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Research on Facility Layout of Prefabricated Building Construction Site

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Abstract: Due to the high degree of mechanization and the good environmental benefits, the prefabricated buildings are being promoted in China. The construction site layout of the prefabricated buildings has important influence on its safety benefit. However, few scholars have studied the safety problem on it. Firstly, in order to give a follow-up study foreshadowing the characteristics of prefabricated buildings are analyzed, the research assumptions are given and three types of safety buffers are established. And then a mult-objective model for the prefabricated buildings site layout is presented: taking into account the limits of noise, the coverage of the tower crane and the possibility of exceeding boundaries and overlapping, the constraints are and designed established respectively; Based on the improved System Layout Planning (SLP) method, the efficiency\cost\safety interaction matrices among the facilities are also founded for objective function. For the sake of convenience, a hypothetical facility layout case of the prefabricated building is used, the optimal solution of that is obtained in MATLAB with particle swarm algorithm (PSO), which proves the effectiveness of the model presented in this paper.

Key words: Prefabricated building, site layout, safety, improved SLP, particle swarm optimization

1. INTRODUCTION

The construction site is considered to be a limited resource space that includes materials, equipment, labor, time and money [1]. There is a close relationship between the facility layout of the construction site and scheduling, cost estimation and other construction management process. Once the construction site layout is short of plan, it may lead to several problems such as space utilization poverty, additional material handling, secondary handling, cross operation, collision, progress delay and other issues [2,3], and eventually affect the duration of the project, cost and safety directly or indirectly.

The existing research on the layout of the construction site has focused on the goal of "reducing the cost of transportation between facilities" [4,5], while ignoring the possible safety problems. A few people are committed to the construction site layout safety research, which generally only use a single safety objective in study. For example: El-Rayes and Khalafallah [3] ensured the safety of the site staff by minimizing the number of road entrances; Sadeghpour et al. [6] protected property safety by increasing the visible area of the warehouse from the security room; Huang and Wong(Huang et al., 2015), Hammad et al. [7] reduced the impact of noise pollution on staff health by making the construction facility away from the site office area. It can be seen that there is almost none research weigh the safety of the site layout issues from the overall perspective so far.

The multi-objective linear programming method is used to set up facility layout model of the prefabricated building in this paper. It not only explores the new object of site layout research, but also identifies the potential risk in the early deployment scheme, in this way, the safety risks can be reduced from the source also called intrinsic safety, this paper has a certain practical significance for the layout of the prefabricated building construction site.

2. Characteristic analysis of prefabricated building construction site layout

2.1. Characteristics of prefabricated building site

Through the analysis of relevant literature on safety of production in prefabricated construction [8] and the site investigation of several prefabricated construction projects, it can be found that:

Firstly, the assembly mode of production reduces the wet operation during the construction process and abates the impact of construction by climate and temperature. It also has a high level of mechanization which brings a remarkably labor saving and significantly reduces the construction safety risks due to high altitude outdoor operations. However, there is no internal and external scaffolding and fence, so it is possible to happen high fall, object strikes and other accidents in the edge of the under-building structure.

Secondly, the prefabricated components are assembled on site that improves the construction environment by reducing dust and waste in the meantime avoiding the vibrations and noise generated from pouring concrete. At the same time, however, the assembly mode of production inevitably increases the noise pollution caused by machinery on site.

Thirdly, Extensive use of adhesives, thinners and other flammable and explosive chemicals in prefabricated building construction requires special attention in flammable and explosive materials warehouse and fire\electric related facilities.

The following layout model will be based on the above three characteristics and solve the problems individually.

