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Optimize location tower crane and supply facilities on construction site by discrete PSO algorithm

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Abstract: The optimal positioning of tower crane locations and material supply points on the construction site is an important task and is considered a complex combinatorial problem. Metaheuristics are popular and effective techniques for solving such problems. This paper introduces the application of the standard Particle Swarm Optimization (PSO) algorithm with discrete integer variables to solve the problem of optimizing the position of tower cranes and material supply points. A calculation program was built and numerical tests with 2 scenarios was conducted. The results show the performance of PSO and the applicability of the algorithm in the class of technical problems similar to the one under consideration.

Keywords: Tower Crane Location, Site Layout Planning, Particle Swarm Optimization (PSO), Swarm Intelligence, Metaheuristic Algorithm.

1. Introduction

Tower crane is an important equipment for transporting materials, machinery and equipment high up, especially when constructing high-altitude construction. Tower crane is used mainly to lift materials such as: reinforcing bars, formworks, concrete, structure components, etc. The location of the tower crane on the construction site is influenced by many factors and vice versa, a good crane placement not only reduces costs but also increases construction progress and ensures safe working conditions. Due to the great influence on the construction process, even though the selection of the location for tower cranes at the construction sites is only a part of the planning of the construction site in general, it is one of the top priorities of planning engineers. Choosing an optimal location for the crane and other related components becomes a work that must be carried out meticulously and scientifically. This is a combinatorial optimization problem [1], which cannot be solved by traditional optimization algorithms.

According to the reference [1], in general, there are three types of methods to solve the above combinatorial problem: exact algorithms, approximation algorithms and heuristic/ metaheuristic algorithms. Of the three methods, the group of metaheuristic algorithms has been interested in strong application and development in recent years. Genetic Algorithm (GA) is a popular metaheuristic algorithm that applies probabilistic search logic, it works well with different objective functions and even with nonlinear solution spaces. The GA has been applied in planning construction facilities and optimizing their layout [2-4]. However, when applying the GA, the optimization problem is solved by applying the principle of evolution, must perform an iterative process, and tends to converge early. Ant Colony Optimization (ACO) algorithm is also applied to the optimization problem of tower crane location [5]. However, the limitations of the ACO algorithm are the large number of parameter values, the oversensitive response to the parameters, and the increased error of the resulting values. New optimization research methods such as Collision Body Optimization (CBO) and Vibration Particle Systems (VPS) are also applied, but these methods have a problem in that it is difficult to present the lifting conditions and the location of the supply points in a simply and easily way [6]. Some other authors have tried to improve the algorithm to create a new calculation tool in order to reduce the calculation time, increase the accuracy of the solution when finding the optimal location for the cranes and supply points, such as: Combination of genetic algorithms (GA) and artificial neural networks (ANN) [7]; Hybrid between Bee Algorithm (BA) and Particle Swarm Optimization (PSO) [8]; Integration of Building Information Modeling (BIM) and Firefly Algorithm (FA) [9]. In order to increase the accuracy when calculating the transportation time of the crane, in [10], the dynamic factor when lifting and rotating the crane has been added, using a combination of the NAG optimization tool and the Simulated Annealing (SA) Algorithm.

In Vietnam, the location of cranes and facilities in a construction site is still organized for construction implementation by design engineers based only on their general knowledge and experience, which usually doesn't take quantitative criteria into account. Therefore, the results of the arrangement of the overall construction site plan, especially the positioning of the location of the crane and the warehouse, are not optimized so it often leads to additional costs, labor time and material wastes, inefficient use of resources and increase in possibility of conflicts. Academically, published research results are also quite meager. Here are two typical papers on this topic. The first one [11] aims to develop an integrated method, combining a building information model (BIM) and a multi-objective optimization tool based on an open-source visual programming named Optimo to automatically create an optimal tower crane positioning layout. The second one [12] proposes a new algorithm model, which is a hybrid of many metaheuristic algorithms, with the name Hybrid of Firefly Algorithm (HFA) in order to solve the problem of optimizing the crane's location.

