



# A hybrid WOA-CBO algorithm for construction site layout planning problem

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## KEYWORDS

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 WOA algorithm;  
 WOA-CBO algorithm.

**Abstract.** The Whale Optimization Algorithm (WOA) is a recently developed swarm-based optimization algorithm inspired by the hunting behavior of humpback whales. This study attempts to enhance the original formulation of the WOA by hybridizing it with some concepts of the Colliding Bodies Optimization (CBO) in order to improve solution accuracy, reliability, and convergence speed. The new method, called WOA-CBO algorithm, is applied to construction site layout planning problem. To show efficiency and performance of the WOA and WOA-CBO in construction site layout problems, three case studies are selected. The first case is a discrete and equal area facility layout problem that every facility can assign to any location; the second case is an unequal area version of discrete facility layout problem with more constraints; and the last case is a continuous model of construction site layouts. These cases are studied by WOA, CBO, and WOA-CBO, and the results are compared with each other.

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## 1. Introduction

Construction Site Layout Planning (CSLP) has been found to be a critical task in construction planning by experts and this task is emphasized on implementing early in the planning phase [1,2].

An appropriate layout of facilities leads to high productivity and project success by minimizing the travel cost, decreasing time and effort spent on material handling, and improving safety, especially for huge construction sites [3,4]. Despite these benefits, owners and bidding contractors are unwilling to spend money for effective site layout planning and management. This is because of the competitive bidding structure of the construction industry. Therefore, especially for

projects with limited budgets, managers prefer to use their previous experience, ad-hoc rules, and first-come-first-serve approach, which leads to inefficiency and productivity losses [2,5].

The purpose of designing a construction site layout is to assign a set of specific temporary facilities such as job office, labor residence, warehouse, and batch plants to the appropriate location, while satisfying a set of design requirements and maximize design quality in terms of design preferences such as minimizing the total travel cost between facilities [2,6].

Construction plant site can be modeled into two types, namely, discrete and continuous. In the first type (discrete), managers identify feasible places for locating facilities; then, these places are divided into rectangular blocks each of which can be assigned to a facility. When costs associated with the flow between facilities are linear with respect to distance traveled and quantity of flow, this type of problem can be formulated as Quadratic Assignment Problem (QAP) [7,8]. The

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QAP is a classic combinatorial optimization problem and is well known for its various applications [9]. QAP is known as a non-polynomial hard (NP-hard) problem and due to combinatorial complexity, it cannot be solved exhaustively for reasonably sized layout problems [6]. As an instance, for  $n$  facilities, the number of feasible configurations is  $n!$  with larger growth than  $e^n$ . This is a huge number, even for a small  $n$ . For 10 facilities, the number of possible alternatives is already well over 3,628,000 or for 15 facilities, it is a 12-digit number. In real problems, a project with  $n = 15$  is known as a small project [10]. In the second type (continuous), facilities can be located in every available spaces unlike the previous model and no predetermined locations are considered. This leads to less limitations in finding proper locations for facilities. In spite of the above-mentioned flexibility, the searching process of this approach is more complicated; therefore, robust methods are required for this type [11].

The aforementioned complexity has motivated researchers to apply various heuristic and meta-heuristic algorithms in order to obtain optimal or near optimal solutions to construction site layout problems.

Li and Love [12] applied the Genetic Algorithm (GA) to find the optimal solution in a site-level unequal-area facility layout problem; also, Cheung et al. [13] used a GA model for optimizing a site pre-cast yard. Osman et al. [14] proposed a hybrid cad-based algorithm using genetic algorithm in order to optimize the location of the temporary facilities on a site. El-rayes et al. [15] employed multi-objective version of GA for solving a continuous and multi-objective site layout problem.

