greenhouses. Subulan et al. [30] introduced a novel unequal-area capability-based facility layout design (UA-CBFLD) problem. In this problem, not only the unequal area requirements of machines are considered but also their appropriate distribution within the workshop. Shao et al. [31] optimized the lateral transfer inventory of auto spare parts production workshop based on neural network forecasting. Li and Li [32] established a bi-objective multi-row layout optimization approach that integrates automated guided vehicle paths to minimize material handling costs and area occupancy. Pérez-Gosende et al. [33] proposed a Multi-Objective Mixed-Integer Nonlinear Programming (MOMINLP) model to address dynamic facility layout planning by considering an alternative approach to the bottom-up method. The proposed model takes into account three objective functions: minimizing the total material handling cost (TMHC) and total rearrangement cost (TRAC), maximizing the overall proximity score between departments (TCR), and maximizing the area utilization rate (AUR). Despite the extensive research optimizing facility layouts in existing studies, there has been limited research focused on optimizing facility layouts from a low-carbon logistics perspective and comprehensively considering material handling costs and non-logistics relationships between operation units.

B. RESEARCH ON THE APPLICATION OF PARTICLE SWARM OPTIMIZATION IN FACILITY LAYOUT

In the facility layout problem, another research focus is the solution of multi-objective planning problems. To address the double row facility layout problem, Amaral [26] proposed a two-stage algorithm. Firstly, an improved heuristic method is applied to optimize a specific type of random double-row layout, and then linear programming is used to adjust the absolute position of each machine in the layout. Zhao and Yuan [34] addressed the comprehensive optimization of shop floor production scheduling and predictive maintenance, taking into full consideration constraints such as product delivery time and changing machine failure rates. They established a multi-objective optimization model and used the Non-Dominated Sorting Genetic Algorithm (NSGA-II) to solve this model. Hu and Chuang [35] used a genetic algorithm to solve a nonlinear programming model for the layout of an established e-commerce warehouse to obtain a scientifically reasonable e-commerce warehouse layout plan. To address the facility layout problem within a factory area, Esmikhani et al. [36] proposed a multi-objective population-based simulated annealing algorithm (MPS) and a modified Non-dominated Sorting Genetic Algorithm II (MNSGA-II). Guan et al. [1] proposed a hybrid evolutionary algorithm to solve the dynamic extended row facility layout problem. In addition to the mentioned algorithms, the Particle Swarm Optimization (PSO) is also a common heuristic algorithm for solving facility layout problems. Guan et al. [37], combining a two-stage method, introduced a multi-objective Particle Swarm Optimization algorithm with an innovative discrete framework to search for feasible solutions locally and globally. Ma et al. [38] leveraged the advantages of both Particle Swarm Optimization and Grey Wolf Optimization to propose a hybrid optimization meta-heuristic called Particle Swarm Optimization-Grey Wolf Optimization (PSO-GWO) for integrating handling routes and information features of multiple transportation modes, including conveyor belts, Automatic Guided Vehicles (AGVs), and other transportation equipment, into a general plant layout planning model. Tang et al. [39] improved the Particle Swarm Optimization (PSO) algorithm to prevent it from getting stuck in local optima, thereby enhancing the accuracy of the solutions. Eswaran et al. [40] employed the modified Particle Swarm Optimization (MPSO) to generate a feasible assembly layout for the Human-Robot Collaboration (HRC) manufacturing system. They compared this enhanced method with Genetic Algorithms (GA), Hybrid Genetic Algorithms (HGA), and Particle Swarm Optimization (PSO). During the iterations of MPSO, appropriate weighted factors were provided for the velocity and direction of specific solutions, enabling the method to converge to a local optimum or global optimum within a certain time frame. While the aforementioned literature has made improvements when using PSO, these enhancements did not take into account the inertia of particles and the variability in particle performance. To address this, this paper introduces the concept of inertia weight and task collaboration to maintain particle inertia and assign different tasks to particles with varying performance, ultimately improving the algorithm's effectiveness.

III. PRODUCTION WORKSHOP FACILITY LAYOUT MODEL

A. PROBLEM DESCRIPTION AND ASSUMPTIONS

The facility layout problem of production workshop is to reasonably arrange the production operation units in the limited space of production workshop [36]. Hence, the facility layout problem can be considered a complex optimization issue, encompassing the determination of the optimal location for the production operation units requiring layout planning, as well as the allocation of available workshop space. In the design process of the actual production workshop facility layout, the operating area of each operating unit is different, and there are certain restrictions on the placement of some operating units. In this paper, four assumptions about production units are made as following:

a. Assuming that the facilities and equipment structures to be arranged within the production space are all rectangular in shape, and the internal component placements within the equipment are optimized.

b. The length and width of each device are known, and the horizontal and vertical placement is also determined. Each device is arranged randomly.

c. Each operating unit is placed in the same direction as the length of the workshop, and all operating units placed in the same row, the coordinates of their center points are on the same horizontal line.

d. Assuming that between every two operation units, the logistics path is parallel to the length and width of the workshop, then the distance of the material handling path can be expressed as: $|x_i - x_j| + |y_i - y_j|$.