2.2. Assumptions of facility layout model

The prefabricated building site and the facilities are abstracted as rectangles with certain size, and the variables in this model are the position coordinates of the facilities: $X_i(i=1,2,\cdots,n)$, that is, the coordinates of the rectangular centroids:

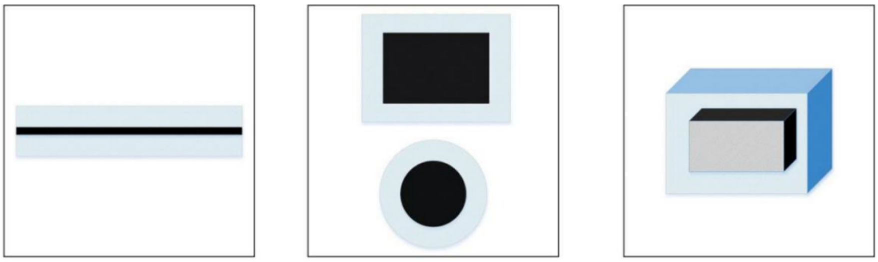
$$X=\{X_1,X_2,\cdots,X_n\}=\{(c_1^x,c_1^y),(c_2^x,c_2^y),\cdots,(c_n^x,c_n^y)\} \quad (1)$$

Where, (c_i^x,c_i^y) is the centroid coordinate of the facility i, and n is the number of objects to be arranged.

2.3. The establishment of safety buffer

Considering the risk of falling accident and object strike mentioned as the first characteristic in **Section 2.1**, this study adds safe buffer area are added into the facilities at the prefabricated building construction site, which can be divided into three types: line-based buffer, plane-based buffer, cuboid-based buffer. as shown in **Fig.1**. The buffer is treated as one of the properties of the facility itself in the subsequent study.

The line-based buffer is the area shown in **Fig.1. (a)**, for example, wires need to generate such buffers; The plane-based buffer area is shown in **Fig.1. (b)**, rectangular regions such as prefabricated component yard, power distributing box, etc. need generate such a buffer; Prefabricated components transported by tower crane will add a buffer around the cube, which called cuboid-based buffer as shown in **Fig.1.(c)**.



(a) (b) (c)

Fig.1. Schematic diagram of the safety buffer

3. Facility layout modeling of prefabricated construction site

3.1. Establish constraints

3.1.1. Noise-based constraints

According to the second characteristic analyzed in **Section 2.1**, the prefabricated construction site is prone to generate sudden, shock and discontinuous noise which may cause health damage to construction personnel. construction process, components yard frequent transport, making lifting and installation work, prone to sudden, impact, discontinuous noise, Noise is an inevitable factor that may cause health damage to the construction workers. Therefore, noise constraints should be established to ensure that the noise at the acoustic sensitive facility is not exceed the acceptable maximum value N_{lim}.

Assuming that the environment of the prefabricated construction site is ideal condition, the shortest safety distance d^s between the acoustic sensitive facility and the sound source can be obtained according to the acoustic noise attenuation formula (**Eq.** (2)) drawn lessons from acoustics.

$$\Delta N_{loss}=10\cdot log(\frac{1}{4}\pi(d^s)^2) \tag{2}$$

where:

d^s	is the shortest distance from the noise source to the facility, a continuous variable
N_{sour}	is the decibel value of noise at the noise source, dB (A)
ΔN_{loss}	is the loss of decibel value of noise during propagation, dB (A)
N_{lim}	is the maximum decibel value of noise acceptably, dB (A)

The noise is divided into two categories: point source and line source. For example, the noise generated by the fixed position facility, such as the tower crane is the point source. Meanwhile, the walking fork truck will form a linear noise source between the two facilities. The point has the shortest distance to the sound sensitive facility is regarded as centrality point of the linear noise source. In this way, the linear noise source is simplified as a point source. By now, as long as the **Eq.** (3) is satisfied, the noise in the sound-sensitive facilities will not exceeding the acceptable range.

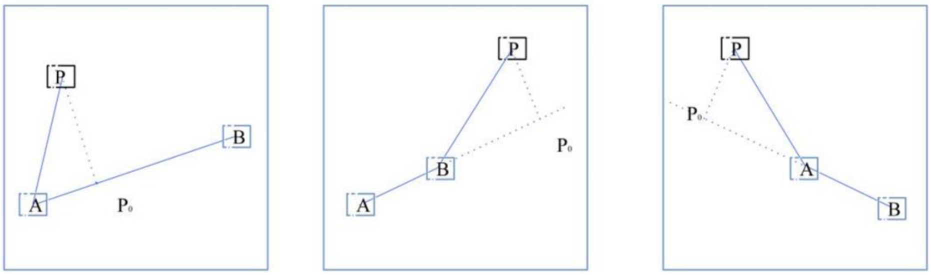
$$N_{sour}-\Delta N_{loss}=N_{sour}-10\cdot log(\frac{1}{4}\pi(d^s)^2)<N_{lim} \tag{3}$$