Many researchers have utilized Particle Swarm Optimization (PSO) in construction site layout field [2,16-18]. For instance, Zang and Wang [17] proposed a PSO model for an un-equal area static CSLP problem under single objective function. Xu and Li [18] considered a Multi-Objective Particle Swarm Optimization algorithm (MOPSO) to solve a dynamic site layout problem in fuzzy random environment. Lien and Cheng [16] proposed a hybrid Particle-Bee Algorithm (PBA) for construction site layout optimization under single objective function to locate facilities in predetermined locations.

Lam et al. [19], Gharaie et al. [20], and Calis and Yuksel [21] also employed another optimization algorithm. They used ant colony to solve a static site layout problem. Ning et al. [22] employed Max-Min Ant System (MMAS), which was one of the standard variants of the Ant Colony Optimization (ACO) algorithms, to solve a dynamic construction site layout planning. Mixed integer programming [23], Tabu search [24], harmony search [4], and colliding bodies optimization [25] are other methods that are used in this field.

In this study, WOA and WOA-CBO algorithms are proposed to solve construction site layout problems. Whale optimization algorithm was developed by Mirjalili and Lewis [26]. WOA-CBO algorithm is an enhanced version of WOA that is introduced in this paper for the first time. Three case studies are conducted to show the efficiency and performance of the WOA and WOA-CBO in both models of construction site layout problem and the obtained results are compared.

## 2. Meta-heuristic algorithms

In this study, we have used two new meta-heuristic algorithms in construction site layout problems; Whale Optimization Algorithm (WOA) and the hybrid Algorithm (WOA-CBO). In this section, first, whale optimization algorithm is explained and then, a new version of whale optimization algorithm is introduced that is called WOA-CBO algorithm.

### 2.1. Whale Optimization Algorithm (WOA)

Whale optimization algorithm is a novel meta-heuristic algorithm, which mimics the social behavior of hump-back whales. This meta-heuristic algorithm has been developed by Mirjalili and Lewis [26]. In this algorithm, the spiral bubble-net feeding maneuver is mathematically modeled to perform optimization. It should be mentioned that bubble-net feeding is a unique behavior that can only be observed in hump-back whales [26]. In order to update the position of the whales during optimization, two behaviors are identified, namely, the shrinking encircling mechanism and the spiral bubble-net feeding maneuver. Since the position of the optimum design in the search space is not known, the basic WOA algorithm assumes that the current best candidate solution is the optimum or is close to the optimum, and the other search agents will update their positions towards the best search agent [26]. The WOA procedure is extracted from [26] and is briefly explained in the following.

The WOA starts with a set of random populations. At each iteration, search agents update their positions according to  $A$  vector's value. Updating mechanism is detailed in following. This process continues until terminating criterion is satisfied.

The WOA algorithm has two phases, namely, exploitation and exploration. This algorithm smoothly transits between exploration and exploitation phases. The transition is done due to variation of  $A$  vector's value.  $A$  vector's value decreases during iterations; half of iterations are assigned to exploration phase, when  $|A| \geq 1$ , and the other half are dedicated to exploitation, when  $|A| < 1$ . Here, the sign  $||$  indicates the absolute value. The vector  $A$  is computed as follows:

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a}, \quad (1)$$

where  $\vec{a}$  linearly decreases from 2 to 0 over the course of iterations and  $r$  is a random vector in [0,1].

2.1.1. Bubble-net attacking method (exploitation phase)

In order to model the bubble-net behavior of humpback whales mathematically, two approaches are considered, namely, shrinking encircling mechanism and spiral updating position. Since the humpback whales swim around the prey within a shrinking circle and along a spiral-shape path simultaneously, WOA assumes that there is a probability of 50% to choose between these two behaviors. Shrinking encircling mechanism is modeled in the following formulae:

$$\vec{C} = 2 \cdot \vec{r}, \tag{2}$$

$$\vec{D} = \left| \vec{C} \cdot \vec{X}_{best} - \vec{X} \right|, \tag{3}$$

$$\vec{X}^{new} = \vec{X}_{best} - \vec{A} \cdot \vec{D}, \tag{4}$$

where  $\vec{X}^{new}$  and  $\vec{X}$  are new position and previous position of whales, respectively;  $\vec{X}_{best}$  is the position vector of the best solution obtained so far;  $A$  and  $C$  are coefficient vectors; and  $||$  is the absolute value.