According to the above assumptions, the layout of the production workshop facilities can be expressed as a continuous space layout optimization problem, but the problem must meet the relevant constraints under certain assumptions. The topology model of the workshop and equipment is shown in Fig. 1.

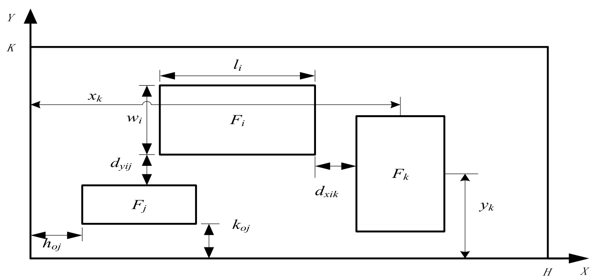

FIGURE 1. The schematic diagram of workshop facilities layout.

The meanings of all variables in the schematic model are as follows:

Notations	content
H	the total length of the workshop
K	the total width of the workshop
$F = (f_1, f_2, \cdots\cdots, f_D)$	the D equipment in the workshop
x_i	the center coordinate of the work unit F_i on the x-axis
y_i	the center coordinate of the work unit F_i on the y-axis
l_i	the length of the operating unit F_i
w_i	the width of the operating unit F_i
d_{xij}	the minimum distance between the work unit i and the work unit j in the x-axis direction
d_{yij}	the minimum distance between the work unit i and the work unit j in the y-axis direction

B. MATHEMATICAL MODEL

The facility layout model proposed in this paper aims at the optimization of the static facility layout of the production workshop, and establishes the objective functions of the lowest handling cost (Z_1) of the production workshop and the largest total non-logistics relationship (Z_2) between operation units, namely:

$$\min Z_1 = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} c_{ij} \cdot q_{ij} \cdot d_{ij} \tag{1}$$

$$\max Z_2 = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T_{ij} b_{ij} \tag{2}$$

Among them, i and j are the number of the functional area, and $i \neq j$.

In order to reduce the computational difficulty and meet the computational efficiency required by the enterprise, the above-mentioned multi-objectives are transformed into single-objectives. Considering the different dimensions of the objectives (1) and (2), the normalization factor is added and the dimensions are unified. At the same time, considering the different characteristics and requirements of different production workshops, the two objective functions are different correspondingly. The proportions are also different, so the weights are assigned respectively. We assume that ω_1 is the weight of the transportation cost item in the production workshop, and ω_2 is the weight of the comprehensive correlation item, $\omega_1 + \omega_2 = 1$. ω_1 and ω_2 are all obtained through expert evaluation according to the different production workshop conditions. The following single objective function expression can be obtained:

$$\min Z = \mu_1 \omega_1 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} c_{ij} q_{ij} d_{ij} - \mu_2 \omega_2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T_{ij} b_{ij} \tag{3}$$

Among:

$$\mu_1 = \frac{1}{\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} c_{ij} q_{ij} d_{\max}}, \mu_2 = \frac{1}{\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T_{ij}} \tag{4}$$

where:

N: the total number of operation units;

c_{ij}: Transportation cost per unit distance from operation unit i to j;

q_{ij}: The average annual material flow between operation units i and j;

d_{ij} : The distance between work units i and j in the shop layout, $d_{ij} = |x_i - x_j| + |y_i - y_j|$.

T_{ij} : The non-logistics correlation value between operation unit i and operation unit j, which is determined after comprehensively considering the closeness of the non-logistics relationship between operation unit i and operation unit j;

b_{ij} : The closeness between operation unit i and operation unit j;

$d_{\max}$: The sum of the length and width of the primary planning area of the production workshop.

The numerical interval [0, $d_{\max}$] is divided into 6 subintervals, and the adjacency between each functional area is judged according to the sub-intervals. The adjacency quantification table corresponding to each subinterval is shown in Table 1.

TABLE 1. Operating unit adjacent to quantify the degree.

Work unit d_{ij}	Relevance value b_{ij}
[0, $d_{\max}$ /6]	1
[$d_{\max}$ /6, $d_{\max}$ /3]	0.8
[$d_{\max}$ /3, $d_{\max}$ /2]	0.6
[$d_{\max}$ /2, $d_{\max}$ /3]	0.4
[$d_{\max}$ /3, $d_{\max}$ /6]	0.2
[$d_{\max}$ /6, $d_{\max}$]	0

The constraints of the optimization model for facilities layout of production workshop are proposed as follows:

a. All facilities cannot be placed on top of each other, and there is a minimum distance d between every two devices. Among them, d_{xjk} is the minimum distance between devices j and k in the X direction, and d_{yjk} is the minimum distance between devices j and k in the Y direction. The constraint condition can be expressed as follows:

$$A_{jk} \cdot B_{jk} = 0 \tag{5}$$

$$A_{jk} = \max\left\{\left(\frac{l_j + l_k}{2} + d_{xjk}\right) - \left|x_j - x_k\right|, 0\right\} \tag{6}$$

$$B_{ik} = \max\left\{\left(\frac{w_j + w_k}{2} + d_{yjk}\right) - \left|y_j - y_k\right|, 0\right\} \tag{7}$$

