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Construction site layout planning using multi-objective artificial bee colony algorithm with Levy flights

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ABSTRACT

Construction site layout planning has been recognized as a critical step in construction planning. The basic function of this process is to find the best arrangement of the temporary facilities according to multiple objectives that may conflict with each other and subjected to logical and resource constraints. The formulation of the construction site layout planning problem as an optimization problem turns out to be a nonlinear programming problem where there are conflicting multi-objectives to be achieved. It is shown that the swarm intelligence based meta-heuristic algorithms are quite powerful in obtaining the solution of such hard to solve type of optimization problems. In this study a multi objective artificial bee colony (MOABC) via Levy flights algorithm is proposed to determine the optimum construction site layout. The model is intended to optimize the dynamic layout of unequal-area under two objective functions. The performance of MOABC with Levy flights is demonstrated on a real benchmark construction engineering of construction site layout planning problem and the optimum solution obtained is compared with the one determined by the ant colony algorithm.

1. Introduction

Construction site layout planning (CSLP) has been recognized as a critical step in construction planning [1]. The basic function of this process is to find the best arrangement of the temporary facilities according to multiple objectives that may conflict with each other and subjected to logical and resources constraints. Minimizing the cost associated with the interaction between facilities and minimizing safety and environmental hazards are most popular conflicting planning objectives that have been studied in recent studies [2–4]. In most of the previous work the CSLP problem is considered a static layout problem assuming that all temporary facilities are assembled at the beginning and kept at their initial locations until the completion of the project [5–8]. However in the real situation, the need of temporary facilities varies during different construction phases of the projects and basically depends on activity schedules. Zouein and Tommelein [9] emphasized the importance of considering the interdependence between activity scheduling and site layout. Because of its significant effects on the reliability of the results, most recent studies consider the dynamic search scheme for solving the CSLP problem [2,3].

Construction site layout planning is considered as 'NP-hard' problem [8] for its complexity. The recent meta-heuristic algorithms based on swarm intelligence have demonstrated their power in finding the solution of such type of optimization problems [10]. This has encouraged researchers to employ these modern meta-heuristic algorithms to determine the solution of their proposed CSLP models. Ning et al. in their work [3] proposed a method to solve the dynamic multi-objective CSLP problem using max–min Ant system (MMAS) which is one of the versions of standard ant colony optimization (ACO) algorithms. Lien and Cheng [8] proposed a hybrid swarm intelligence based particle-bee algorithm for construction site layout optimization under single objective function to locate facilities in predetermined locations. Li and Love [5] presented an investigation of applying the Genetic Algorithm to attain the optimal solution for single objective CSLP problem to accommodate facilities of unequal area in predetermined locations. Zang and Wang [11] proposed a particle swarm optimization (PSO) based methodology. They modeled the CSLP problem to optimize static layout under single objective function to accommodate facilities of un-equal area in predetermined locations. Another study related to particle swarm optimization (PSO) was developed by Jiuping Xu and Zongmin Li [2]. Their approach uses multi-objective particle swarm optimization (MOPSO) algorithm. The approach is applied to solve the multi objective dynamic CSLP problem. Osman et al. proposed a hybrid cad-based algorithm using genetic algorithm (GA) in order to optimize the assignment of un-equal area facilities to any unoccupied space at a construction site [12].

The artificial bee colony (ABC) algorithm is one of the most recent swarm intelligence based algorithms introduced by Dervis Karaboga which mimics the foraging behavior of honey bees [13]. In this study a multi objective artificial bee colony (MOABC) algorithm is used to

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Table 1
The six-value scale commonly used in industrial facility layout.

Desired relationship between facilities	Proximity weight
Absolutely necessary (A)	81
Especially important (E)	27
Important (I)	9
Ordinary closeness (O)	3
Unimportant (U)	1
Undesirable (X)	0

obtain the solution of the CSLP problem. The standard MOABC algorithm is enhanced with Levy flights type of random walks for finding new food sources which is conducted by employed bees. The objective of the study is to optimize the dynamic layout problem under two objective functions of minimizing the safety hazards/environmental concerns and the total handling cost of interaction flows between facilities. The model regards the CSLP problem as a non-linear layout problem with un-equal area facilities that can be aligned horizontally or vertically. Furthermore the model takes into account the presence of obstructions for determining travel distances.

The remainder of the paper is organized as follows. In Section 2, the CSLP model is described; in Section 3 the multi-objective ABC algorithm with Levy flights is explained. Section 4 presents the design examples. The conclusion is presented in Section 5.