Additionally, spiral-shape movement of whales is simulated in the following formulae:

$$\vec{D}' = \left| \vec{X}_{best} - \vec{X} \right|, \tag{5}$$

$$\vec{X}^{new} = \vec{D}' \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}_{best}, \tag{6}$$

where  $b$  is a constant that defines the spiral shape of movement and  $l$  is a random number in [-1,1].

2.1.2. Search for prey (exploration phase)

When  $|A| \geq 1$ , exploration phase is in progress. WOA updates the position of a whale in the exploration phase according to a randomly chosen whale instead of the best search agent. Thus, the new position is computed by the following formula:

$$\vec{D} = \left| \vec{C} \cdot \vec{X}_{rand} - \vec{X} \right|, \tag{7}$$

$$\vec{X}^{new} = \vec{X}_{rand} - \vec{A} \cdot \vec{D}. \tag{8}$$

2.2. Colliding Bodies Optimization (CBO)

Colliding Bodies Optimization (CBO) is a recently developed population-based meta-heuristic algorithm that is inspired by one-dimensional collision between two bodies, Kaveh and Mahdavi [27]. The CBO algorithm starts with a random population of Colliding Bodies (CB). Each CB is known as a solution candidate. The masses of these bodies are calculated according to their objective function values. The CBs are sorted in an ascending order of their fitness values, and then divided into two equal groups, namely, stationary and moving. The lower half of the CBs are in the stationary group and the rest of them are in the moving one. The moving CBs move towards stationary CBs and a collision happens between pairs of CBs. This causes their positions to be updated. The repetition of these actions leads to reaching the optimal position in the search space.

2.3. WOA-CBO Algorithm

In order to modify and improve the updating mechanism of the standard WOA, a modified version of the WOA is considered. This proposed modification is inspired by the CBO [27] and ECBO [28] algorithms.

In this modified version of the WOA, all whales are sorted according to their objective function values in ascending order. Then, whales are divided into two equal groups, namely, explorer and imitator whales. The lower half of whales are called explorer whales; these whales are good agents. The upper half of whales are called imitator whales. Now, unlike in the standard WOA, all search agents do not update their positions towards only the best search agent; instead, explorer whales update their positions towards the current best whale to find better solutions and imitator whales update their position towards the lower half to improve their position. In other words, each imitator whale follows its pair in explorer group and improves its position. Whales group and pair of imitator whales are shown in Figure 1.

Another modification is considering a memory to save some best agents in each iteration. These agents are added to populations in place of the same number of current worst agents.

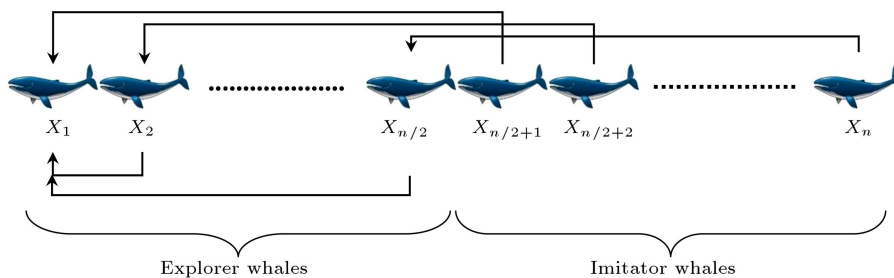


Figure 1. Whales group and pair of imitator whales.



**Step 6: Termination criterion check.** The optimization process is terminated after a fixed number of iterations. If this criterion is not satisfied, we should go to Step 2.