b. The workshop facility layout should meet the following two constraints: first, all equipment must be within the overall length and width of the workshop. Second, a certain distance should be maintained between the equipment and the surrounding walls of the workshop, that is, there is a minimum distance constraint H_{oj} and K_{oj} between the equipment and the wall. Among them, H_{oj} represents the minimum distance between the device j and the wall in the X-axis direction, and K_{oj} represents the minimum distance between the device j and the wall in the Y-axis direction. The constraints are as follows:

$$\frac{l_j}{2} + H_{oj} - x_j \leq 0 \tag{8}$$

$$\frac{w_j}{2} + K_{oj} - y_j \leq 0 \tag{9}$$

$$x_j - \left(H - \frac{l_j}{2} - H_{oj}\right) \leq 0 \tag{10}$$

$$y_j - \left(K - \frac{w_j}{2} - K_{oj}\right) \leq 0 \tag{11}$$

c. During the facility layout process in production workshop, the positions of some certain facilities or work units have been fixed. For example, the heat treatment facilities, which are quite special, should be placed at the corners of the space. In the layout model, they are regarded as existing operation units, and their areas are located as fixed areas. No other operation units are considered to be assigned in these areas. D_k is used to represent the fixed area, which is:

$$\left(x_i - \frac{l_i}{2}, x_i + \frac{l_i}{2}, y_i - \frac{w_i}{2}, y_i + \frac{w_i}{2}\right) \notin D_k \tag{12}$$

d. Alternative constraints of different production workshops.

Based on the multi-objective characteristics of the production workshop facility layout, it is impossible to use all objectives as optimization objectives or transform them into fitness functions. Therefore, this paper regards the logistics cost objectives and non-logistics objectives as optimization objectives and all other objectives are used as constraints. Different production workshops select different constraints according to their different optimization priorities or strategic decision directions.

1) CONSTRAINTS ON AREA UTILIZATION RATE

The area utilization rate has become a key indicator for measuring facility layout design in modern enterprises, because it greatly affects the cost of facility layout. In standard operating conditions, when the enterprise can ensure safe production, a higher area utilization rate corresponds to a reduced layout cost. The area utilization rate of facility layout problem can be expressed by the formula:

$$R_s = \frac{\sum_{i=1}^{n} A_i}{\sum_{i=1}^{n} A_i + \sum B_j} \geq r_s \tag{13}$$

where:

R_s represents the area utilization rate;

$\sum_{i=1}^{n} A_i$ represents the sum of the occupied area of facilities;

$\sum B_j$ represents the sum of the vacant areas that are not used by facilities;

i represents the i-th device;

r_s represents the requirement standard of area utilization rate.

2) EQUIPMENT UTILIZATION CONSTRAINTS

This paper assesses equipment utilization using time utilization as the measure, with the exclusion of machine tool maintenance time from the equipment utilization calculation. Due to the need for maintenance or repair of the equipment, the time taken for the machine tool to stop from the machining state is the machine downtime. Therefore, the equipment utilization rate can be expressed by equation (14):

$$R_{EU} = \frac{T_o}{T_A} \times 100\% \geq r_{EU} \tag{14}$$

where:

R_{EU} represents equipment utilization rate;

T_o represents the working time, mainly including processing, auxiliary, and unloading time;

T_A represents the available time of equipment;

r_{EU} represents the requirements of equipment utilization rate.

3) CONSTRAINTS ON THE UTILIZATION OF WORKERS' WORKING HOURS

The utilization rate of workers' working hours is the ratio of the actual working time of workers to the total working hours of manufacturing, and it is an index used to measure the efficiency of worker. This utilization rate is closely related to the time of preparation, operation, schedule, interruption, and termination. In standard operating conditions, a longer operation time corresponds to a higher utilization rate of working hours, whereas a longer interruption time results in a lower utilization rate of working hours. The higher the utilization rate of working hours, the more fully utilized the working hours. The expression of utilization rate of workers' working hours is shown in formula (15):

$$R_L = \frac{T_w}{T_T} \times 100\% \geq r_L \tag{15}$$

where:

R_L is the utilization rate of workers' working hours;

T_w is the working hours of workers;

T_T is the total time of workers in the factory;

r_L is requirements of utilization rate of workers' working hours.

4) MATERIAL TRANSFER TIME CONSTRAINTS

The expression of the model for minimizing the material transfer time is shown in equation (16):

$$T = \sum_{i=1}^{n}\sum_{j=1}^{n} \frac{f_{ij}}{a_{ij}} \times \frac{d_{ij}}{V_{ij}} \leq t \tag{16}$$

where:

T is the material transfer time;

f_{ij} is the The volume of goods between facilities;

d_{ij} is thematerial transfer distance;

a_{ij} is the volume of goods transported in a single pass;

V_{ij} is the conveying speed of workers when transporting materials;

5) CONSTRAINTS ON PROXIMITY RELATIONSHIP

The proximity relationship can also be used as an indicator to measure the material transfer volume of adjacent facilities. The proximity relationship model necessitates that two pieces of equipment in the production workshop exhibit a close logistics relationship, with the aim of minimizing the cost and time required for material transmission. It can be obtained by following equation:

$$A = \sum_{i=1}^{n}\sum_{j=1}^{n} (b_{ij} \times a_{ij}) \geq a \tag{17}$$

where:

A is the proximity relationship;

b_{ij} is he closeness between operation unit i and operation unit j;

a_{ij} is the proximity relationship value.