Until now, the only common point of the researches to solve the optimization problem of tower crane and material supply point location is the objective function built on time/cost for the transportation of the crane. However, between the variable and the function along with the restriction conditions, it can't be expressed explicitly by analytic expressions. Therefore, it is not possible to use exact methods to solve but almost all use heuristic/metaheuristic algorithms. In addition, the ways of handling variables and limiting conditions are so different which makes the calculation programs cumbersome, difficult to prepare input data, and in turn reduce the applicability of the research results. Currently, PSO is considered as one of the leading swarm intelligence algorithms widely used in hybrid techniques due to its simplicity, global optimal search ability and faster convergence speed [13]. Next sections of the paper will present the content of building a problem model, then use the standard PSO algorithm with discrete integer variables in order to find the solution when optimizing the location of the tower crane and material supply points on the construction site for a single tower crane use case and uniform material supply (each selected supply point only contains and supplies one type of material).

2. Problem model

2.1. Assumptions

- Detailed ground layout of the known construction area (the perimeter of the construction site, the shape and the location of the main building, the expected location of ancillary works...);

- Possible points for the tower cranes positioning and points for future warehouses positioning S_i can be determined according to the construction site and the shape of the building; The locations for which the material is supplied D_j is deterministic and unchangeable;

- The area of each supply location S_i is large enough to accommodate the necessary materials;

- For each pair S_i - D_j, the transport demand levels are known, for example: material type, total quantity, maximum load to be transported, etc.

- Technical features of the crane to ensure the job is done: The reach of the tower crane is determined by the length of the boom and its lifting capacity is determined by the load radius curve in which the larger the load, the smaller the operating radius of the crane. Therefore, the positions of the supply points and the demand points must be within the allowable weight radius of the tower crane.

2.2. The tower crane location and supply points optimization problem

The location optimization problem for crane tower and material supply points (OLTC_S) is stated like the following:

"Find a set that includes the location of the crane and the location of the supply points, so that the total amount of money of material transported by the crane from the supply point to all the points to be supplied is minimized."

Math expression form:

$$F_{\text{cost}} = f\left(Cr_k, S_1, \ldots, S_i\right) \rightarrow \min \quad (1)$$

where, F_{cost} is the cost (money) to transport the total amount of materials by crane; Cr_k, is the location of the crane tower on the construction layout, which has the coordinates of $\left(Cr_k^x, Cr_k^y, Cr_k^z\right)$; S_i is the location of i^{th} supply point $\left(i = 1 \div nS\right)$, which has the coordinates of $\left(S_i^x, S_i^y, S_i^z\right)$.

Thus, in order to build an objective function for the problem, it is necessary to clarify the relationship between the coordinates of the crane placement points $\left(Cr_k^x, Cr_k^y, Cr_k^z\right)$ and the material supply points $\left(S_i^x, S_i^y, S_i^z\right)$ with the demand points $\left(D_j^x, D_j^y, D_j^z\right)$ and the transportation cost. Because the demand points are fixed, attention is focused on the allowable positions of the supply points. The limitation of cost considerations is to consider only the costs directly related to the uptime of the crane.

2.3. Create an objective function for the OTCL_S problem

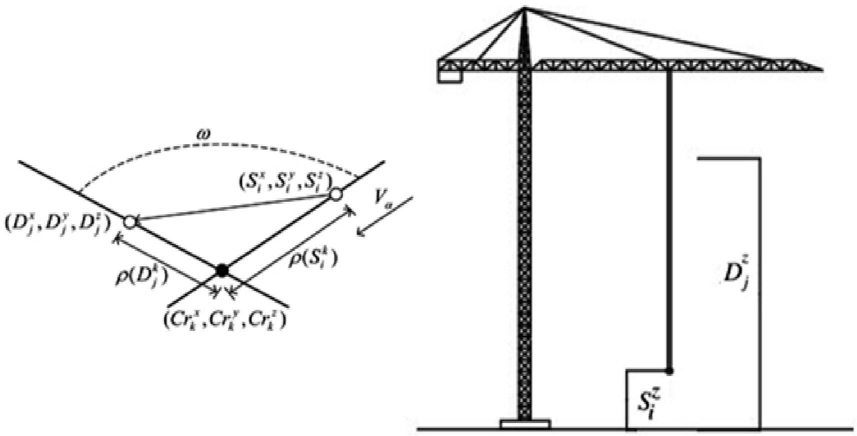

Fig 1. Hook travel time calculation diagram for (a) Radial and tangent movements, (b) Vertical movement

First, it is necessary to calculate the lifting time in relation to the location of the crane, the loading position and the delivery position. This time interval is inconsistent with the cycle time concept which is commonly presented in the tower cranes' capacity calculation documents but ignores all time components that are not affected by Cr_k, S_i and D_j location. The equations for calculating the travel time of the hook during the transportation of materials from the supply point to the demand point presented below are taken from the model of Zhang et al [14].

