BALANCING COMPOSITE MOTION OPTIMIZATION FOR CONSTRUCTION SITE FACILITY LAYOUT PROBLEMS

Duc Nang Bui[1], Nguyen Dung Nhan Bui[2,*], Tien Tinh Nguyen[1]

[1]*Institute of Techniques for Special Engineering, Le Quy Don Technical University*

[2]*Faculty of Transport Economics, University of Transport Technology*

Abstract

The arrangement of construction facilities on the construction site is one of the important problems of construction organization, but at the same time it represents a complex combinatorial optimization problem. Metaheuristic methods are recognized as powerful and effective tools in solving such problems. The Balancing Composite Motion Optimization (BCMO) algorithm is a recently proposed metaheuristic algorithm. This article introduces the results of establishing a problem model and applying the BCMO algorithm with discrete variables receiving integer values to solve the problem of arranging service facilities on the construction site based on a static model. A numerical experiment with three static problem cases selected from the sample problems is conducted. The obtained layout options are compared with the results from other algorithms, thereby demonstrating the proposed algorithm's advantages: its ease of implementation, capability to search for and identify multiple good solutions, and fast convergence speed. The numerical experiment also shows the need for further experimentation and exploration to enhance the algorithm.

Keywords: *Construction site; facility layout; Balancing Composite Motion Optimization (BCMO); optimization; metaheuristic.*

1. Introduction

Designing the overall construction site is an important task in construction organization because it directly affects the results of construction business activities in terms of progress, cost, productivity, and labor safety [1]. Building and solving the problem of optimally arranging a set of temporary technical facilities serving construction (generally called service facilities) at specific locations within the construction site while meeting the constraints on the arrangement, is one of the key issues in optimizing overall construction site design. However, similar to problems in other industrial or service production environments, it belongs to the class of nondeterministic polynomial-hard (NP-hard) problems [2], [3]. The complexity of the problem increases exponentially with the number of service facilities that need to be arranged. Therefore, it is challenging to develop an accurate and effective algorithm to solve this type of problem.

[*] Corresponding author, email: nhanbnd@utt.edu.vn
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One of the approaches developed to solve the problem of optimally arranging service facilities on construction sites is the application of approximate algorithms, especially search and discovery algorithms (heuristic, metaheuristic). Comprehensive assessments of various approaches to the problem of arrangement of service facilities can be found in recent studies [4], [5]. Among metaheuristic algorithms, the application of Genetic Algorithm – GA [6]-[9], Ant Colony Optimization – ACO [10]-[13], Particle Swarm Optimization – PSO [14]-[17], Harmony Search – HS [18], Colliding Bodies Optimization – CBO [19], Vibrating Particles System – VPS [20], and some other algorithms as well as variations of the above algorithms have been widely reported. Each algorithm has its advantages and disadvantages therefore, research on improving and developing these algorithms remains an active area of study.

The Balancing Composite Motion Optimization (BCMO) algorithm was introduced by D. T. Le, Q. H. Nguyen, X. H. Nguyen in 2020 [21]. Unlike other metaheuristic algorithms, BCMO does not require dependent parameters, which has simplified its implementation for solving various optimization problems. BCMO has been successfully applied in some types of optimization problems in mechanics [22], [23], and energy [24]. In the construction field, BCMO has been applied to solve the optimization problem of balancing the time - cost of the project [25]. These results indicate that BCMO possesses several advantages over similar algorithms and needs to be further explored and exploited through practical problems in engineering, organization and construction management.

This article introduces the results of establishing a problem model and using the BCMO algorithm with discrete variables receiving integer values to solve the problem of arranging service facilities on the construction site based on a static model. To provide a comprehensive and accessible understanding of the models and algorithms for practicing engineers, three representative cases of static problems with numerical examples selected from sample problems are introduced including: (1) locations without surface area restrictions which means a location can arrange any service facility; (2) some service facilities are pre-designated in terms of location; and (3) in addition to the condition of case 2, the surface area of some locations is small for some service facilities, which means the problem of unequal area between service facilities and locations.