6) REVERSE LOGISTICS CONSTRAINTS

In the product manufacturing process, due to the processing requirements, the process of transporting materials from certain equipment to its upstream equipment is called as backtracking [41]. Equation (18) is the minimum logistics reversal model:

$$F_b = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\sum_{k=1}^{n-1}\sum_{l=k+1}^{n} f_{ij} d_{ij} x_{lk} x_{jl} \leq f_b \tag{18}$$

where:

F_b is the amount of materials in reverse logistics;

f_{ij} is the reverse flow between equipment i and j;

x_{ik}, x_{jl}: if the devices i and j are placed at positions k and l, the value is 1,otherwise the value is 0;

f_b is the logistics reverse volume requirements.

7) CONSTRAINTS ON THE MATERIAL TRANSFER VOLUME OF ADJACENT UNITS

In a manufacturing system, the amount of material transfer between units often accounts for half or even higher of the total transfer volume. Therefore, in the unit layout, the logistics transfer volume or cost between adjacent units is very important indicator of the unit layout. The material transfer volume model of adjacent units is shown in formula (19):

$$F_a = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} f_{ij} d_{ij} X_{ijkl} \leq f_a \tag{19}$$

where,

$$X_{ijkl} = \begin{cases} 1, & \text{Adjacent in the same row} \\ 1, & \text{Adjacent in the same column} \\ 0, & \text{Otherwise} \end{cases}$$

f_a is the material transfer volume requirement of adjacent units.

IV. IMPROVED PSO ALGORITHM BASED ON TASK COLLABORATION

The proposed production workshop facility layout optimization problem is a multi-objective optimization problem. The Particle Swarm Optimization (PSO) algorithm is one of the most common meta-heuristic algorithms. Due to its ease of implementation and fewer parameters [42], it is widely used for solving optimization problems. Therefore, this paper intends to employ the PSO algorithm to address the proposed multi-objective optimization model. However, traditional PSO algorithms are prone to getting trapped in local optima when dealing with complex multi-modal optimization problems [43]. To solve this problem, a PSO algorithm based on task collaboration is designed. For the PSO algorithm, the introduction of the inertia weight can maintain the particle inertia and improve the algorithm effect [44], [45]. However, in order to get better results, it must ensure that the parameter values are appropriate. Thus, the idea of task collaboration is introduced to assign different tasks to particles with different performance. For example, to enhance the precision of particle swarm optimization, the enhanced PSO method based on task collaboration assigns smaller ω values to high-performing particles, enabling them to conduct more accurate searches within narrower ranges, reducing the risk of overlooking the optimal position. Conversely, particles with lower performance are assigned larger ω values, allowing them to explore larger ranges and locate the optimal position more swiftly. Considering the differences between different particles, the improved PSO based on task collaboration can obviously improve the optimization performance [46], [47].

The core of the improved PSO based on task collaboration can be expressed as: when the particle swarm iterate to the t-th generation, the relative fitness range [FL, FH] of the current particle swarm is calculated, and the inertia weight can be linearly taken according to the above fitness range.

$$\omega_i' = \frac{(\omega_{\max} - \omega_{\min})(F_L - F_i)}{F_H - F_L} + \omega_{\max} \tag{20}$$

In summary, the advantage of the improved PSO based on task collaboration is that the particles can obtain different ω values at different stages of the calculation process, which significantly balances the global and local search capabilities of the particle swarm. The steps of the improved PSO algorithm are as follows.

A. CODE DESIGN

For the production facility layout optimization problem, it is assumed that there are D work units in the workshop, and this paper represents the facility layout design of each workshop as a particle, then the code of each particle is a 2D-dimensional vector. Among them, the first D dimension represents the X coordinate of each work unit, and the last D dimension represents the Y coordinate of each work unit. The flight speed of each particle is also 2D-dimensional vector. Among them, the first D dimension represents the moving speed of each work unit in the X direction, and the latter D dimension represents the moving speed of each device in the Y direction.

$$P = (x_1, \ldots, x_d, y_1, \ldots, y_d) \tag{21}$$
$$V = (v_{x1}, \ldots, v_{xd}, v_{y1}, \ldots, v_{yd}) \tag{22}$$

In the optimization process, the particles mainly follow the optimal particle to search in the solution space by tracking two extreme values. The two extreme values are: individual extreme value *pBest*, i.e., the optimal solution found by the particle, and the global extreme value *gBest* i.e., the optimal solution found in the entire population, so as to achieve its self-renewal. The position of each particle can be transformed according to formula (23) ∼ formula (26):

$$v_{xid}(t+1) = w \cdot v_{xid}(t) + c_1 \cdot rand() \cdot [p_{xid}(t) - x_{id}(t)] + c_2 \cdot rand() \cdot [p_{xgd}(t) - x_{id}(t)] \tag{23}$$
$$v_{yid}(t+1) = w \cdot v_{yid}(t) + c_1 \cdot rand() \cdot [p_{yid}(t) - y_{id}(t)] + c_2 \cdot rand() \cdot [p_{ygd}(t) - y_{id}(t)] \tag{24}$$
$$x_{id}(t+1) = x_{id}(t) + v_{xid}(t+1) \tag{25}$$
$$y_{id}(t+1) = y_{id}(t) + v_{yid}(t+1) \tag{26}$$

where, t is the number of iterations; c_1 and c_2 are acceleration coefficients, which are non-negative constant; $rand()$ is a random number uniformly distributed between (0, 1); w is the coefficient of inertia, which is a non-negative constant; p_i is the best position experienced by the i-th particle, p_g is the best position experienced by all particles in the group.