It is thus clear evident that ascertaining the shortest distance d^s is the most crucial step, so a discussion is given for it in the following:

1) The minimum distance between the point noise source i and the noise sensitive facility j is shown in **Eq.** (4):

$$d_{ij}^s=\sqrt{\left(c_i^x-c_j^x\right)^2+\left(c_i^y-c_j^y\right)^2} \tag{4}$$

2) There are three cases in the linear noise source. Assuming that facility A and B are the two endpoints of the linear noise source and facility P is the noise sensitive facility. For example, the noise is generated by the car crane and facility A, B is the under built buildings and components yard respectively, simultaneously, facility P is the staff quarters. The minimum distance between car crane and staff quarters is shown in **Fig.2**:



(a) (b) (c)

Fig.2. Schematic diagram of the shortest linear noise source distance

$$\alpha=\frac{(\overrightarrow{AP}\cdot\overrightarrow{AB})}{|\overrightarrow{AB}|^2}=\frac{|\overrightarrow{AP}|}{|\overrightarrow{AB}|}cos\,\theta=\frac{(c_b^x-c_a^x)\cdot(c_p^x-c_a^x)+(c_b^y-c_a^y)\cdot(c_p^y-c_a^y)}{\sqrt{(c_b^x-c_a^x)^2+(c_b^y-c_a^y)^2}} \tag{5}$$

Define α is equal to the expression in **Eq.** (5), and it can be judged from the direction of the vector:

(1) If $0<\alpha<1$, the centroid projection of the noise sensitive facility projects on line AB, as shown in **Fig.2. (a)**, the shortest distance d^s is:

$$d_{Pl}^s=sqrt(\left(c_p^x-c_{p_0}^x\right)^2+\left(c_p^y-c_{p_0}^y\right)^2) \tag{6}$$

$$c_{p_0}^x=c_a^x+r\cdot(c_b^x-c_a^x) \tag{7}$$

$$c_{p_0}^y=c_a^y+r\cdot\left(c_b^y-c_a^y\right) \tag{8}$$

(2) If $\alpha \geqslant 1$, the centroid projection of the noise sensitive facility projects on the extension line of AB on the left, as shown in **Fig.2. (b)**, the shortest distance d^s is:

$$d^s_{Pl}=sqrt(\left(c^x_p-c^x_b\right)^2+\left(c^y_p-c^y_b\right)^2) \tag{9}$$

(3) If $\alpha \leqslant 0$, the centroid projection of the noise sensitive facility projects on the extension line of AB on the right, as shown in **Fig.2. (c)**, the shortest distance d^s is:

$$d^s_{Pl}=sqrt(\left(c^x_p-c^x_a\right)^2+\left(c^y_p-c^y_a\right)^2) \tag{10}$$

where:

d_{ij} is the distance between facility *i* and facility *j* measured by Euclidean-based method, $i\neq j$

c^x_i is the horizontal coordinate of facility *i*, continuous variable, $c^x_i\geq 0$

c^y_i is the vertical coordinate of facility *i*, continuous variable, $c^y_i\geq 0$

i,j is construction site facilities, including temporary facilities and permanent facilities

θ is the angle between $\overrightarrow{AP}$ and $\overrightarrow{AB}$, continuous variable, $\theta\in(0,\pi]$

d^s_{Pl} is the shortest distance from point *P* to line *l*

Thus, the noise-based constraints is established as shown in **Eq.** (11):

$$d^s>sqrt(10^{\frac{N_{sour}-N_{lim}}{10}}\cdot\frac{4}{\pi}) \tag{11}$$

3.1.2. Tower crane constraints

It is necessary to ensure some facilities (c^x_i, c^y_i) (eg, component yard, etc.) be located within the radius of the tower boom for the normal construction. The center coordinates of the tower crane is (c^x_t, c^y_t) whose boom length is R. These facilities need to meet the following constraints at the same time:

$$\sqrt{\left(\left(c^x_i\pm\frac{l_i}{2}\right)-c^x_t\right)^2+\left(\left(c^y_i\pm\frac{w_i}{2}\right)-c^y_t\right)^2}\leq R \tag{12}$$

where:

l_i is the length of the facility *i* in the x-axis direction

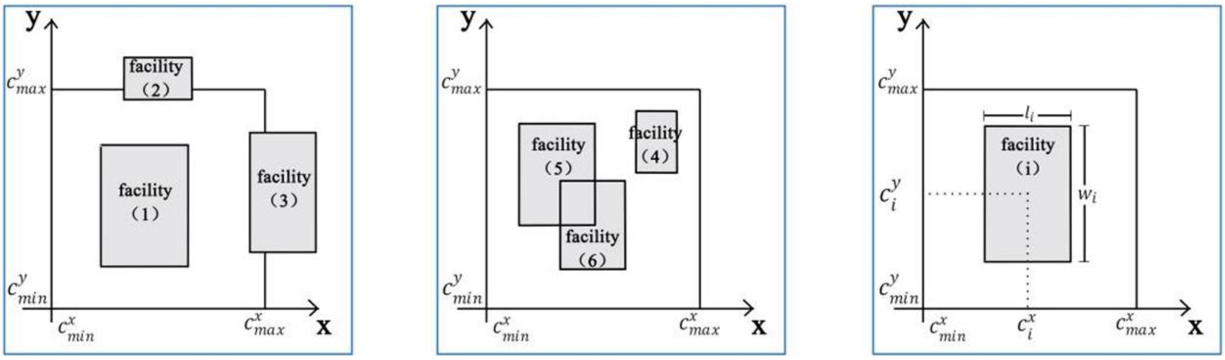
w_i is the width of the facility *i* in the y-axis direction

3.1.3. Boundary and overlapping constraints

In order to avoid infeasible solutions in the final calculation results, the facilities cannot be arranged and accommodated within all the locations on site. Therefore, establish the construction site boundary constraints and the anti-overlapping constraints [9,10].

1） Construction site boundary constraint

If conditions in **Eqs.** (13) -(16) are satisfied, all facilities will be located inside the construction site, as shown in **Fig.3. (a)**, the facility (1) meets the boundary constraints, while facilities (2) and (3) violate the constraints.



(a) (b) (c)

Fig.3. Schematic diagram of boundary and overlapping constraints

$$c^x_{min}+\frac{l_i}{2}-c^x_i\leq 0 \tag{13}$$

$$c^x_i+\frac{l_i}{2}-c^x_{max}\leq 0 \tag{14}$$

$$c^y_{min}+\frac{w_i}{2}-c^y_i\leq 0 \qquad (15)$$

$$c^y_i+\frac{w_i}{2}-c^y_{max}\leq 0 \qquad (16)$$

where:

$c^x_{min}(c^x_{max})$ is the left (right) boundary of the construction site

$c^y_{min}(c^y_{max})$ is the bottom(upper) boundary of the construction site

2) anti-overlapping constraints

anti-overlapping constraints are enforced to guarantee that there is no overlapping between any pair of facilities. No overlapping is achieved, if at least one of the conditions in both **Eqs.** (17) and (18) are satisfied. As shown in **Fig.3.** (b)., the facility (4) satisfies the constraints, while facilities (5) and (6) violate the constraints.

$$-/c^x_i-c^x_j/+\frac{l_i}{2}+\frac{l_j}{2}\leq 0 \qquad (17)$$

$$-/c^y_i-c^y_j/+\frac{w_i}{2}+\frac{w_j}{2}\leq 0 \qquad (18)$$

3.2. Objective function

Systematic Layout Planning (SLP) is a commonly used method of process specialization layout. By analyzing the interaction among various units, the relative distance is determined. In this paper, the improved SLP method is put forward, and the efficiency, cost and safety interaction relationship matrices are established for each objective function.

3.2.1. Efficiency objective function

The construction process has a direct impact on the construction efficiency, so it’s important to arrange the facilities based on the construction process of prefabricated building to improve the construction efficiency. Some processes must be close to each other here, for example: building yard need be close to the under built building, and the dormitory should be set near the office.