2. Materials and methods

2.1. Service facility arrangement problem on construction site - static model

The problem presented in this study can be described as follows: On a construction site, n potential locations have been determined to arrange temporary technical facilities such as office buildings, workers' camps, warehouses, and factories to serve the construction process. There are m facilities that need to be arranged, in which the condition is that $m \leq n$. The following important parameters are provided:

- The distances between predefined locations (in meters);

- The frequency of construction worker trips between pairs of service facilities (in number of trips per day).

The objective is to determine an arrangement of service facilities at the predetermined locations (each location containing only one service facility) such that the total daily travel distance between the service facilities of the construction workers is minimized.

The research problem described above can be modeled as a Quadratic Assignment Problem – QAP [7], [9], [13] in which the number of service facilities and locations are equal ($m = n$). If the number of service facilities is less than the number of locations, "dummy" facilities are added to ensure equality. The "dummy" facilities will have a travel frequency or distance to the remaining facilities of 0, so that they do not affect the layout.

Mathematically, the problem is stated as follows:

Minimize the function

$$TD = \left(\sum_{i=1}^{n}\sum_{x=1}^{n}\sum_{j=1}^{n}\delta_{x,i} f_{i,j} d_{i,j}\right) \qquad (1)$$

Constraints

$$\sum_{x=1}^{n}\delta_{x,i} = 1 \quad \{i = 1, 2, \ldots, n\} \qquad (2)$$

where TD is the total distance, n is the number of service facilities and locations, $\delta_{x,i}$ is the permutation matrix variable ($\delta_{x,i} = 1$ if facility x is arranged at location i, $\delta_{x,i} = 0$ otherwise), $f_{i,j}$ is the frequency of trips of the contractor between facilities i and j, and $d_{i,j}$ is the distance between locations i and j .

The above statement is sufficient for the first case, where the locations are not limited in surface area (which means a location can accommodate any service facility). In the second case, wheresome facilities are pre-assigned to specific locations, and in the third case, which involves the problem of inequality between service facilities and locations, the objective function remains TD, as given in (1), and the external constraints (2) will have appropriate additional constraints added during the later implementation of the algorithm.

2.2. Balancing Composite Motion Optimization (BCMO) algorithm

The BCMO algorithm is one of the population-based optimization methods. It is developed under the assumption that the solution space is considered Cartesian, and the search movement of candidate solutions is balanced between global search and local search. These assumptions allow the best ranking individuals in each generation to increase their search in their current local space or move to another local space to continue searching. Randomized tests based on mathematical models are constructed to control the movement tendency of candidate solutions. During the optimization process, if each individual maintains a balance between exploration ability and exploitation ability, the search ability of the whole population can also be balanced, thus achieving the optimal solution.

The schematic diagram of the BCMO algorithm is shown in Fig. 1.