B. PARAMETER DESIGN

1) FITNESS FUNCTION

When transforming the objective function into a fitness function, the fitness function *fitness_F* is designed to ensure that the fitness function is non-negative.

$$fitness\_F = \frac{1}{\mu_1\omega_1 \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} c_{ij}q_{ij}d_{ij} - \mu_2\omega_2 \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} T_{ij}b_{ij} + MAX} \tag{27}$$

where, *MAX* is a sufficiently large constant.

2) SETTING OF ACCELERATION FACTOR (c_1, c_2)

In order to ensure the algorithm's search quality and optimization speed, this paper selects five representative acceleration coefficient schemes into the improved PSO algorithm, and analyzes and compares the optimization results to select the best acceleration coefficient scheme under the optimal result.

3) SETTING OF PSO INERTIA COEFFICIENT (w) BASED ON TASK COLLABORATION

On the basis of the inertia coefficient of improved PSO based on task collaboration, according to formula (28), this paper assigns variable inertia weights to different particles. In the iterative process, a linear value between $\omega_{\max}$ and $\omega_{\min}$ is selected according to the fitness of the particle for ω.

$$\omega_i' = \frac{(\omega_{\max} - \omega_{\min})(F_L - F_i)}{F_H - F_L} + \omega_{\max} \tag{28}$$

To better illustrate the improvements made in this paper to the PSO, we present the improved PSO algorithm, as shown in Algorithm 1.

The advantages of the Task Cooperative Particle Swarm Optimization (PSO) algorithm are: it assigns different ω values to particles at different stages of the computation process, effectively balancing the search capability of the particle

Algorithm 1 Improved PSO Algorithm

Initialize:
For each particle i, initialize the position p_i and velocity v_i.
For each particle i, randomly initialize *pbest* as the current position p_i.
Initialize the global best position *gbest* as the position of one of the particles.
parameters:
Maximum number of iterations: *max_iterations*
Initial weight factor: *w_max*
Final weight factor: *w_min*
Individual acceleration coefficient: c_1, c_2
***for* each iteration from 1 *to* *max_iterations*:**
  Calculate the current weight factor w:
  $\omega_i' = \frac{(\omega_{\max}-\omega_{\min})(F_L-F_i)}{F_H-F_L} + \omega_{\max}$
  ***for* each particle i:**
    Generate random numbers *rand* () (between 0 and 1).
    Update the velocity:
    $v_{xid}(t+1) = w \cdot v_{xid}(t) + c_1 \cdot rand() \, . \, [p_{xid}(t) - x_{id}(t)] + c_2 \cdot rand() \, . \, [p_{xgd}(t) - x_{id}(t)]$
    $v_{yid}(t+1) = w \cdot v_{yid}(t) + c_1 \cdot rand() \, . \, [p_{yid}(t) - y_{id}(t)] + c_2 \cdot rand() \, . \, [p_{ygd}(t) - y_{id}(t)]$
    Update the position:
    $x_{id}(t+1) = x_{id}(t) + v_{xid}(t+1)$
    $y_{id}(t+1) = y_{id}(t) + v_{yid}(t+1)$
    ***If* *fitness_F* is better than *fitness_F_pbest*:**
      Update *pbest* to p_i
      ***If* *fitness_F* is better than *fitness_F_gbest*:**
        Update *gbest* to *pi*
    End If
  End For
End For
Return *gbest* as the best solution.

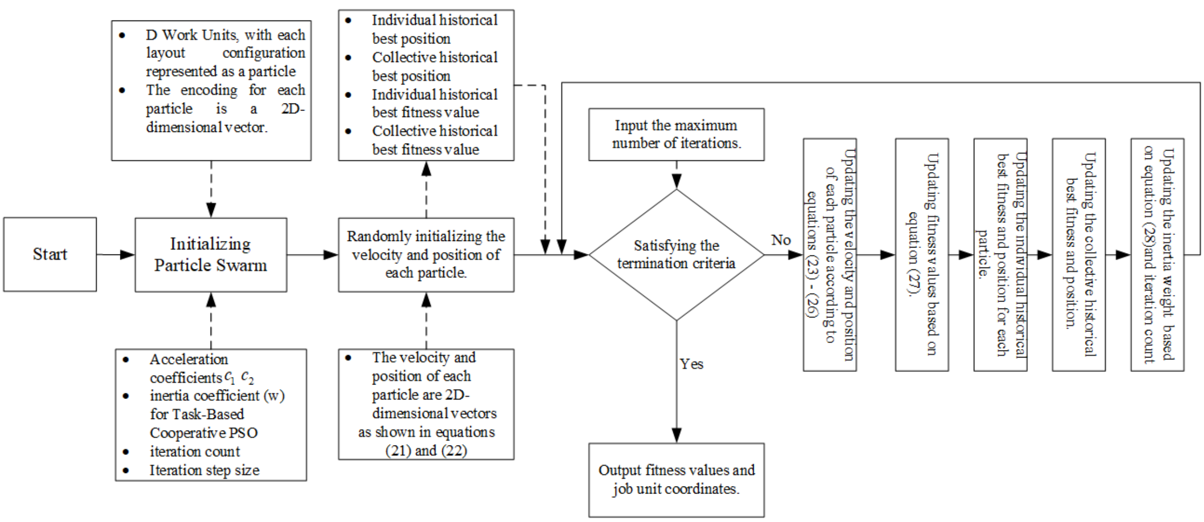

FIGURE 2. Improved PSO flowcharts.