The adjacency interaction relationship is analyzed at first where the adjacency strength level $\alpha_{ij}$is used to quantify the elements. The strength level and meaning of $\alpha_{ij}$are shown in **Table 1**, and the adjacency interaction relationship matrix is shown in **Fig.4.** (a):

Table 1. Strength levels and meanings of $\alpha_{ij}\left(\beta_{ij}/\gamma_{ij}\right)$

$\alpha_{ij}\left(\beta_{ij}/\gamma_{ij}\right)$	Strength levels	Meanings
1	A	Adjacency demand (Logistics frequency / Destructiveness) is very high
0.8	E	Adjacency demand (Logistics frequency / Destructiveness) is high
0.6	I	Adjacency demand (Logistics frequency / Destructiveness) is general
0.4	O	Adjacency demand (Logistics frequency / Destructiveness) is low
0.2	U	Adjacency demand (Logistics frequency / Destructiveness) is very low
0	V	There is no Adjacency demand (Logistics frequency / Destructiveness)

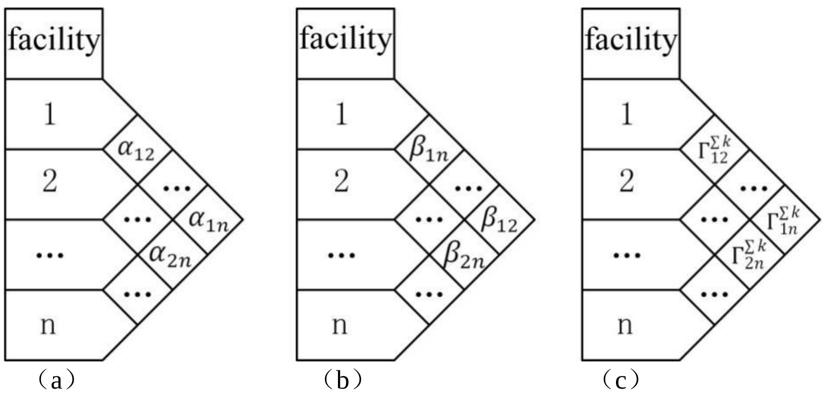


Fig.4. Schematic diagram of field boundary constraints

The efficiency objective function is committed to improving work efficiency using **Eq.** (19): the closer the facilities are, the more efficient the staff will be. And according to the adjacency interaction relationship matrix, facilities with higher adjacency requirements will be given greater weight in the calculation.

$$min\{\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\alpha_{ij}d_{ij}\} \quad (19)$$

3.2.2. Cost objective function

Facility layout directly affect the material, machinery and personnel flow on site, thereby affecting the transportation costs. Hence, the logistics strength β_{ij} is introduced into the arrangement of facilities, whose levels and meanings are as shown in **Table 1**. For example, the frequency of lifting the prefabricated component from the prefabricated building yard to the under built building is very high. The logistics frequency interaction relationship matrices among facilities is given using the logistics strength β_{ij}, as shown in **Fig.4.** (b).

Transport costs can be controlled by using the cost objective function in **Eq.** (20). The distance between the facilities is proportional to the cost of transport. And according to the logistics frequency interaction relationship matrix, facilities with higher logistics strength will be given greater weight in the calculation.

$$min\{\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\beta_{ij}d_{ij}\} \quad (20)$$

3.2.3. Safety objective function

In the prefabricated building construction site, unsafe accidents may occur when facilities are too close to each other: collision, fire, explosion, car accident, electric shock and numerous other unsafe events on assembly site are closely related to the layout planning.

In this part, identify the types of unsafe events that may occur on the site and give a destructive strength value denoted by $\gamma_{ij}$for each unsafe event. The strength levels and meanings of γ_{ij} are shown in **Table 1.** Assuming that the same type of unsafe event will produce the same degree of destructive, there are k types of unsafe events $(k=1, 2, \cdots, m)$and the destructive strength $\gamma^k$of all unsecured events are listed in **Eq.** (21):

$$\Gamma=[\gamma^1 \quad \cdots \quad \gamma^k \quad \cdots \quad \gamma^m] \quad (21)$$

Then, the unsafe events that may occur between facilities according to the destructive strength of each event in Γ. If there are more than one kind of risk between facilities i, j, accumulate the destructive strength and get superimposed hazard value $\Gamma_{ij}^{\Sigma k}$ in the form of **Fig.4.** (c).