2. Modeling of construction site layout problem model

Construction site layout planning layout model is designed to arrange temporary facilities required at various time intervals (phases) of construction project under set of constraints while achieving multi objective functions. Generally in multi-objective optimization problems pareto optimal solutions are determined so that decision makers can choose their preferred plan among these pareto optimal solutions [2]. The efficiency of CSLP model will be significantly affected by its precision in representing the actual situations.

2.1. Objective functions

Two objective functions are considered in the model. The first objective function is to minimize the total handling cost of interaction flows between facilities. The second is to minimize safety hazards/environmental concerns. The objective functions are mathematically defined as follows:

$$f_1 = \mathrm{Min} \sum_{p=1}^{np} \sum_{i=1}^{n} \sum_{j=1}^{n} C_{ijp} r_{ij} P_{ijp} \tag{1}$$

$$f_2 = \mathrm{Min} \sum_{p=1}^{np} \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{-1}{SE_{ijp}} e_{ij} P_{ijp} \tag{2}$$

$$e_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{3}$$

where (x_i, y_i) and (x_j, y_j) are the Cartesian coordinates of the centroids of facility i and j respectively which are treated as design variables. e_{ij} is the Euclidean distance between centroids of facilities i and j. r_{ij} is the modified rectangular distance between centroids of facilities i and j that considers the presence of obstruction which will be described later. C_{ijp} represents either the actual transportation cost between facilities i and j at phase p taking into consideration the number of trips made, or a relative proximity weight that reflects the required closeness based on interactions between facilities i and j at phase p. P_{ijp} represents the permutation matrix of the presence of facilities i and j at phase p. Obtaining accurate values for actual inter-facility transportation can become quite difficult [12] which promotes the use of proximity weights [3,12]. Table 1 shows a common scale used in industrial facility layout problems [14]. Section 4.2.3 presents an example of using this approach.

SE_{ijp} represents closeness relationship values for safety and environmental concerns. In this study, as shown in Eq. (2), the negative sign and the inverse of safety relationship values $\left(\frac{-1}{SE_{ijp}}\right)$ is used to maximize distances between facilities of higher SE value.

2.2. Dynamic search

Zouein and Tommelein [15] defined dynamic layout construction as the process of creating a sequence of layouts to span the duration of construction of a project when given the activity schedule. The dynamic layout approach can be classified into two searching schemes, discrete searching scheme [16] and continuous search scheme [3,17]. The major differences between the two schemes are described as follows. In the continuous search scheme, the temporary facilities will not be relocated during the various project phases. Accordingly, the arrangement of facilities for the whole construction period can be positioned on a single site layout. However, in the discrete searching scheme the locations of temporary facilities in one phase are independent to their locations in the other phases. This searching scheme involves the re-handling cost which results in more labor cost and time consumption. Hence, facilities already present on site may be relocated there if its value in the new position outweighs its relocation cost [16]. Moreover, the relocation of the facilities during their demand period will undesirably affect their availability and would cause interruption to ongoing activities. For these reasons, the continuous searching scheme is more

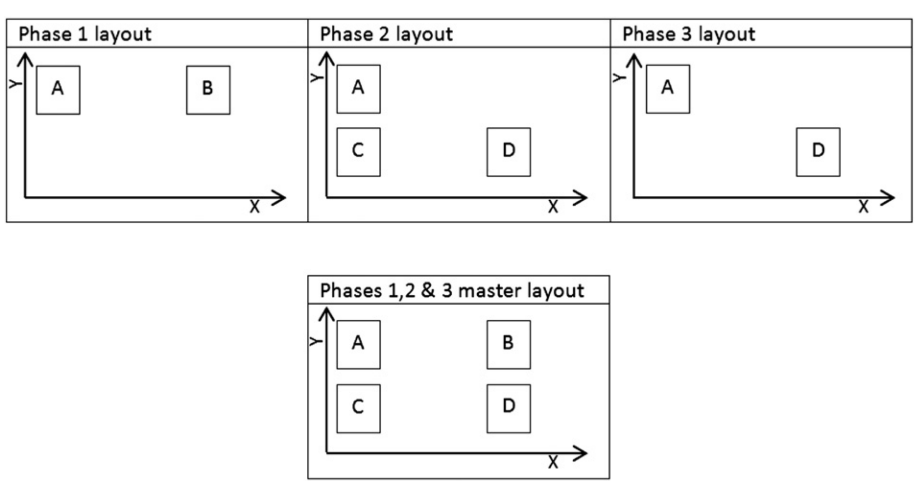

Fig. 1. Continuous dynamic search scheme.