swarm between global and local aspects. The flowchart of Algorithm 1 is shown in Fig. 2.

V. CASE STUDY

A. CASE BACKGROUND

Company *A* primarily manufactures fuel injection systems. Due to high market demand and diverse customer requirements, the company organizes its production using multi-variety, small-batch production approach to meet the market's demand for product variety. In order to smoothly achieve the company's future production development goals, which include doubling production within two years and quadrupling it within four years, a new factory area was constructed. The aim was to achieve a scientifically planned facility layout in the new factory area, addressing the root causes of production disorder and excessive logistics flow. The improvements in the construction of the new factory area, enhanced product development capabilities, continuous expansion of production scale, and the growth of the workforce, along with further innovation in development concepts, have brought both opportunities and challenges to the company. We intend to conduct logistics analysis and facility layout planning for this workshop, optimize the flow of materials within the workshop, reduce handling volume, and ultimately enhance the overall competitiveness of the enterprise.

Through multiple on-site surveys of Company A's needle valve component production workshop and interviews with several professionals in the company and the workshop, the problems currently existing in the facility layout of the needle valve component production workshop can be summarized as follows:

① The layout is primarily in the form of cluster arrangement. Cluster layout offers strong adaptability to product variations and high flexibility. However, when product processes are complex and require multiple types of equipment, materials have to continuously move back and forth between different processes and equipment. This increases the number of material handling operations and distances, often leading to issues such as material flow crossing and reverse flows.

② In terms of material handling, the needle valve component production workshop has problems with excessively long transport routes, significant material flow crossings, and excessive material handling volumes.

③ There are inconsistencies or conflicts between the equipment layout in the needle valve component production workshop and the main production processes of the products. These issues result in high workshop logistics costs, a significant backlog of work-in-progress inventory, a negative impact on production efficiency, and unstable product delivery times, contributing to production planning chaos.

To test the effectiveness of the production workshop facility layout optimization model and method proposed in this paper and to assist Company A in achieving its production goals, the diesel generator's needle valve production workshop of Company A in China was chosen as the research subject. There are 17 work units in the workshop, and the area of each unit is shown in Table 2.

TABLE 2. Area of work unit.

Area number	Name	Length	Width
1	Grinder area	12	7
2	Lathe area	23	11
3	Machining center area	24	9
4	Jet drilling area	16	10
5	Electric spark area	10	6
6	Light decoration area	12	6
7	Electrolysis machine bed area	18	9
8	Computer Numerical Control (CNC) cylindrical grinding area	16	8
9	Assembly area	18	9
10	Cross-cutting machine area	14	8
11	Magnetic flaw detection machine area	12	6
12	Cleaning machine area	16	9
13	Laser engraving area	14	7
14	Red set equipment area	16	10
15	Cooling cavity area of needle valve body	14	7
16	High pressure cleaning machine area	14	8
17	Fitter platform area	14	7

B. RESULTS AND DISCUSSION

1) PARAMETER DESIGN

a: FITNESS FUNCTION

According to the formula (4) and the known conditions of production, $\mu_1 = 2.62 \times 10^{-9}$ $\mu_2 = 0.0056$ is calculated. In this paper, due to the characteristics of multi-variety and small batch, it is necessary to minimize the logistics volume as far as possible, so the expert gets $\omega_1 = 0.6$ $\omega_2 = 0.4$. Then, the Fitness function can be obtained as the following equation (29), as shown at the bottom of the next page.

b: ALTERNATIVE CONSTRAINTS

Based on the production mode of multi variety and small batch, through expert evaluation and selection, the logistics reverse return volume is taken as one of the constraints of the production workshop of company A. According to the expert experience, f_b =3 × 107kg.

$$F_b = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \sum_{k=1}^{n-1} \sum_{l=k+1}^{n} f_{ij} d_{ij} x_{lk} x_{kl} \leq f_b = 3 \times 10^7 \quad (30)$$

c: SETTING OF ACCELERATION FACTOR (c_1, c_2)

In order to ensure the optimization quality and speed of the algorithm, this paper introduces five representative acceleration coefficient schemes into PSO algorithm for optimization, and analyzes and compares the optimization results to select the best acceleration coefficient scheme under the optimal result.

d: SETTING OF INERTIA COEFFICIENT OF THE IMPROVED pso BASED ON TASK COLLABORATION

In this paper, for the inertia coefficient of the improved PSO based on task collaboration, different particles are given different inertia weights ω_i' in the process of programming and calculation according to equation (31), in which $\omega_{\max} = 0.95$ and $\omega_{\min} = 0.64$.

$$\omega_i' = \frac{(\omega_{\max} - \omega_{\min})(F_L - F_i)}{F_H - F_L} + \omega_{\max} \quad (31)$$

TABLE 3. The volume of material handling between the equipment.