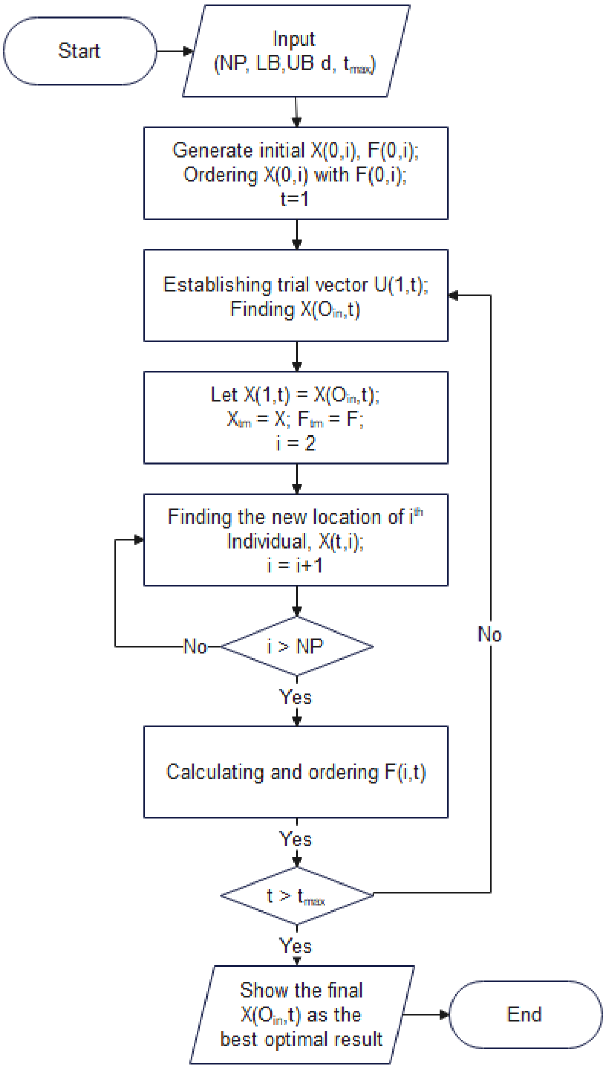

Fig. 1. Flow chart of the original BCMO.

The BCMO algorithm is implemented through the following three main steps:

- *Step 1*: Create the initial population.

Similar to other metaheuristic optimization algorithms, the initial population in BCMO is formed according to the law of uniform distribution in the solution space according to the following equation:

$$\mathbf{x}_i = \mathbf{x}_i^L + \mathbf{rand}(1, d) \times \left(\mathbf{x}_i^U - \mathbf{x}_i^L\right) \tag{3}$$

where $\mathbf{x}_i^L$, $\mathbf{x}_i^U$ are the lower and upper bounds of the i^{th} variable; $rand(1, d)$ is the vector of magnitude d that satisfies the uniform distribution law in the interval [0, 1], and d is the number of input parameters.

- *Step 2*: Determine the current global score and the best individual.

In this step, the absolute motion vector $\mathbf{v}_i$ of the i^{th} individual in each generation is composed of two components. The first is the relative motion with respect to the j^{th} individual with a better level, the second is the relative motion of the j^{th} individual with respect to the global optimal point **O**. The vector $\mathbf{v}_i$ is determined as follows:

$$\mathbf{v}_i = \mathbf{v}_{i/j} + \mathbf{v}_j \tag{4}$$

where $\mathbf{v}_i$, $\mathbf{v}_j$ are the motions of the i^{th} and j^{th} individuals relative to point **O**, respectively, and $\mathbf{v}_{i/j}$ are the relative motions of individual i relative to individual j.

However, point **O** has not been determined. To solve this, the concept of "*alternative global optimal point*" is introduced in the algorithm, denoted by $\mathbf{O}_{in}$, and can be received from the Eq. (5):

$$\mathbf{x}_{O_{in}}^t = \begin{cases} \mathbf{u}_1^t & if \quad f\left(\mathbf{u}_1^t\right) < f\left(\mathbf{x}_1^{t-1}\right) \\ \mathbf{x}_1^{t-1} & \text{otherwise} \end{cases} \tag{5}$$

where u_1^t is the best individual of the current generation and is determined using the population information of the previous generation:

$$\mathbf{u}_1^t = \frac{\mathbf{LB} + \mathbf{UB}}{2} + \mathbf{v}_{k1/k2}^t + \mathbf{v}_{k2/1}^t \tag{6}$$

with **LB** and **UB** are the lower and upper bounds of the solution space, respectively, $\mathbf{v}_{k1/k2}^t$ and $\mathbf{v}_{k2/1}^t$ are the pseudo-relative movements of the individual k_1^{th} with respect to the individual k_2^{th} and of the individual k_2^{th} with respect to the previous best individual, respectively, k_1 chosen randomly in the interval $[2, NP]$ (*NP* is the number of individuals in the population), and $k_2 < k_1$.

- *Step 3*: In the solution space, calculate the total motion of the individual.