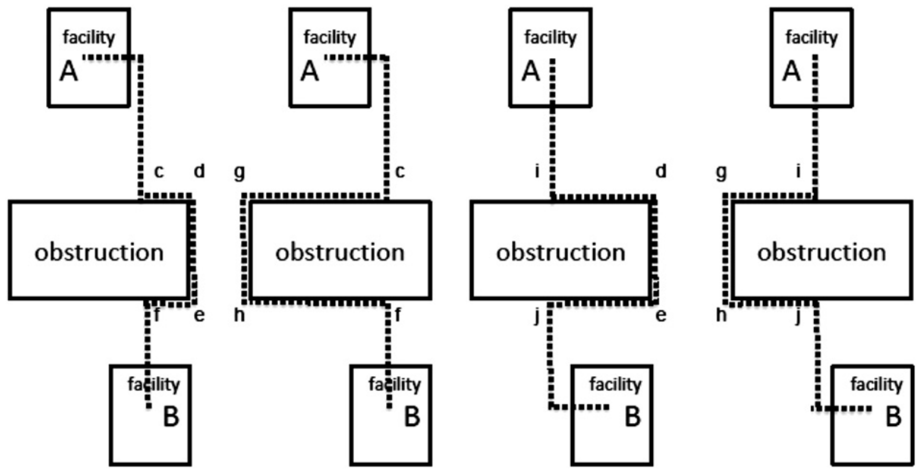

Fig. 2. Possible rectangular routes not passing through the obstruction.

favorable. Therefore, a continuous dynamic searching scheme, rather than a discrete dynamic searching scheme was employed in this work.

Fig. 1 illustrates the continuous dynamic search scheme for locating four temporary facilities in a hypothetical site with three phases. Facility A is required in the three construction phases, facility B is needed in phases 1 and 2, facility C is needed in phase 2 only, and facility 4 is needed in phases 2 and 3. Fig. 1 also illustrates that the optimum layout, when using continuous dynamic searching scheme, can be represented in a single plan. In this searching scheme the location of any facility is determined from optimizing the layout in all phases together. For example, when minimizing for single cost based objective function, the location of facility B is determined to have minimum layout cost in all phases and not only for phase 1 which is the time facility B is needed.

2.3. Distance measurement

For determining the first objective function that minimizes total handling cost of interaction flows between facilities this study proposes more accurate approach to represent the actual travel distances between facilities. Neglecting the presence of obstruction can significantly affect the reliability of the results. The rectangular distance is modified to consider presence of obstructions. Obstruction can be a building under construction or any other facility.

In the modified rectangular distance measurement approach, if an obstruction exists in the rectangular route between two facilities, the route is modified to avoid passing through the obstruction via the shortest path. For example, in Fig. 4 there are four possible routes to avoid passing through the obstruction. The first route A, c, d, e, f, B is the shortest among the four routes. The proposed model measures the travel distance between Facility A and Facility B by calculating the length of route A, c, d, e, f, B. The distance added to the basic rectangular distance to prevent passing through the obstruction is referred here as "obstruction distance". The modified rectangular distance R_{ij} is the result of adding the minimum obstruction distance (MOD) to the basic rectangular distance and mathematically represented as follows

$$R_{ij} = \left(\left|x_i - x_j\right| + \left|y_i - y_j\right|\right) + MOD \tag{4}$$

where (x_i,y_i) and (x_j,y_j) are the Cartesian coordinates of the centroids of facility i and j respectively (Figs. 2 and 3).

For determining the second objective function that minimizes safety hazards/environmental concerns the Euclidean distance is considered as the safety and environmental issues depends on closeness of facilities rather than travel distance.

2.4. Facilities type and size

Fixed facilities are those facilities whose locations are predetermined and fixed during the process of assigning facilities to free locations. For example, the security hut is commonly assigned to the main gate, and materials hoist is dependent on the structural elements to which they are tied, as such, planners usually freeze this type of facility in a set location [1].