	1	2	3	4	5	…	14	15	16	17
1	0	9214	0	0	0	…	0	0	0	0
2	0	0	338403	89079	0	…	0	12636	0	0
3	0	0	0	13438	0	…	0	0	1812	0
4	0	0	0	0	1376	…	0	12636	20312	0
5	0	0	0	0	0	…	0	0	0	0
…	…	…	…	…	…	…	…	…	…	…
14	0	0	0	0	0	…	0	27610	0	0
15	0	0	0	0	0	…	0	0	56180	0
16	0	0	0	0	0	…	0	0	0	0
17	0	0	0	0	0	…	0	0	0	0

TABLE 4. The relevant parameters of 5 representative acceleration coefficients.

Parameters	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Dim	34	34	34	34	34
$PNum$	500	500	500	500	500
c_1, c_2	1.2, 1.2	1.4955, 1.4955	1.9, 1.9	2, 2	2.1, 2.1
$\omega_{\max}, \omega_{\min}$	0.95, 0.64	0.95, 0.64	0.95, 0.64	0.95, 0.64	0.95, 0.64
n	5000	5000	5000	5000	5000
t_1, t_2	100, 100	100, 100	100, 100	100, 100	100, 100

As the unit price and volume of material handling between the equipment are fixed, the material handling cost is only related to the handling distance between the equipment. Among these, the site dimensions of Company A's needle valve couple production workshop are 150m × 24m, with the occupied area of each equipment detailed in Table 2. The volume of material handling between the equipment is shown in Table 3.

2) SIMULATION EXPERIMENT AND PARAMETER ANALYSIS

Based on the parameters designed in 1) and the research data in Table 3, we used the task-collaboration-based improved PSO to optimize the production workshop facility layout, with the relevant parameters shown in Table 4. Since different settings of the acceleration coefficient will produce different results under various conditions, to ensure the optimization quality and speed of the improved PSO, five representative acceleration coefficients were selected during the optimization process. The optimization schemes for the production workshop facility layout were calculated for each acceleration coefficient, and the scheme with the best optimization result was chosen as the final scheme.

The improved PSO is coded by the MATLAB R2010a and run on a PC with an Intel Core i3-2330M 2.20 GHz CPU and 4 GB RAM. In order to ensure the reliability and credibility of the optimization effect, the five different schemes are run 1000 times respectively, and the comparison of optimization results of different schemes is shown in Table 5. It can be concluded that when the acceleration coefficient $c_1 = c_2 = 2$ under scheme 4, the effect of optimization is the best. Under this coefficient, the average adaptation value is 0.07924, and the final result of the scheme 4 is shown in Table 6. After the test of production practice, the optimized facility layout scheme can indeed reduce the material handling cost of the workshop. In summary, the Improved PSO based on task collaboration is effective approach to solve the optimization problem of the production workshop facility layout.

The final workshop layout is as shown in Fig. 3. In Fig.3, numbers represent device IDs, shapes and sizes represent the operational unit, and the combination of number and

$$fitness\_F = \frac{1}{1.57 \times 10^{-9} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} c_{ij} q_{ij} d_{ij} - 2.24 \times 10^{-3} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T_{ij} b_{ij} + MAX} \tag{29}$$

TABLE 5. The comparison of optimization results of different schemes.

	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
c_1, c_2	1.2，1.2	1.4955，1.4955	1.9，1.9	2，2	2.1，2.1
Result 1	0.06593	0.06791	0.07322	0.07866	0.07461
Result 2	0.06864	0.06920	0.07305	0.08003	0.07409
Result 3	0.06899	0.06799	0.07468	0.07901	0.07631
Average fitness value	0.06785	0.06836	0.07365	0.07924	0.07500

TABLE 6. The final result of scheme 4.

Operation unit	X coordinate	Y coordinate
1	82	8
2	14	7
3	15	19
4	72	16
5	142.5	9
6	136	16
7	40	17
8	93	16.5
9	125	8
10	66.5	6.5
11	55	9
12	36	6
13	58	16
14	108	16
15	96	8
16	108	6.5
17	121	15

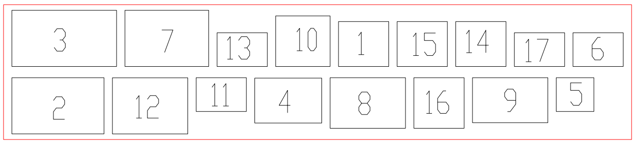

FIGURE 3. The optimization scheme.

position indicates the optimized position of the operational unit through the proposed model. For instance, the position corresponding to number 3 is (15, 19). The coordinates of each operational unit are shown in Table 6.