In step 3, the total search motion $\mathbf{v}_j$ is determined as the following:

$$\mathbf{v}_j = \boldsymbol{\alpha}_j \left(\mathbf{x}_{O_{in}} - \mathbf{x}_j \right) \tag{7}$$

where $\boldsymbol{\alpha}_j$ is the first derivative of the distance between the j^{th} individual and $\mathbf{O}_{in}$, calculated as the following equation:

$$\boldsymbol{\alpha}_j = L_{GS} \times \mathbf{dv}_j \tag{8}$$

with L_{GS} is the overall search step length of the j^{th} individual, $\mathbf{dv}_j$ is the direction vector probability 0.5 of having positive or negative sign.

Similarly, with formulas (7) and (8), the relative motion of the i^{th} individual with respect to the j^{th} individual can be obtained in such a way:

$$\mathbf{v}_{i/j} = \boldsymbol{\alpha}_{ij} \left(\mathbf{x}_j - \mathbf{x}_i \right) \tag{9}$$

Finally, formula (10) is used to calculate the position of the i^{th} individual in the next generation:

$$\mathbf{x}_i^{t+1} = \mathbf{x}_i^t + \mathbf{v}_{i/j} + \mathbf{v}_j \tag{10}$$

3. Results and discussions

3.1. Model and data of the numerical experimental problem

Three sample research cases are selected as the basis for model evaluation from the literature [6], [7], [10]. These studies collectively analyze a service facility layout problem using different heuristic algorithms to obtain the optimal solution. They are frequently adopted by other studies for testing, comparison and evaluation.

Figure 2 shows the construction site plan of the two buildings. Within the construction site boundary, 11 potential locations (labeled L1 to L11) have been identified for placing service facilities.

The list of service facilities to be arranged is shown in Tab. 1. The distance between predetermined locations is given in Tabs. 2, 3 presents the frequency of daily movement of construction workers between facilities.

Three test cases are examined to account for location constraints of service facilities:

- Case 1 (C1): All 11 locations have sufficient surface area to accommodate one of the listed service facilities.

- Case 2 (C2): The main gate (code MG, number in the catalog is 11) is selected to be fixed at position number 10; the secondary gate (code SG, number in the catalog is 8) is selected to be fixed at position number 1.

- Case 3 (C3): In addition to the conditions as in C2, there is an additional condition that the three service facilities including SO (order number 1), LR (order number 3) and BW (order number 10) have a construction surface area larger than the area of locations 7 and 8. As a result, they cannot be arranged there.

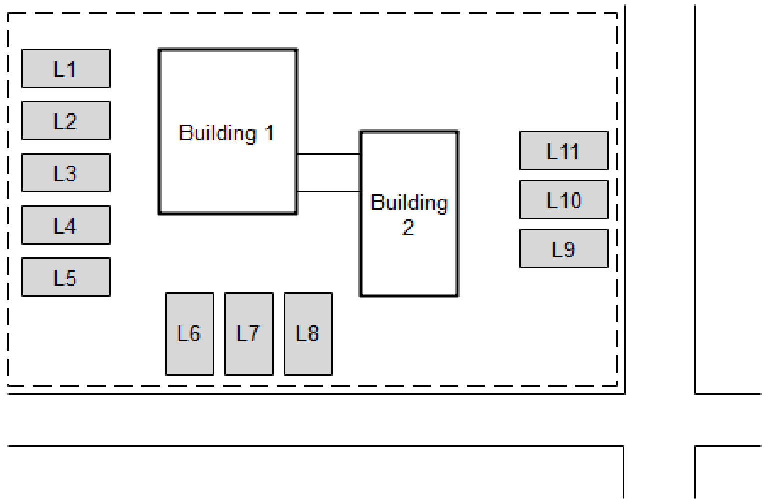

Fig. 2. Site plan with 11 predetermined locations for service facilities.