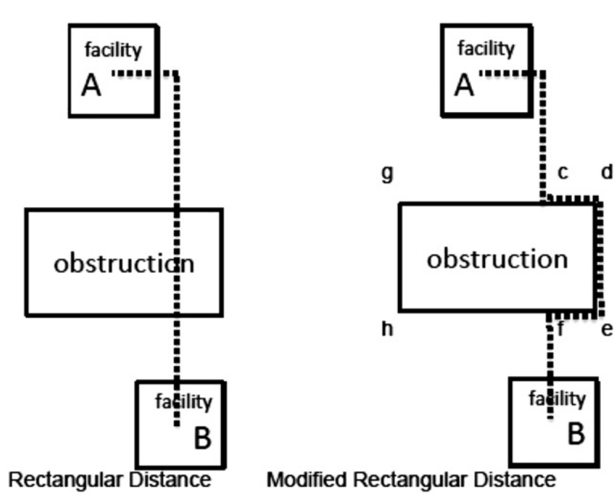

Fig. 3. Traveling distance measurement.

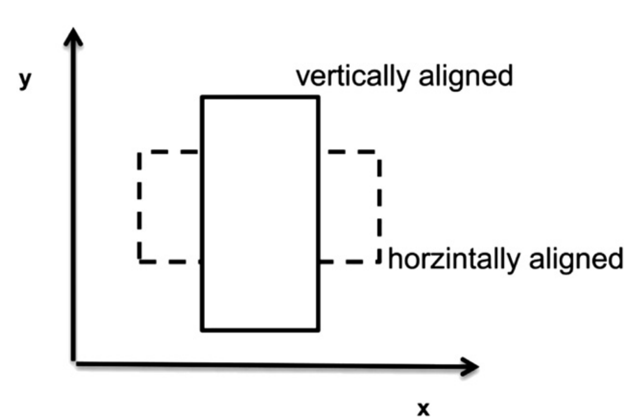

Fig. 4. Facility alignment alternatives.

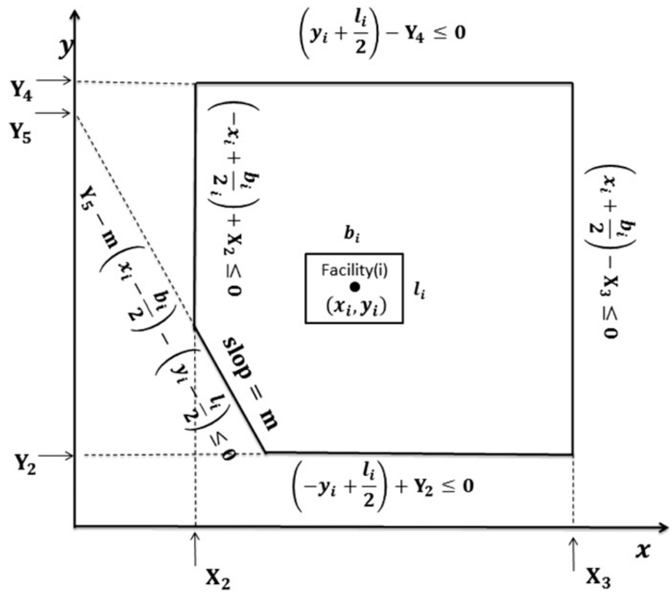

Fig. 5. Example for boundary constrains.

In order to improve practicality of the model this work allows unequal area facilities to be aligned vertically or horizontally, as shown in Fig. 4.

2.5. Overlapping constrains

To prevent overlapping of facilities with each other or with buildings, the following constrains are set,

$$0.5\left(b_i + b_j\right) + h_{ij} - \left|x_i - x_j\right| \le 0 \ \text{(horizontal overlapping)} \quad (4)$$

$$0.5\left(l_i + l_j\right) + v_{ij} - \left|y_i - y_j\right| \le 0 \ \text{(vertical overlapping)} \quad (5)$$

$$\min\left\{0.5\left(b_i - b_j\right) + h_{ij} - \left|x_i - x_j\right|, 0.5\left(l_i - l_j\right) + v_{ij} - \left|y_i - y_j\right|\right\} \le 0 \quad (6)$$

Eq. (6) ensures that only one of the two constrains will hold, in that it allows multiple facilities to be assigned in the same row or column.