3) COMPARATIVE ANALYSIS

In order to further test and verify the performance of the improved PSO, we compared the improved PSO with the traditional PSO and SGA (Simple Genetic Algorithm). Using the same parameters, we applied the above algorithms to the problem of production workshop facility layout, and each algorithm was run 50 times. The results are shown in Figure 2 and Table 7. From Figure 4 and Table 7, it can be seen that the improved PSO can obtain a better solution with better fitness values compared to PSO and SGA. Furthermore, the improved PSO obtained the optimal solution at an average of 107 iterations, whereas the traditional PSO and SGA required an average of 135 and 158 iterations, respectively, which is significantly more than the improved PSO algorithm. In terms of runtime, the traditional PSO and SGA spent more time to achieve the optimal solution compared to the improved PSO. Therefore, compared to SGA and traditional PSO, the improved PSO can obtain better solutions and has higher operational efficiency when solving the production workshop facility layout problem. This further indicates that the improvements made to the PSO in this study are effective.

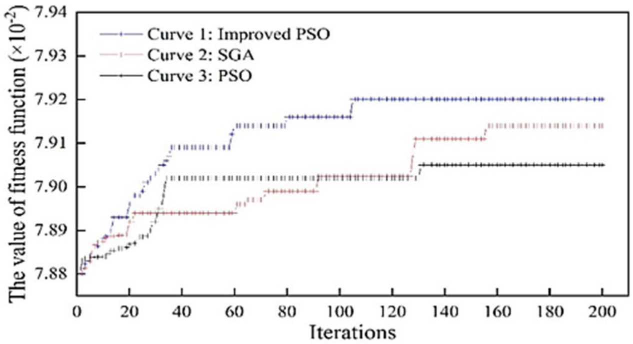

FIGURE 4. The comparative running results.

TABLE 7. Comparison of the performance of improved PSO, SGA and PSO.

Algorithm	Optimal result	Iterations	Running time
Improved PSO	0.07924	107	4.15
SGA	0.07914	158	5.46
PSO	0.07903	135	5.31

C. RESEARCH SIGNIFICANCE

This study addresses issues in the facilities layout in workshops and proposes a novel multi-objective optimization model. Additionally, improvements have been made to the Particle Swarm Optimization (PSO) algorithm for solving the model. This research enables a scientifically and reasonably arranged facilities layout planning, reducing transportation distance and frequency, lowering production costs, and enhancing the economic efficiency of enterprises. We summarize the significance of this study from both academic and practical perspectives. The academic and practical significance of this study can be summarized as follows:

In academic terms, this study employs an improved Particle Swarm Optimization (PSO) method to address the proposed facility layout planning model, innovatively establishing a new approach to solving facility layout problems. Furthermore, the feasibility of this novel method has been validated through practical applications, providing a theoretical foundation for logistics operations and facility planning in production workshops.

From the practical application perspective, the research significance of this paper can be summarized in three aspects: Firstly, the proposed facility layout planning method provides layout solutions for the facilities in production workshops. The layout scheme considers both logistics and non-logistics factors quantitatively, resulting in a smoother overall logistics system. This, in turn, reduces logistics costs, enhances production efficiency, and ultimately improves the competitiveness of the enterprise. Secondly, the internal layout of an enterprise, along with its logistics system, integrates various elements such as information, transportation, inventory, storage, material handling, and packaging, involving various aspects of the enterprise. The research presented in this paper has the capability to enhance the operations of the enterprise from a logistics perspective, thereby improving the overall management level of the company. Finally, the proposed methods can also serve as a reference for optimizing the facility layout of other production workshops.

VI. CONCLUSION

The facility layout of a production workshop exerts a direct influence on production efficiency, comprehensive operational costs, and material handling benefits, subsequently impacting the overall competitiveness of manufacturing enterprises. Addressing the optimization challenges of production workshop facility layout, this study establishes a comprehensive optimization model with the primary objectives of minimizing the handling costs within the production workshop and optimizing the non-logistical relationships among activity units. Subsequently, recognizing the multi-objective decision-making characteristics associated with production workshop facility layout, an enhanced Particle Swarm Optimization (PSO) algorithm, based on task collaboration, is proposed. To assess the algorithm's performance, numerical examples are employed to validate the efficacy and optimization capabilities of the enhanced task collaboration-based PSO algorithm. This improved PSO algorithm enhances global and local search capabilities by endowing particles with varying inertia weights during different phases, achieving a more balanced search process overall. Comparative analysis demonstrates that the enhanced PSO algorithm yields superior optimization results, requiring less iteration and reduced computational time when compared to traditional PSO and SGA algorithms. This improvement presents a more effective approach for solving the objective functions.

This study assumes that the processing tasks and processing techniques in the production workshop are deterministic. However, in current practical production, workshop production requirements are moving towards multi-variety and small-batch production. Therefore, this study has some limitations in addressing issues related to multi-variety, small-batch production workshops. Future research will focus on dynamic workshop layout and robust workshop layout, further refining algorithm structures and optimization processes to enhance the efficiency of optimization design methods and expand their application scope. Additionally, in terms of optimization algorithms, we improved the PSO based on task collaboration relationships, but this enhancement only considered the variation of weight values. Therefore, in future research, we will further optimize parameters and integrate the improved PSO algorithm with other algorithms for application to optimization problems in different scenarios.

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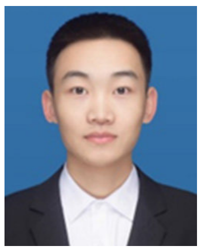

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