When the crane is in operation, the hook carries the movable material from the supply point S_i to the receiving point (Demand point) D_j. As such, the position of the material when being moved will change in space relative to the position of the hook and can be divided into two movements: horizontal and vertical (Figure 1).

Time for trolley radial movement with radial velocity V_a (V_a in m/min):

$$T_a = \frac{\left|\rho\left(Cr_k, S_i\right) - \rho\left(Cr_k, D_j\right)\right|}{V_a} \tag{2}$$

Time for trolley tangentially movement with slewing velocity of jib ω (ω in radians/min):

$$T_w = \frac{1}{\omega}\arccos \times \left(\frac{\rho\left(Cr_k, S_i\right)^2 + \rho\left(Cr_k, D_j\right)^2 - l\left(S_i, D_j\right)^2}{2.\rho\left(Cr_k, S_i\right).\rho\left(Cr_k, D_j\right)} \right) \tag{3}$$

In Eqs. (2) and (3), $\rho(Cr_k, S_i)$, is the distance from the crane to the supply point, $\rho(Cr_k, D_j)$ is the distance from the crane to the demand point, $l(S_i, D_j)$ is the distance from the supply point to the demand point, and they can be calculated using the Eqs. (4), (5) and (6), respectively:

$$\rho\left(Cr_k, S_i\right) = \sqrt{(S_i^x - Cr_k^x)^2 + (S_i^y - Cr_k^y)^2} \tag{4}$$

$$\rho\left(Cr_k, D_j\right) = \sqrt{(D_j^x - Cr_k^x)^2 + (D_j^y - Cr_k^y)^2} \tag{5}$$

$$l\left(S_i, D_j\right) = \sqrt{(D_j^x - S_i^x)^2 + (D_j^y - S_i^y)^2} \tag{6}$$

The time for horizontal hook movements could be calculated in Eq. (7):

$$T_{h(ij)} = \max(T_a, T_w) + \alpha.\min(T_a, T_w) \tag{7}$$

The factor α in Eq. (7) takes into account the possibility of a combination between radial and rotational motion, taking a value from 0 to 1 depending on the skill of the crane operator and the field conditions. However, empirical surveys conducted by Kogan [15] have shown that an experienced crane operator usually performs simultaneous operations in 76% of the total cycle duration, as a result, a value α = 0.25 can be taken [13].

The vertical movement time in each transport from S_i to D_j with the vertical velocity V_v (V_v in m/min) can be calculated following:

$$T_{v(ij)} = \frac{\left|D_j^z - S_i^z\right|}{V_v} \tag{8}$$

The total time for each transportation of materials from S_i to D_j is given in Eq. (9):

$$T_{ij} = \max\left(T_{h(ij)}, T_{v(ij)}\right) + \beta.\min(T_{h(ij)}, T_{v(ij)}) \tag{9}$$

The coefficient β refers to the degree of change of coordinates of the hook in the horizontal and vertical axis. With safety requirements, it is assumed that the hook moves continuously in two directions, thus taking $\beta = 1$.

Eq. (9) just only calculates the time of the crane when it is loaded, not taking into account the time of no-load movement (the hook moves from the demand point to the supply point). Usually, this interval is taken equal to the load movement time. Thus, the position of Cr_k, S_i, and D_j does not affect the no-load movement time and most of the authors when building the OLTC_S problem do not take this time into account. In this study, only the load movement time is considered.

The total cost for a crane to transport materials from *ns* supply points to *nd* request points with *nm* material types in a construction segment is calculated in Eq. (10):

$$TC = \sum_{i=1}^{ns}\sum_{j=1}^{nd}\sum_{l=1}^{nm} Q_{lj}.T_{ij}.C_u \tag{10}$$

in which Q_{lj} is the quantity of material of type l supplied to the j^{th} demand point; T_{ij} is the time for a material transferred by crane time from supply point *i* to demand point *j* which is calculated by Eq. (9); C_u is the unit price of crane use over time.

It should be noted that in (10), 1 unit of Q_{lj} is the amount of material corresponding to the lifting capacity in one go for that type of material. As such, Q_{lj} is also the number of lifts required to transport all the *l*-type material supplied to the j^{th} demand point.

Equation (10) is the objective function of the OLTC_S problem.