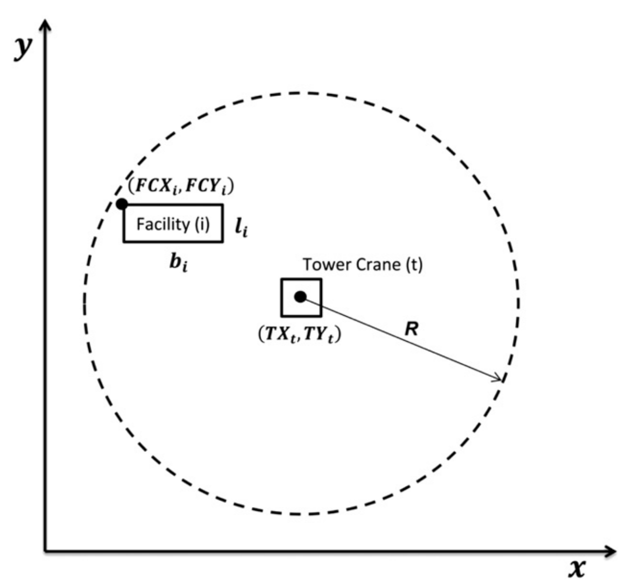

Fig. 6. Tower crane reachable radius.

b_i and l_i are the horizontal and vertical dimensions of facility i, and h_{ij} and v_{ij} are minimum allowable horizontal and vertical distances between facilities i and j.

2.6. Site boundary constrains

Facilities have to be located within the boundaries of the construction site. The equations for site boundary constrains are written in the form of the equation of a straight line. For a facility (i) of size $(b_i \times l_i)$ horizontal and vertical boundary constrains can be represented mathematically in the following forms and as shown in Fig. 5.

2.7. Tower crane access constrains

Some of the temporary facilities like steel yards, rebar bending yards, and material laydown areas have to be positioned within the reachable radius of tower cranes as illustrated in Fig. 6. For a facility (i) and a tower crane (t) with reachable radius R, this constraint is mathematically represented as follows:

$$\sqrt{(FCX_i - TX_t)^2 + (FCY_i - TY_t)^2} - R \le 0. \quad (7)$$

FCX_i and FCY_i represent the Cartesian coordinates of the farthest corner of a facility (i) from the tower crane. TX_t and TY_t represent the Cartesian coordinates of tower crane (t).

3. Multi-objective artificial bee colony algorithm with Levy flights (MOABC)

3.1. Artificial bee colony (ABC) algorithm

Introduced by Dervis Karaboga in 2005, ABC algorithm simulated the foraging behavior of a bee colony. Bees aim to maximize the nectar amount unloaded to the food stores in the hive. In the ABC algorithm a honey bee swarm is classified to three categories: employed bees, onlooker bees, and scout bees. Half of the colony bees are employed bees and each food source is exploited by only one employed bee that carries information about this particular food source and share information with other bees waiting in the hive. The information is shared via wiggle dancing. The other half includes the onlooker bees who try to find a food source by means of the information given by the employed bees. Exhausted food sources are abandoned and the employed bees whose food source has been abandoned become scout bees. Scout bees randomly search the environment in order to find new food sources.

Table 2
Site facilities and their dimensions.

No.	Temporary and fixed facilities	Facility type	Dimension (m^2)	Service phase
F1	Sample room	Non-fixed	25	3
F2	Equipment maintenance plant	Non-fixed	25	1,2,3
F3	Electrician hut	Non-fixed	25	1,2,3
F4	Tool shed	Non-fixed	50	1,2,3
F5	Rebar bending yard	Non-fixed	100	1,2,3
F6	Carpentry workshop	Non-fixed	100	1,2
F7	#1 Material laydown area	Non-fixed	100	1,2,3
F8	#2 Material laydown area	Non-fixed	100	1,2,3
F9	#1 Tower crane	Fixed	50	1,2
F10	#2 Tower crane	Fixed	50	1,2
F11	#1 Material hoist	Fixed	25	2,3
F12	#2 Material hoist	Fixed	25	2,3
F13	#3 Material hoist	Fixed	25	2,3
F14	#4 Material hoist	Fixed	25	2,3
F15	Site office	Fixed	50	1,2,3
F16	Security hut at site entrance	Fixed	9	1,2,3
F17	Security hut at site exit	Fixed	9	1,2,3