### 3. Application of the algorithms

As mentioned before, the discrete model of construction site layout problems is concerned with assigning a number of predetermined facilities ( $n$ ) uniquely to a number of predetermined locations ( $m$ ); thus, the number of locations should be equal to or greater than the number of facilities [12]. The other type of site layout problem is continuous model, in which facilities can be located in any available spaces.

For implementing WOA and WOA-CBO in discrete model, each search agent (whale) is considered as a solution candidate. These whales move in  $n$  dimensional search space to find optimum solution; The number of search space’s dimensions is equal to the number of facilities and each dimension is assigned to a particular facility. The value of dimensions represents the assigned number of locations to the corresponding facilities. Since every location is capable of containing only one facility, dimensions of each whale should not have the same value; violation of this point makes the solution infeasible. Therefore, some attention in updating mechanism is required for this type of problems. In continuous models, the position of each facility is represented by coordinates of the center of gravity of the facilities ( $X_i, Y_i$ ). Thus, the number of variables of each whale is twice the number of facilities. An important point in this type of modelling is that facilities should be located within boundaries of the site and they should not have overlap with each other [15].

### 4. Case studies of construction site layout

In order to show the efficiency and performance of

the WOA and WOA-CBO in construction site layout problems, three case studies are selected. The first case is an equal area facility layout problem in which every facility could be assigned to any location. The second one is an unequal area facility layout problem with more constraints. These two case studies are examples of discrete model. As an example of continuous model, a third case study is provided. These case studies are solved by WOA and WOA-CBO, and the results are compared. The proposed algorithms are coded in MATLAB R2011a and executed on Intel®Core™ i7 processor(1.73 GHz) and 4 GB RAM under the windows 10 Home 64-bit operating system. The detailed case studies and the results are as follows.

#### 4.1. Case study 1

This case study is taken from Ref. [29] and it is known as an equal area problem. The purpose of this problem is finding the optimal arrangement for placing 11 facilities into 11 pre-determined locations on the site. Table 1 shows the 11 facilities and their notes. As it can be seen, the main gate and side gate are fixed on the pre-determined locations. The travel distance between predetermined locations and trip frequency on a single day between facilities are presented in Tables 2 and 3, respectively.

The objective of this case is to minimize the total travel distance of the site personnel between the facilities. The total travel distance is calculated by Eq. (13):

$$\begin{aligned} \text{Minimize } TD &= \sum_{i=1}^n \sum_{j=1}^n \sum_{l=1}^n \sum_{k=1}^n x_{ik} \times x_{jl} \times f_{ij} \times d_{kl}, \\ \text{Subject to } \sum_{i=1}^n x_{ij} &= 1, \quad \sum_{j=1}^n x_{ij} = 1, \end{aligned} \tag{13}$$

where  $n$  is number of facilities.  $x_{ik} = 1$  when the facility  $i$  is assigned to the location  $k$ ; otherwise, it is

**Table 1.** Facilities and their notes for Case 1.

Index number	Facilities	Note
1	Site office	—
2	False work workshop	—
3	Labor residence	—
4	Storeroom 1	—
5	Storeroom 2	—
6	Carpentry workshop	—
7	Reinforcement steel workshop	—
8	Side gate	Fixed to 1
9	Electrical, water, and other utilities control room	—
10	Concrete batch workshop	—
11	Main gate	Fixed to 10

**Table 2.** Travel distance between pre-determined locations.

Distance	Location										
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11
Location L1	0	15	25	33	40	42	47	55	35	30	20
L2	15	0	10	18	25	27	32	42	50	45	35
L3	25	10	0	8	15	17	22	32	52	55	45
L4	33	18	8	0	7	9	14	24	44	49	53
L5	40	25	15	7	0	2	7	17	37	42	52
L6	42	27	17	9	2	0	5	15	35	40	50
L7	47	32	22	14	7	5	0	10	30	35	40
L8	55	42	32	24	17	15	10	0	20	25	35
L9	35	50	52	42	37	35	30	20	0	5	15
L10	30	45	55	49	42	40	35	25	5	0	10
L11	20	35	45	53	52	50	40	35	15	10	0