3. PSO Algorithm

The PSO algorithm is a global optimization method proposed by Kennedy and Eberhart in 1995, inspired by the behavior of some animals living in group, such as birds and fish [16]. PSO algorithm studies on a set of np particles, the position of each particle can be the solution of the problem in D-dimensional space. The change of state (position) of each particle follows the following 3 principles:

(1) Maintain part of its existing inertia;

(2) Under the influence of the best score the particle has ever achieved.

(3) Under the influence of the particle (individual) that currently has the best position.

The above three principles in two-dimensional space can be described as shown in Figure 2 and expressed by the mathematical expression (11) [17]:

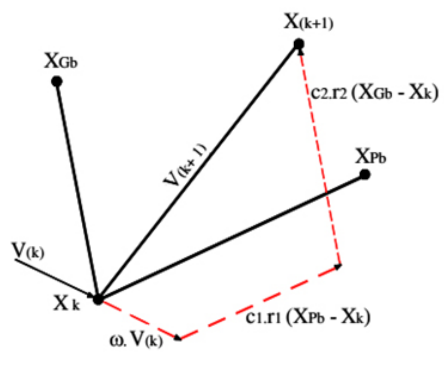

Fig 2. Particle motion in the plane - PSO algorithm

$$\left.\begin{aligned} &V_i^{k+1} = \\ &\omega.V_i^k + c_1.r_1^k\left(Xpbest_i^k - X_i^k\right) + c_2.r_2^k\left(Xgbest^k - X_i^k\right) \\ &X_i^{k+1} = X_i^k + V_i^{k+1} \end{aligned}\right\} \quad (11)$$

The quantities in Eq. (11) are explained as follows:

X_i^k - The coordinate vector of the position of the particle "i" at its "k" times;

V_i^k - The flight velocity of particle "i" at its "k" times;

X_i^{k+1} - The coordinate vector of the position of the particle "i" at its "k+1" times;

V_i^{k+1} - The flight velocity of particle "i" at its "k+1" times;

$Xpbest_i^k$ - The coordinate vector of the best position of the particle "i" at its "k" times;

$Xgbest^k$ - The coordinate vector of the position of the best particle in the swarm until "k" times;

ϖ - Inertial weight;

r_1^k, r_2^k - Two random variables with uniform distribution between 0 and 1 at the k^{th} iteration;

c_1, c_2 - Velocity coefficients (or learning factors).

To manage any changes in particle velocity, the relevant upper and lower limits are defined as follows:

$$V_{min} \le V_i \le V_{max} \quad (12)$$

The algorithm represented by Eq. (11) above is called the standard PSO algorithm. The steps of the algorithm are as follows:

- Step 1: Construct the initial n individuals (particles) X_0 by randomly choosing in the allowed area. Determine the initial speed V_0 (usually take V_0 in units);

- Step 2: Calculate the value of the objective function for all individuals in the group;

- Step 3: Determine the optimal position of the individual (particles) at the present time $Xpbest$ and the seed with the best value in the group $Xgbest$.

- Step 4: Calculate the new velocity and position of each individual according to the Eq. (11).

- Step 5: Repeat from step 2 when the stopping condition is not satisfied, usually the stopping condition is determined by the maximum number of iterations.

Although the initial step of the PSO algorithm is similar to that of many other metaheuristic algorithms, the technique for finding optimal solutions is completely different. Instead of the hybrid, mutation, and selection operator; PSO algorithm determines the new position of each individual according to the movement speed from the previous time, the best position that the individual has achieved in the previous generation and the position of the best individual in the current population. The parameters that play an important role affecting the search efficiency of the algorithm include: *ω, c1, c2,* V_{max}.

The standard PSO algorithm or the continuous PSO algorithm is applicable to continuous problems and can't be used for discrete problems. Various approaches have been proposed to solve discrete problems with PSO [18, 19]. Basically, this algorithm only takes into account the integer parts of the motion velocity vector components. Since the new velocity V_i^{k+1} from Eq. (13) is an integer, the new position vector components will also be integers.

$$V_i^{k+1} = round\left(\omega.V_i^k + c_1.r_1^k\left(Xpbest_i^k - X_i^k\right) + c_2.r_2^k\left(Xgbest^k - X_i^k\right)\right) \quad (13)$$

The particle velocity is calculated by Eq. (13) and obeys exactly the limits established by expression (12).