The destructive on the global site is expressed by **Eq.** (22). The distance between the facilities is inversely proportional to the probability and destructive of unsafe events caused by proximity. According to the destructive interaction relationship matrix, facilities with lower destructive strength will be given greater weight in the calculation.

$$max\{\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\gamma_{ij}^{\Sigma k}d_{ij}\} \quad (22)$$

3.3. Global facility layout model

In summary, the construction site optimization problem can be abstracted as a multi-objective linear optimization problem, the mathematical model is shown in **Eq.** (23).

Since there are three objective functions in the facility layout model established in this paper, and these goals cannot be compared directly, thus there will be a series of Pareto optimal solutions. In order to facilitate the calculation, the preference is used to determine the weights ω of the different objective function targets, thereby determine the best compromised solution:

$$minF(X)=\left(f_1(X),f_2(X),\cdots,f_\rho(X)\right)=min\left\{\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\omega_1\alpha_{ij}d_{ij}+\omega_2\beta_{ij}d_{ij}+\omega_3\gamma_{ij}^{\Sigma k}d_{ij}\right\}$$

$$
s.t.\begin{cases}
N_{sour} - 10 \cdot log(\frac{1}{4}\pi(d^s)^2) < N_{lim} \\
c_{min}^x + \frac{l_i}{2} - c_i^x \le 0 \\
c_i^x + \frac{l_i}{2} - c_{max}^x \le 0 \\
c_{min}^y + \frac{w_i}{2} - c_i^y \le 0 \\
c_i^y + \frac{w_i}{2} - c_{max}^y \le 0 \\
\sqrt{\left(\left(c_i^x + \frac{l_i}{2}\right) - c_t^x\right)^2 + \left(\left(c_i^y + \frac{w_i}{2}\right) - c_t^y\right)^2} \le R \\
\sqrt{\left(\left(c_i^x + \frac{l_i}{2}\right) - c_t^x\right)^2 + \left(\left(c_i^y - \frac{w_i}{2}\right) - c_t^y\right)^2} \le R \\
\sqrt{\left(\left(c_i^x - \frac{l_i}{2}\right) - c_t^x\right)^2 + \left(\left(c_i^y + \frac{w_i}{2}\right) - c_t^y\right)^2} \le R \\
\sqrt{\left(\left(c_i^x - \frac{l_i}{2}\right) - c_t^x\right)^2 + \left(\left(c_i^y - \frac{w_i}{2}\right) - c_t^y\right)^2} \le R \\
-\left|c_i^x - c_j^x\right| + \frac{l_i}{2} + \frac{l_j}{2} \le 0 \quad or \; -\left|c_i^y - c_j^y\right| + \frac{w_i}{2} + \frac{w_j}{2} \le 0 \\
c_i^x \epsilon R^+ \\
c_i^y \epsilon R^+
\end{cases} \tag{23}
$$

4. Optimization model by particle swarm algorithm

The global facility layout model of the prefabricated building is a multi-objective liner programming problem. Since transports it into a single-objective programming, particle swarm optimization algorithm is chosen for its fast convergence and High-precision among GA, ACO etc. heuristic algorithms.

Suppose for a n-dimensional optimization problem: the current position vector and velocity vector of the *i*th particle are $x_i=(x_{i1},x_{i2},\cdots,x_{iD})$ and $v_i=(v_{i1},v_{i2},\cdots,v_{iD})$, respectively. If $p_i=(p_{i1},p_{i2},\cdots,p_{iD})$ is the best previously visited position or the personal best position of the *i*th particle and $p_g=(p_{g1},p_{g2},\cdots,p_{gD})$ represents the global best position of the swarm, the velocity and position of each particle are updated using **Eqs.** (24) and (25) [11,12]:

$$V_i^{k+1}=V_i^k+c_1\cdot r_{1i}^k\cdot\left(P_i^k-X_i^k\right)+c_2\cdot r_{2i}^k\cdot\left(P_g^k-X_i^k\right) \tag{24}$$

$$X_i^{k+1}=X_i^k+V_i^{k+1} \tag{25}$$

where:

D the number of dimensions, $d=1,2,\cdots,D$

N the swarm size, $i=1,2,\cdots,n$

c_1, c_2- are the cognitive coefficient and social coefficient, respectively. These two constants allow the particles to have the ability to make self-summary and learn from the outstanding individual in the swarm. Thus, approaching the historical bests position as well as the global best position in the swarm.

r_1, r_2 - are two random vectors, whose range of value is [0,1]

The basic steps of the particle swarm algorithm are as follows:

Table 2. The basic steps of the particle swarm algorithm

	steps of the particle swarm algorithm
STEP1:	Initialize. Generate initial searching point position and speed randomly;
STEP2:	Evaluate each particle position and calculate the fitness value of the particle;
STEP3:	Update the optimal position. Set the coordinates of current position to each particle and compare the fitness value with individual extreme p_{best} and global extreme g_{best}. Assign the larger values to the latest p_{best} and p_{best};
STEP4:	Particle update. Update the speed and position of each particle by **Eqs.** (24) and (25).
STEP5:	Cheek whether reach the end conditions. If the current iteration reaches the maximum times or the result already within the minimum range of error requirements, then the iteration is stopped and the global optimal solution can be output; otherwise, go to STEP2.

5. Model implementation

A case study is implemented in order to validate the proposed model. The dimensions of the site are 70 × 115 m and the nature of the required facilities are shown in **Table 3**. It is known that the location of tower crane and the under built building are both (13,50). Facilities 1and 5 must be within the radius of the tower crane's boom which is 50 meters long. The condition of noise in the prefabricated building is listed in **Table 4.**

Table 3. The name, size and safety buffer of the facilities

Sequence number	Name	Original size		Size adding safety buffer	
		The length along Y direction (m)	The width along the X direction (m)	The length along Y direction (m)	The width along the X direction (m)
F1	Prefabricated yard	5	23	7	25
F2	office	6	30	6	30
F3	dormitory	6	30	6	30
F4	Distribution box shelter	3	3	4	4
F5	Welding machine shed	6	4	8	6
F6	Flammable and explosive goods warehouse	6	4	8	6
F7	under built building	40	20	43	23

Table 4. The characteristics of main noise sources

Noise source	Features	Decibel	Position
Tower crane	Point acoutic source	85 dB	Prefabricated component yard
Auto-crane	Linear acoutic source	83 dB	Between the Under built building and prefabricated component yard

The noise/coverage/boundary and overlap constraints are established according to the method mentioned in **Section3.1**. To avoid repetition, it's not described in this section. In order to establish the objective function, the values of **Table 5** - **Table 6** can be determined by experts' scores.

Table 5. Destructive strength $\gamma^k$of unsecured events

Type	fire	collision	explosion	noise	car accident	electric shock
k	1	2	3	4	5	6
γ^k	0.8	0.6	1	0.2	0.4	0.6

Table 6. Destructive strength $\gamma^k$of unsecured events

Facility	F1	F2	F3	F4	F5	F6	F7
F1	\	2,4,5	2,4,5	2	none	none	none
F2		\	none	none	none	1,3	4
F3			\	4	none	1,3	4
F4				\	none	1,3,6	none
F5					\	1,3,6	6
F6						\	1,3
F7							\

As space is limited, the adjacency interaction relationship matrix, the logistics frequency interaction relationship matrix and the destructive interaction relationship matrix are given in **Fig.5** directly.