**Table 3.** Trip frequency between facilities.

Trip frequency	Facility										
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
Facility F1	0	5	2	2	1	1	4	1	2	9	1
F2	5	0	2	5	1	2	7	8	2	3	8
F3	2	2	0	7	4	4	9	4	5	6	5
F4	2	5	7	0	8	7	8	1	8	5	1
F5	1	1	4	8	0	3	4	1	3	3	6
F6	1	2	4	7	3	0	5	8	4	7	5
F7	4	7	9	8	4	5	0	7	6	3	2
F8	1	8	4	1	1	8	7	0	9	4	8
F9	2	2	5	8	3	4	6	9	0	5	3
F10	9	3	6	5	3	7	3	4	5	0	5
F11	1	8	5	1	6	5	2	8	3	5	0

equal to 0;  $x_{jl}$  has the same concept. Coefficient  $f_{ij}$  is the frequency of trips made by construction personnel between facilities  $i$  and  $j$  per day. Coefficient  $d_{kl}$  is the distance between the locations  $k$  and  $l$ .

#### 4.2. Result and discussion for Case 1

This case study was adapted from 50 independent optimization runs through 200 iterations with population size of 50 by WOA and WOA-CBO. This was done to get valid statistical results (see Table 4). In Table 4, it can be seen that the average, worst, and standard deviations of the WOA-CBO are 12558, 12756, and 43.28, respectively, which are better than those of WOA. These results indicate that the considered modification has been rewarding and better solution with higher stability has been obtained.

As a comparison between WOA-CBO and CBO, the performance of the WOA-CBO is nearly similar to

that of the CBO. The best solution obtained in this study is 12546, which is reduced by 16.86% compared to that in the Ref. [29]. Table 5 shows a comparison between the present work and Ref. [29] for Case 1. Figure 3 compares the convergence curves of WOA, CBO, and WOA-CBO. As can be seen in this figure, WOA-CBO algorithm has higher convergence speed than the other algorithms, especially WOA.

#### 4.3. Case study 2

This case is an unequal area version of the first case and is taken from [12]. In this case, 3 facilities among 11 facilities are too large and cannot be placed in smaller locations. Locations 7 and 8 are assumed to be smaller than the others. Table 6 shows the 11 facilities and their notes. Travel distance between locations, trip frequency, and objective function are similar to those in Case 1.

**Table 4.** Results of 50 independent runs for Case 1.

Algorithm	Best	Average	Worst	Difference best-average solution%	Difference best-worst solution%	Std. dev
WOA	12546	12567	12768	0.167	1.769	59.89
CBO [25]	12546	12558	12768	0.096	1.769	45.51
WOA-CBO	12546	12558	12756	0.096	1.674	43.28

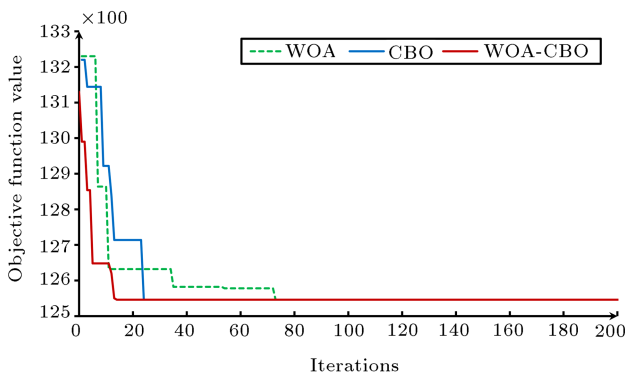
**Table 5.** A comparison between present work and Ref. [29] for Case 1.