4. Numerical Expression

4.1. Model and data of the numerical example

The model and data of the numerical example problem are taken from [20]. In Figure 3 is a floor plan of a high-rise building construction that has been built in Hong Kong. The floors have the similar structures, are in the construction phase of the body structure, and are required to be provided with three types of materials from 3 separate warehouses including: large panel formwork, precast concrete facade unit, reinforcing bars. Concrete mixture is provided by pump

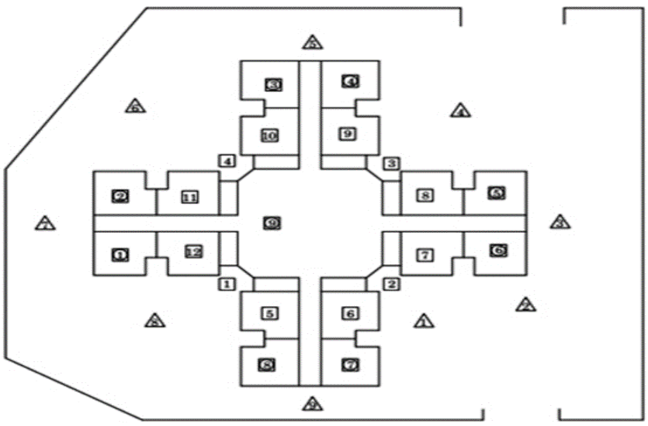

Fig 3. Construction layout and the demand point positions, the available material supply points and the available tower crane points [20].

The areas need to be supplied materials are presented by the coordinates of center points from $D_1 \div D_9$. The position of the tower crane and the warehouse positioning points can be arbitrarily selected in the free area of the ground with the help of a computer. A simpler and more effective method is to choose manually on the basis of experience. The number of possible points chooses to place the crane (nCr), to place the supply warehouse (nS) is not limited in number, the numbering of the selected locations can be arbitrary. A list of points to be supplied D_j, storage locations S_i and crane installation points Cr_k is given in Table 1.

Table 1. Coordinates of the demand point positions, the available material supply points and the available tower crane points

Number	Coordinates of potential material demand points D_j			Coordinates of available material supply points S_i			Coordinates of available tower crane points Cr_k		
	x	y	z	x	y	z	x	y	z
1	34	41	15	73	26	2	45	36	30
2	34	51	15	83	31	2	65	36	30
3	51	65	15	87	45	1.5	65	57	30
4	60	65	15	73	67	1.5	45	57	30
5	76	51	15	55	73	1.5	51	33	30
6	76	41	15	35	67	0	60	33	30
7	60	26	15	22	46	0	70	41	30
8	51	25	15	36	27	1	70	52	30
9	43	44	15	55	15	1	60	58	30
10							51	58	30
11							42	52	30
12							42	41	30

There are 3 types of materials for demand points:

- Type A_1: Provide large panel formworks, volume is Q_{A1} = 10 units;

- Type A_2: Provide precast concrete facade units, the volume is Q_{A2} = 20 units;

- Type A_3: Provide reinforcing bars, volume is Q_{A3} = 30 units.

Other parameters:

- Hook's hoisting velocity V_h = 60m/min;

- The radial velocity V_a = 53.3 m/min;

- The slewing velocity of the jib V_w = 7.57 rad/min;

- The operating cost of a tower crane per unit of time C_u = 1.92 USD/min.

Requirement: Choose the location of the crane and three warehouse locations (from the list) for minimal transportation costs, examined in two cases:

- *Case 1:* Out of 9 warehouse locations, type A1 materials can choose from 6 locations: S_1, S_2, S_3, S_4, S_5 and S_6; material type A2 can choose from 4 positions: S_1, S_2, S_3 and S_4; and A3 grade materials can choose from 5 positions: S_5, S_6, S_7, S_8 and S_9.

- *Case 2:* All 9 locations where warehouses can be arranged are all suitable to be selected as supply points for one of three types of materials A1, A2 and A3.

4.2. PSO algorithm for the problem OLTC_S

With the data of the above problem, there are 4 independent integer variables to choose from. The symbol X_1 represents the crane location and takes integer values from 1 to 12; X_2 represents the supply point A_1 and takes integer values from 1 to 6 (survey case 1) or from 1 to 9 (survey case 2); X_3 represents the supply point A_2 which takes integer values from 1 to 4 (survey case 1) or from 1 to 9 (survey case 2); and X_4 represents the supply point A_3 which takes integer values from 5 to 9 (survey case 1) or from 1 to 9 (survey case 2). $[X_1, X_2, X_3, X_4]$ is the ordinal number of the elements in the list (table 1) corresponding to the *xyz* coordinate values. Each set $[X_1, X_2, X_3, X_4]$ gives an objective function value according to Eq. (10). Figure 4 shows the optimal problem-solving diagram when using the PSO algorithm.