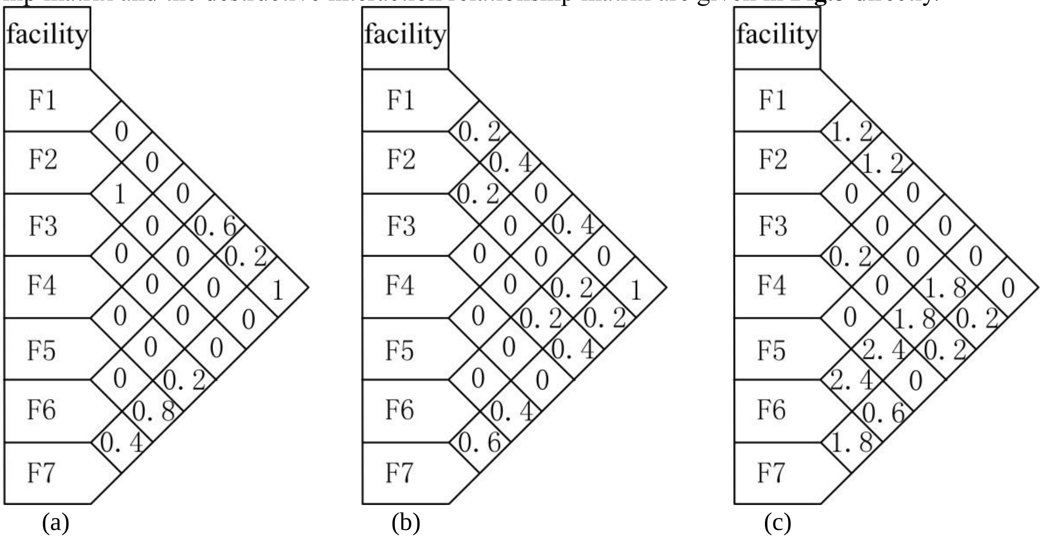


Fig.5. The results of interaction relationship matrices

Finally, use the particle swarm optimization algorithm to search optimal solution for the global facility layout model in MATLAB. **Fig. 6** reveals the optimal layout scheme and the best individual adoption parameters p_{best}.

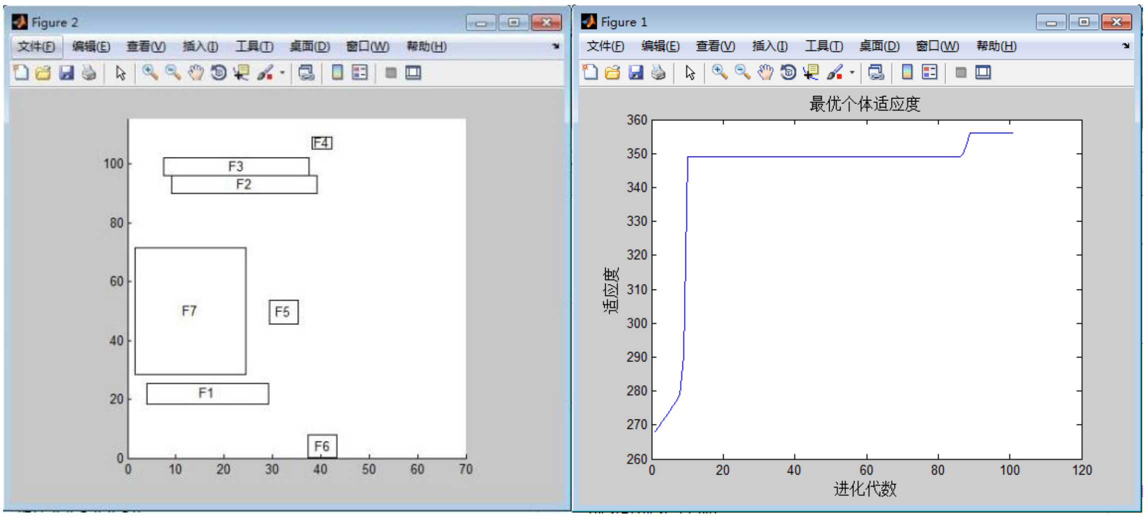


Fig.6. The optimal layout scheme in MATLAB

6. Conclusion

This paper presented a new model for the optimization of the prefabricated building construction site:

1) The restriction of noise and tower crane were taken into account when setting up constraints;

2) Considered efficiency, cost and safety goals in the objective function by drawing the idea of SLP method;

3) The particle swarm optimization was used in MATLAB to validate the proposed model

Additional future developments of this research are: generating the three-dimensional layout, especially focusing on the tower crane.

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