Algorithms	Total distance	Best layout										
		$F_1$	$F_2$	$F_3$	$F_4$	$F_5$	$F_6$	$F_7$	$F_8$	$F_9$	$F_{10}$	$F_{11}$
WOA*	12546	9	11	4	5	7	6	3	1	2	8	10
WOA-CBO*	12546	9	11	4	5	7	6	3	1	2	8	10
GA [29]	15090	11	5	8	7	2	9	3	1	6	4	10

\*Current study.

**Table 6.** Facilities and notes for Case 2.

Index number	Facilities	Note
1	Site office	Large size
2	False work workshop	-
3	Labor residence	Large size
4	Storeroom 1	-
5	Storeroom 2	-
6	Carpentry workshop	-
7	Reinforcement steel workshop	-
8	Side gate	Fixed to 1
9	Electrical, water, and other utilities control room	-
10	Concrete batch workshop	Large size
11	Main gate	Fixed to 10



**Figure 3.** Convergence curves of WOA, CBO, and WOA-CBO for Case 1.

**4.4. Result and discussion for Case 2**

This case study has also adapted 50 independent optimization runs through 200 iterations with population size of 50 by WOA and WOA-CBO. Statistical results of this case are prepared in Table 7. From Table 7, it

can be observed that the average, worst, and standard deviations of WOA-CBO are 12648, 12768, and 52.84, respectively, which are better than those of WOA. These results indicate that the considered modification has also been rewarding in unequal area problem, which has more constraints. The best solution obtained in this study is 12606, which is reduced to 16.85% compared to [12]. Table 8 shows a comparison between the present work and Ref. [12] for Case 2. The convergence curves of the WOA and WOA-CBO are presented in Figure 4. These curves also emphasize that WOA-CBO has lower speed than WOA.

**4.5. Case study 3**

As we mentioned previously, this case study is an example for continuous model and is extracted from Ref. [15]. Site form and its dimensions are depicted in Figure 5. Temporary and fixed facilities, associated dimensions, and center coordinate of the fixed facilities are listed in Table 9. The purpose of the case study

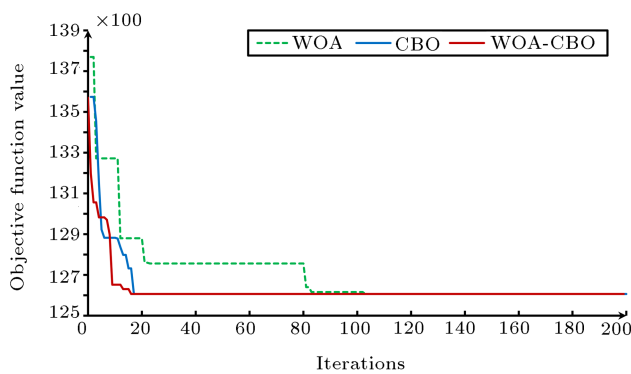
**Table 7.** Results of 50 independent runs for Case 2.

Algorithm	Best	Average	Worst	Difference best-average solution%	Difference best-worst solution%	Std. dev
WOA	12606	12665	12808	0.47	1.60	60.53
CBO	12606	12650	12706	0.35	0.79	54.04
WOA-CBO	12606	12648	12702	0.33	0.76	52.84

**Table 8.** A comparison between the present work and Ref. [12] for Case 2.

Algorithms	Total distance	Best layout										
		$F_1$	$F_2$	$F_3$	$F_4$	$F_5$	$F_6$	$F_7$	$F_8$	$F_9$	$F_{10}$	$F_{11}$
WOA*	12606	11	9	5	6	8	3	7	1	4	2	10
WOA-CBO*	12606	11	9	5	6	8	3	7	1	4	2	10
GA [12]	15160	11	5	9	7	2	8	3	1	6	4	10

\*Current study.