Tab. 1. List of temporary technical facilities serving construction

No.	Service facilities	Symbol
1	Site office	SO
2	Falsework workshop	FS
3	Labor residence	LR
4	Storeroom 1	S1
5	Storeroom 2	S2
6	Carpentry workshop	CW
7	Reinforcement steel workshop	RW
8	Side gate	SG
9	Electrical, water and other utility control room	UR
10	Concrete batch workshop	BW
11	Main gate	MG

Tab. 2. Distance between proposed locations for service facilities (m)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	0	15	25	33	40	42	47	55	35	30	20
2	15	0	10	18	25	27	32	42	50	45	35
3	25	10	0	8	15	17	22	32	52	55	45
4	33	18	8	0	7	9	14	24	44	49	53
5	40	25	15	7	0	2	7	17	37	42	52
6	42	27	17	9	2	0	5	15	35	40	50
7	47	32	22	14	7	5	0	10	30	35	40
8	55	42	32	24	17	15	10	0	20	25	35
9	35	50	52	44	37	35	30	20	0	5	15
10	30	45	55	49	42	40	35	25	5	0	10
11	20	35	45	53	52	50	40	35	15	10	0

Tab. 3. Frequency of travel of construction workers between service facilities (number of trips/day)

	SO	**FS**	**LR**	**S1**	**S2**	**CW**	**RW**	**SG**	**UR**	**BW**	**MG**
SO	0	5	2	2	1	1	4	1	2	9	1
FS	5	0	2	5	1	2	7	8	2	3	8
LR	2	2	0	7	4	4	9	4	5	6	5
S1	2	5	7	0	8	7	8	1	8	5	1
S2	1	1	4	8	0	3	4	1	3	3	6
CW	1	2	4	7	3	0	5	8	4	7	5
RW	4	7	9	8	4	5	0	7	6	3	2
SG	1	8	4	1	1	8	7	0	9	4	8
UR	2	2	5	8	3	4	6	9	0	5	3
BW	9	3	6	5	3	7	3	4	5	0	5
MG	1	8	5	1	6	5	2	8	3	5	0

3.2. Program to calculate using BCMO algorithm for service facility layout problems

Based on the given problem data there are 11 independent integer variables to choose from, denoted by $X_i\,(i = 1, 2, \ldots, 11)$, representing the service facilities. Each variable takes an integer values corresponding to the position numbers in which they can be arranged (as in C1, from 1 to 11). The selection principle ensures that neither of the two facilities share the same position.

The standard BCMO algorithm or continuous BCMO algorithm is applicable to continuous problems and cannot be used directly for discrete problems without additional transformations. Various approaches have been proposed to solve discrete problems with PSO [26], [27], and similar approaches are applied here to BCMO. Basically, this algorithm only considers the integer parts of the position vector components in Eqs. (3), (8), and (10). Here we use rounding.

The program is written in the Matlab environment named BCMO_CSLP. In addition to the stopping condition, which is the limit of the number of iterations, the BCMO_CSLP program is supplemented with the following stopping condition:

If $\varepsilon = \left| \min\left(F_i\right) - \frac{\sum_{i=1}^{np} F_i}{np} \right| < 10^{-10}$ the program will stop.

The control parameters of the BCMO in the program are selected as follows:

Number of individuals in population: np = 50; maximum number of iterations: $iter_{\max} = 1000$.

3.3. Numerical test results and discussions

In this study, 30 independent tests were conducted for each case. In C2, after running 30 tests, there were many good options with the same TD objective function value founded. Additional tests were performed to further explore and identify all desired solution potions.

The comparison between the BCMO results and those reported by other studies is presented in Tabs. 4-6. In the table, the "Algorithm" entry with BCMO* refers to the results obtained in this study. The numbers on each row in the "Best Arrangement" entry represent the arrangement of the service facilities represented by the corresponding numbers in Tab. 1 on location L1 to L11 according to the best option selected by the algorithm.

From the above result tables, it can be observed that the BCMO algorithm effectively identified optimal solutions when compared to those obtained by other algorithms, and even found many optimal solutions with the identical objective function value, similar to the PSO algorithm. As in C2, there are up to 6 solutions discovered, and in C3, there are 2 discovered.