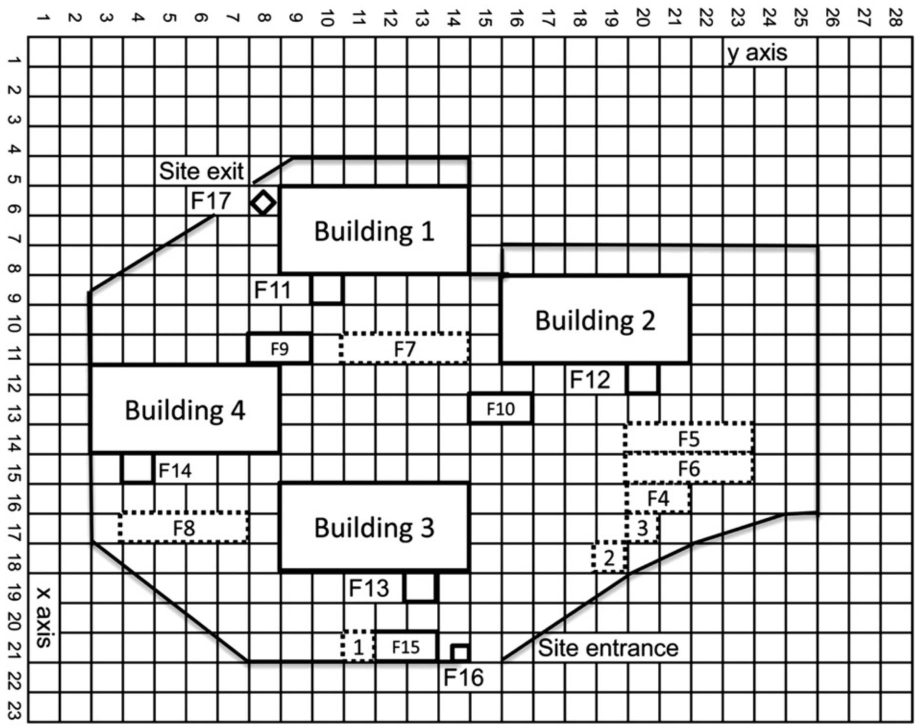

Fig. 7. Original construction site layout prepared by the contractor for design example 1.

ABC has been widely applied to solve real world problems. A comprehensive survey for ABC algorithm applications was presented by D. Karaboga et al. in [18]. Results show that ABC algorithm is better than or similar to those of other population based algorithms [19]. Karaboga and Akay in [20] proposed new version of the ABC algorithm to solve the constrained optimization problem under a single objective. The number of studies extended the standard version of ABC to search for optimality under multi-objective problems [21,22].

3.2. Multi-objective artificial bee colony algorithms

Two multi-objective optimization algorithms (MOABC) are coded in this study both of which are based on the ABC algorithm originated by Karaboga and Akay in [20]. The difference between these algorithms is that the first algorithm does not make use of Levy flights while the other does. These are named Basic-MOABC and MOABC via Levy flights. This is carried out in order to investigate the effect of Levy flights in the performance of multi-objective optimization algorithms. Both algorithms have the same basic steps which are described below:

Step 1 Generate randomly an initial population of sn solutions, where the number of solutions (sn) equals to half of the colony size (CS). The initial solution is set within the upper and lower boundaries.

Step 2 Calculate the value of objective functions, violation to constraints, and fitness of evaluated solution. The fitness of initial food sources is calculated based on non-domination as follows.

$$Fit(i) = ND(i)/sn \tag{8}$$

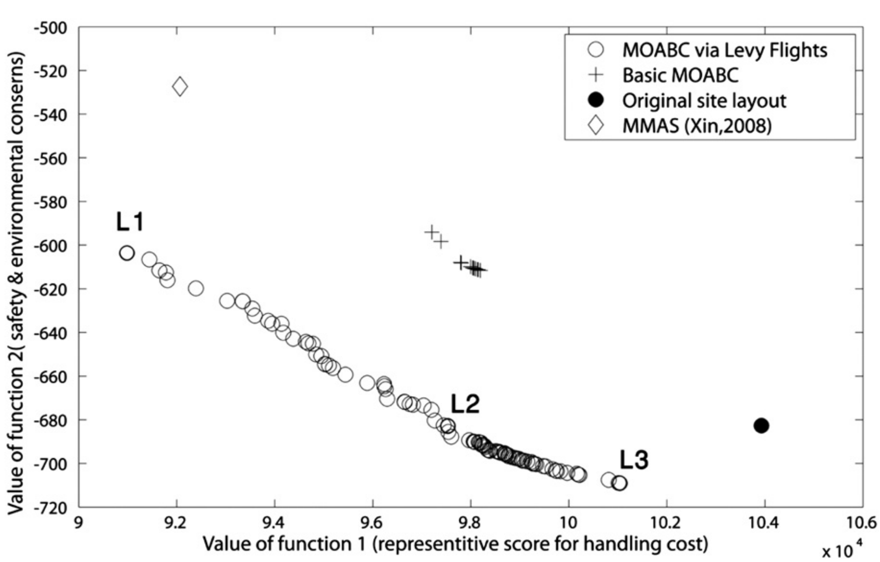

Fig. 8. Pareto front for the CSLP problem for design example 1.