Each individual is initially selected according to the following principle: The location of crane *Cr* is randomly selected from one of the 12 locations in the list, the location for A_1 is randomly selected from the 9 specified locations, similar to A_2 and A_3 such that $(A_1 \neq A_2 \neq A_3)$. From the values of *Cr*, A_1, A_2, and A_3, the corresponding coordinates are derived and the objective function value is calculated by Eq. (10). After *np* times like that, the initial population is obtained. The process of finding the optimal solution is an iterative process until the stopping criterion is reached.

The program is written in the MATLAB environment, named PSO_LTCS. Along with the stopping condition is the limit of iterations, in the PSO_LTCS program, the stopping condition is added as follows:

$$\text{If } \varepsilon = \left| min(F_i) - \frac{\sum_{i=1}^{np} F_i}{np} \right| < 10^{-8}$$

then the calculation program will stop.

The control parameters in the PSO program are selected as follows:

Number of individuals in the population: *np*=30; the largest number of iterations taken depending on the survey case; inertial weight: $\omega = 0.9$; velocity factors: $c_1 = c_2 = 1.8$, and V_{max} are taken at the midpoint of the search domain corresponding to each variable.

4.3. Results and discussion

In this study, 30 independent test runs were performed for each scenario with the maximum number of iterations taken as 5000 times for survey case 1 and taken as 200 for survey case 2 (to compare with results of other algorithms). The results of survey case 1 are given in table 2 and survey case 2 are given in table 3. The calculated results are compared with the results of previous researches by some other algorithms to clarify the efficiency of the PSO algorithm.

In survey case 1, it can be seen that the results obtained by PSO approach are better than those optimized by GA [20]. The total cost in transporting the required material is 507.2380 units under PSO, which is 6.2% less than the total cost under GA optimization. The PSO algorithm fully converges to the best value and is a globally optimal solution with an average number of iterations approximately 1580 times.

In the case of survey 2, the best results found by PSO also match with the results of calculations by Mixed-Integer Linear Programming (MILP) algorithm [21], Enhanced Colliding Bodies Optimization (ECBO) algorithm, and Vibrating Particle System (VPS) algorithm [22]. However, the convergence speed of PSO is slower in comparison to ECBO and VPS when evaluates the mean and standard deviation of the objective function after 30 iterations.

Table 2. Optimal results for survey case 1 - supply point selection possibilities are different for each material

Method	Tower crane location	Order of allocation of supply points to material type			Cost (USD)			Average iterations
		A_1	A_2	A_3	Best	Mean	Std deviation	
GA [20]	2	3	2	9	540.7587	N/A	N/A	N/A
PSO	8	2	1	5	507.2380	507,2380	0.0000	1582

Note: N/A: Not available

Table 3. Optimal results for survey case 2 - supply point selection possibilities are the same for each material

Method	Tower crane location	Order of allocation of supply points to material type			Cost (USD)			Average iterations
		A_1	A_2	A_3	Best	Mean	Std deviation	
MILP [21]	8	2	5	1	504.7631	N/A	N/A	N/A
ECBO [22]	8	2	5	1	504.7631	504.8804	0.6423	200
VPS [22]	8	2	5	1	504.7631	504.8383	0.4121	200
PSO	8	2	5	1	504.7631	511.7006	4.6292	200

Note: N/A: Not available

5. Conclusion

From the research results presented above, it can be seen that PSO solves quite effectively the combinatorial problem with discrete integer variables. In both survey cases, the PSO algorithm converges on the global optimal solution. In the same group of evolutionary algorithms, the solution chosen by PSO is better than the solution provided by GA. The applied results obtained from the discrete PSO algorithm show that this is a promising and feasible tool to solve the location optimizing problems of the tower cranes and material supply warehouses in particular, construction site planning problem in general on actual projects.

On the other hand, the numerical results also show the limitation of the discrete PSO algorithm using the transformation from the standard PSO algorithm by taking the velocity integer part, which is the slow speed of convergence to the global optimal solution. However, this is a very complicated problem because the convergence velocity of the algorithm depends on many factors such as the magnitude of the inertia weight factor ω learning factors c_1 and c_2 velocity $V_{\max}$ and $V_{\min}$ how to get the integer V_i^{k+1}... More experiments with other variants of PSO are needed in order to have accurate assessments as well as to suggest solutions to improve the convergence velocity of the algorithm.

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