Tab. 4. Comparison results of C1

Algorithm	Best layout											Corresponding TD value
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	
GA [9]	1	10	5	3	4	7	9	6	8	2	11	12150
ACO [13]	1	10	5	3	4	7	9	6	8	2	11	12150
PSO [17]	1	10	5	3	4	7	9	6	8	2	11	12150
BCMO*	1	10	5	3	4	7	9	6	8	2	11	12150

Tab. 5. Comparison results of C2

Algorithm	Best layout											Corresponding TD value
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	
GA [6]	8	5	7	10	2	9	4	3	6	11	1	15090
GA [9]	8	9	7	6	4	3	5	10	1	11	2	12546
ACO [10]	8	6	9	7	4	3	5	10	1	11	2	12546
ACO [13]	8	6	9	7	4	3	10	5	1	11	2	12578
CBO [19]	8	9	7	6	4	3	5	10	1	11	2	12546
PSO [17]	8	6	9	7	4	3	5	10	1	11	2	12546
	8	6	9	7	3	4	5	10	1	11	2	12546
	8	9	7	3	6	4	5	10	1	11	2	12546
	8	9	7	3	4	6	5	10	1	11	2	12546
	8	9	7	6	3	4	5	10	1	11	2	12546
	8	9	7	6	4	3	5	10	1	11	2	12546
BCMO*	8	6	9	7	4	3	5	10	1	11	2	12546
	8	6	9	7	3	4	5	10	1	11	2	12546
	8	9	7	3	6	4	5	10	1	11	2	12546
	8	9	7	3	4	6	5	10	1	11	2	12546
	8	9	7	6	3	4	5	10	1	11	2	12546
	8	9	7	6	4	3	5	10	1	11	2	12546

Tab. 6. Comparison results of C3

Algorithm	Best layout											Corresponding TD value
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	
GA [7]	8	5	7	10	2	9	4	6	3	11	1	15160
GA [9]	8	10	6	9	4	3	7	5	2	11	1	12606
ACO [13]	8	10	6	9	4	3	7	5	2	11	1	12606
PSO [17]	8	10	6	9	3	4	7	5	2	11	1	12606
	8	10	6	9	4	3	7	5	2	11	1	12606
BCMO*	8	10	6	9	3	4	7	5	2	11	1	12606
	8	10	6	9	4	3	7	5	2	11	1	12606

The testing process also shows that the BCMO exhibits a relatively fast convergence speed, with most tests terminating based on the additional condition. Figs. 3-5 show the distribution of the terminating calculation moments, while Fig. 6 presents the statistical results of the number of iterations in all 3 cases of the numerical example problem with 100 calculations for the BCMO algorithm. This finding is significant when compared with the well-knownPSO algorithm for the same problem, as reported in [17]. Most PSO experiments terminated atthe maximum number of iterations (1000 times), whereas only a few stopped according to the additional convergence condition.

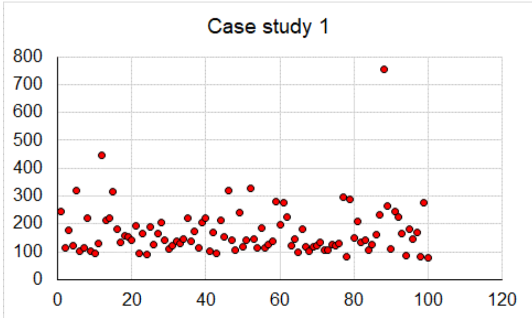

Fig. 3. Distribution plot of loop stopping times over 100 experiments of BCMO_CSLP - Case study 1.

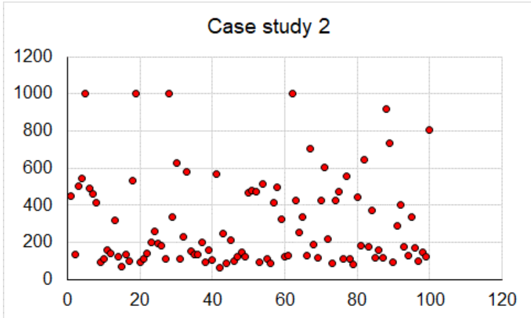

Fig. 4. Distribution plot of loop stopping times over 100 experiments of BCMO_CSLP - Case study 2.