**Figure 4.** Convergence curves of WOA, CBO, and WOA-CBO for Case 2.

is to locate the temporary facilities in the available spaces properly to minimize the travel cost, which is calculated by Eq. (14):

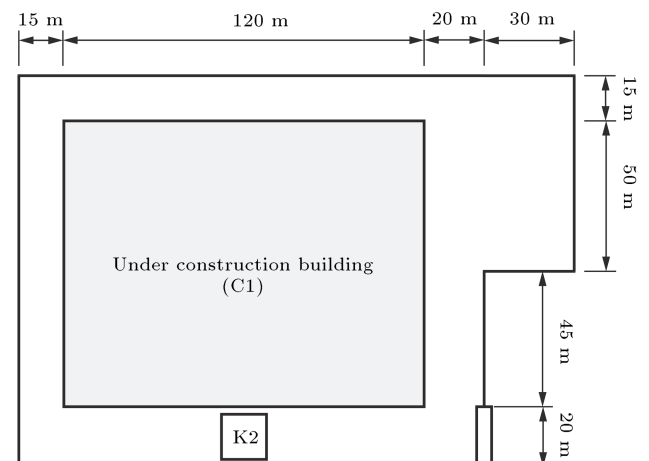
$$\text{Minimize } TC = \sum_{i=1}^{n-1} \sum_{j=i+1}^n (C_{ij} \times d_{ij}), \quad (14)$$

where  $C_{ij}$  represents the travel cost per unit between facilities  $i$  and  $j$  that are presented in Table 10 and  $d_{ij}$  is the distance between these facilities.

#### 4.6. Result and discussion for Case 3

This case is more complicated than the previous two cases and it can be a better criterion for evaluating capability and performance of algorithms. Thus, WOA, CBO, and WOA-CBO are implemented on this problem.

Statistical results of this case study, after 30 independent runs through 20,000 iterations with population size of 200, are provided in Table 11. These results show that WOA-CBO has found the least cost layout,



**Figure 5.** Site form and dimensions.

and has better average and the worst result among the other algorithms. Although the best result of the WOA is better than that of CBO, its average and standard deviation are worse, and by considering our modifications, the weaknesses are improved in WOA-CBO algorithm. The best obtained solution cost is 8477.4 and the corresponding layout is shown in Figure 6. The convergence curves of the WOA, CBO, and WOA-CBO for finding the best layout are presented in Figure 7. As it can be seen in this figure, WOA-CBO finds better layout, and it has an acceptable convergence speed.

#### 5. Conclusions

In this study, the application of a recently developed meta-heuristic algorithm, known as whale optimization algorithm, was proposed to solve construction site



**Table 9.** Temporary and fixed facilities and the associated data.

Index	Temporary and fixed facilities	Length (m)	Width (m)	X coord.	Y coord.
F1	Parking lot	20	20	-	-
F2	Office 1	20	5	-	-
F3	Office 2	20	5	-	-
F4	Office 3	20	5	-	-
F5	Office 4	20	5	-	-
F6	Workshop	5	4	-	-
F7	Storage 1	6	5	-	-
F8	Storage 2	4	5	-	-
F9	Electric generator	2	2	-	-
F10	Toilets	5	6	-	-
F11	Fire station	3	3	-	-
F12	Inflammable materials storage	3	3	-	-
C1	Building	120	95	75	67.5
K2	Tower crane	15	15	75	10
G3	Entrance gate	-	-	155	10