Table 3
Comparison with original site layout.

Layout	F1	F2	Δ% for F1	Δ% for F2
Original layout (OL)	103,930	−683	–	–
L1	90,983	−604	−12.5	11.6
L2	97,529	−683	−6.2	0.0
L3	101,039	−709	−2.8	−3.8
MMAS	92,065	−527	−11.4	22.8

Note: Δ% for F1 = (F1(L1) − F1(OL)) / F1(OL), Δ% for F2 = (F2(L1) − F2(OL)) / |F2(OL)|.

$Fit(i)$ refers to the fitness of solution i, and $ND(i)$ refers to number of other solutions that do not dominate solution i.
For minimization problems, solution vector $\mathbf{u}$ is said to dominate another vector $\boldsymbol{v}$ if and only if $u_i \leq v_i$ for $\forall\ i \in \{1, \ldots n\}$ and $\exists\ i \in \{1, \ldots n\} : u_i < v_i$. In other words, no component of $\mathbf{u}$ is larger than the corresponding component of $\boldsymbol{v}$, and at least one component is smaller.

Step 3 Find pareto optimal by applying modified Deb's rules which search for feasible solutions on the assumption that any feasible solution is better than any infeasible one [23]. Deb's method uses a tournament selection operator, where two solution vectors $\mathbf{u}$ and $\mathbf{v}$ are compared at a time by applying the following criteria:

- Any feasible solution ($violation_u \leq 0$) is preferred to any infeasible solution ($violation_v > 0$), solution vector $\mathbf{u}$ is dominant;
- Among two feasible solutions ($violation_u \leq 0, violation_v \leq 0$), for minimization problems, apply domination criteria mentioned in Step 2 i.e. solution vector $\mathbf{u}$ is said to dominate another vector $\boldsymbol{v}$ if and only if $u_i \leq v_i$ for $\forall\ i \in \{1, \ldots n\}$ and $\exists\ i \in \{1, \ldots n\} : u_i < v_i$;
- Among two infeasible solutions ($violation_u > 0, violation_v > 0$), the one having smaller constraint violation is preferred ($violation_u < violation_v$), solution vector $\mathbf{u}$ is dominant.

The following are the steps of the search processes of the employed bees, the onlooker bees and scout bees till reaching a maximum number of cycles or a stop criterion.

Step 4 Produce a new food source s_i for the employed bee of food source x_i.
For Basic-MOABC algorithm, a new food source is generated as follows:

$$s_{ij} = \begin{cases} x_{ij} + \varnothing_{ij}\left(x_{ij} - x_{kj}\right), & \text{if } R_j < MR \\ x_{ij}, & \text{otherwise} \end{cases} \tag{9}$$

where $k \in \{1,\ldots sn\}$ is the randomly chosen index, $\varnothing$ is the uniformly distributed random real number in the range $[-1,1]$, and R_j is the uniformly distributed number in the range [0,1]. MR is the control parameter of the ABC algorithm in the range [0,1] which controls the number of parameters to be modified. If no parameter is changed, one random parameter is to be changed by

$$s_{ij} = x_{ij} + \varnothing_{ij}\left(x_{ij} - x_{kj}\right) \tag{10}$$

where j is the randomly distributed integer $[1,d]$, and d is the number of parameters.
For MOABC via the Levy Flight algorithm, in order to maximize the efficiency of food source searches conducted by employed bees, this work proposes to use Levy flights to produce a new food source s_i for the employed bee of food source x_i as follows:

$$s_i = x_i + \propto_0 \frac{u}{|v|^{1/\beta}}\left(x_i - x_j\right). \tag{11}$$

Generating random walk with Levy flights is explained in Section 3.3.

Step 5 Evaluate the new solution, compare to current solution and keep the dominant solution by rules described in (Step 3).