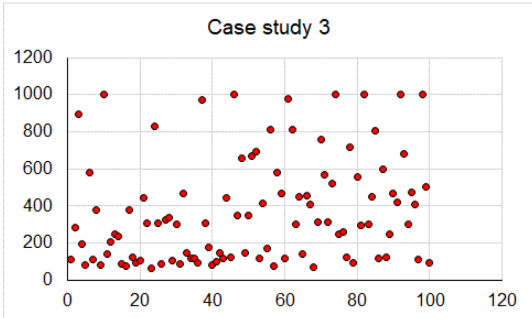

Fig. 5. Distribution plot of loop stopping times over 100 experiments of BCMO_CSLP - Case study 3.

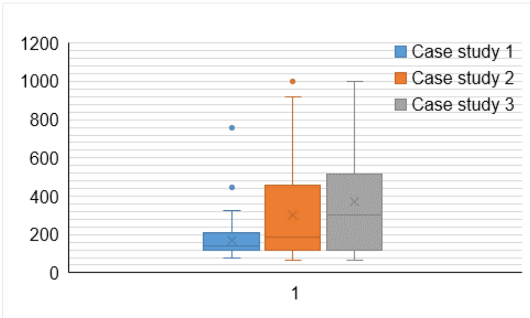

Fig. 6. Boxplot of statistical analysis results of the number of iterations over 100 experiments of BCMO_CSLP.

4. Conclusion

From the research results presented above and previous research results [25], it can be observed that the BCMO algorithm demonstrates high effectiveness in solving combinatorial problems with discrete integer variables and is capable of searching and discovering many better solutions than other algorithms. The application results obtained from the discrete BCMO algorithm show that it is a promising and feasible tool for solving general construction site planning problems as well as its sub-problems on real projects.

In addition to the advantage of being relatively simple to implement, as it does not require any dependent parameters, the fast convergence speed is also an advantage of the algorithm. However, this advantage should be interpreted with caution, as early termination of the optimization process does not always guarantee the global optimum. As a result, it is very possible that the calculation program has fallen into a local "trap", limiting its exploration capability. Further research is required to enhance the efficiency and robustness of the algorithm.

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SỬ DỤNG THUẬT TOÁN BCMO GIẢI CÁC BÀI TOÁN BỐ TRÍ CƠ SỞ VẬT CHẤT TRÊN CÔNG TRƯỜNG XÂY DỰNG

Bùi Đức Năng[1], Bùi Nguyễn Dũng Nhân[2], Nguyễn Tiến Tĩnh[1]
[1]*Viện Kỹ thuật công trình đặc biệt, Trường Đại học Kỹ thuật Lê Quý Đôn*
[2]*Khoa Kinh tế vận tải, Trường Đại học Công nghệ Giao thông vận tải*

Tóm tắt: Việc sắp xếp bố trí các cơ sở vật chất phục vụ thi công trên công trường là một trong những bài toán quan trọng của công tác tổ chức xây dựng công trình, nhưng đồng thời cũng là loại bài toán tối ưu tổ hợp phức tạp. Các phương pháp metaheuristic được đánh giá là có khả năng mạnh mẽ và giải quyết có hiệu quả cao lớp các bài toán như vậy. Thuật toán Balancing Composite Motion Optimization (BCMO) là một thuật toán metaheuristic mới được đề xuất gần đây. Bài báo trình bày việc xây dựng mô hình bài toán và sử dụng thuật toán BCMO với các biến nguyên rời rạc để giải quyết bài toán bố trí cơ sở phục vụ trên mặt bằng thi công theo mô hình tĩnh. Một thử nghiệm số với ba trường hợp của bài toán tĩnh chọn từ các bài toán mẫu được tiến hành. Kết quả được so sánh với kết quả nhận được từ các thuật toán khác, cho thấy các ưu điểm của thuật toán là dễ sử dụng, khả năng tìm kiếm và phát hiện nhiều giải pháp tốt, tốc độ hội tụ nhanh. Quá trình thử nghiệm số cũng cho thấy sự cần thiết phải thử nghiệm, khám phá để tiếp tục cải thiện thuật toán.

Từ khóa: *Công trường xây dựng; bố trí cơ sở; Balancing Composite Motion Optimization (BCMO); tối ưu; metaheuristic.*

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