**Table 10.** Travel cost per unit between facilities.

$C_{ij}$	Facility $j$															
	Facility $i$	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	C1	K1	G1
F1	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F2	4	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F3	4	7.5	0	-	-	-	-	-	-	-	-	-	-	-	-	-
F4	4	7.5	7.5	0	-	-	-	-	-	-	-	-	-	-	-	-
F5	4	5.5	5.5	2.5	0	-	-	-	-	-	-	-	-	-	-	-
F6	1.5	1	1	1	1	0	-	-	-	-	-	-	-	-	-	-
F7	1.5	1	1	1	1	9.5	0	-	-	-	-	-	-	-	-	-
F8	1.5	1	1	1	1	9.5	6.5	0	-	-	-	-	-	-	-	-
F9	1.5	2	1	3	3	3	3	3	0	-	-	-	-	-	-	-
F10	1.5	7.5	7.5	7.5	7.5	6.5	6.5	6.5	1	0	-	-	-	-	-	-
F11	1.5	1	1	1	1	1	1	1	1	1	0	-	-	-	-	-
F12	1.5	1	1	1	1	3.5	1	1	3.5	1	1	0	-	-	-	-
C1	1.5	3.5	3.5	3.5	3.5	6.5	4.5	4.5	5.5	3	1	4.5	0	-	-	-
K1	0	7.5	5.5	7.5	7.5	9.5	9.5	9.5	0	0	1	4.5	5	0	-	-
G1	1.5	0	0	0	0	3	7*	7*	0	0	0	1	0	0	0	0

\*Current study.

**Table 11.** Results of 30 independent runs for Case 3.

Algorithm	Best	Average	Worst	Difference	Difference	Std. dev
				best-average solution%	best-worst solution%	
WOA	9049.2	12424	16830	37.29	85.98	2531.7
CBO	10605	12123	13146	14.31	23.96	351.46
WOA-CBO	8477.4	10066	12927	18.73	52.48	1380

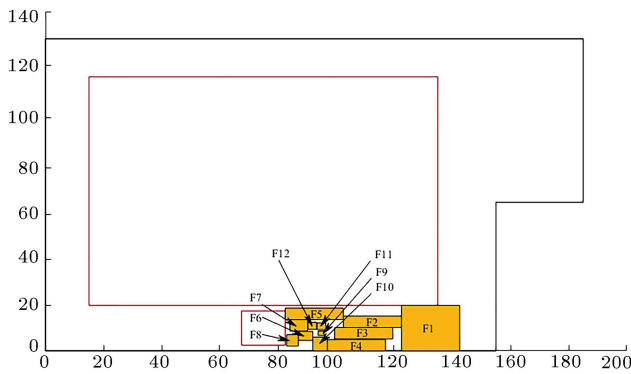


Figure 6. The lowest cost layout obtained.

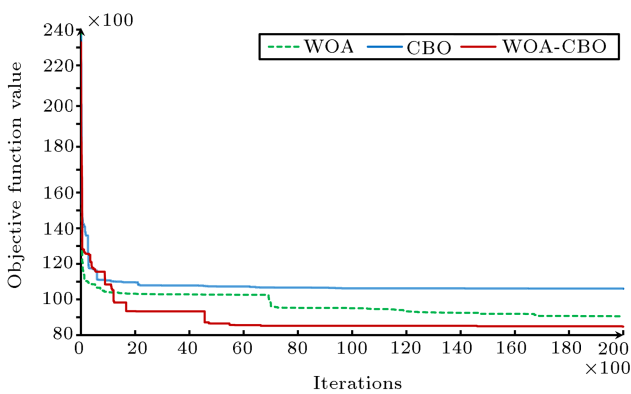


Figure 7. Convergence curves of WOA, CBO, and WOA-CBO for Case 3.

layout problem. This algorithm was inspired by the hunting behavior of humpback whales. In order to modify and improve the updating mechanism of the standard WOA, a hybrid WOA-CBO was introduced in this paper. This new version of WOA was called WOA-CBO. These algorithms were applied to three case studies that contained both discrete and continuous models. The results of this experiment verified that the proposed approach was applicable for construction site layout problem. Also, a comparison between WOA and WOA-CBO indicated that the proposed modification was efficient and obtained better solution with more stability. Thus, it can be concluded that these algorithms are competitive with other meta-heuristic algorithms and can be used in construction site layout problems.

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