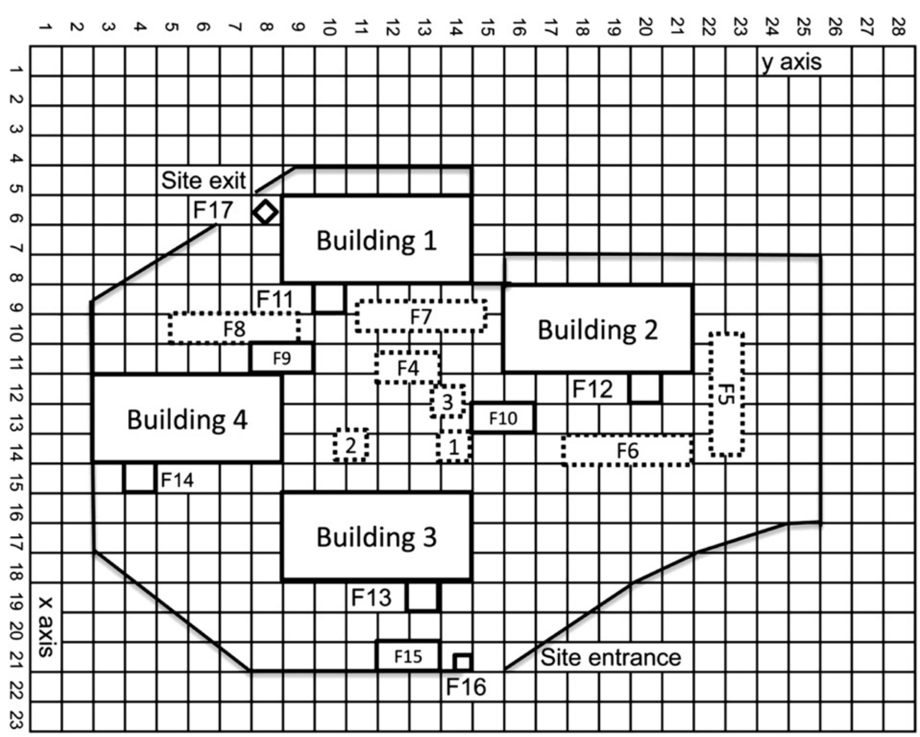

Fig. 9. Construction site layout alternative L1.

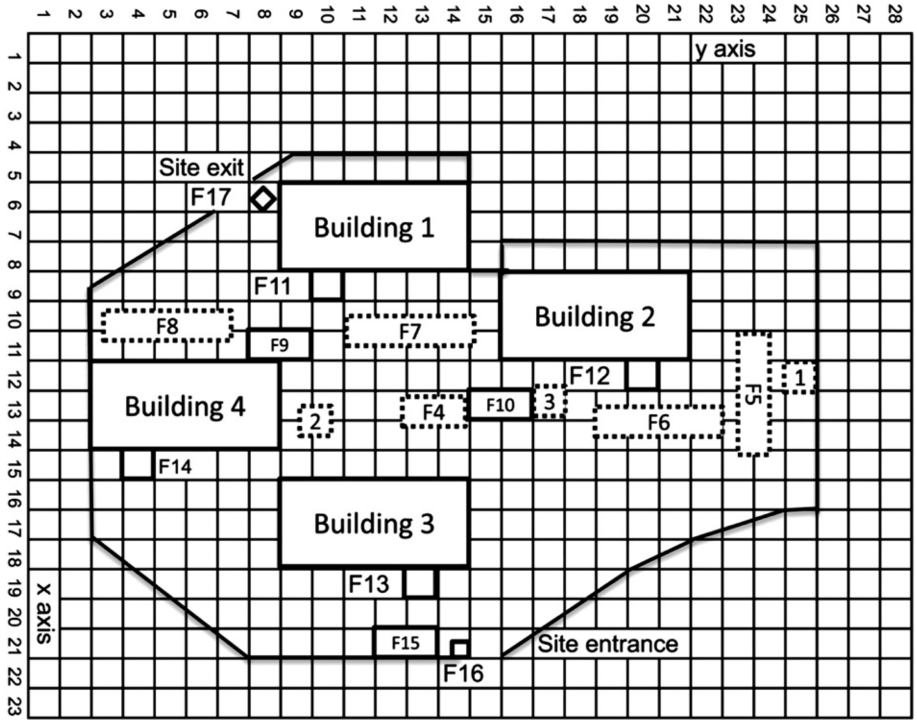

Fig. 10. Construction site layout alternative L2.

Step 6 Calculate probabilities of sending onlooker bees.

$$P_i = \begin{cases} 0.5 + \left(\dfrac{Fit(i)}{\sum_i^{sn} Fit(i)}\right) \times 0.5, & \text{if solution is feasible} \\ 0.5 + \left(\dfrac{violation(i)}{\sum_i^{sn} violation(i)}\right) \times 0.5, & \text{if solution is infeasible} \end{cases} \tag{12}$$

Step 7 Based on probability value calculated in Step 6, onlooker bee evaluates the information taken from all employed bees and produces a new solution by Eqs. (9) and (10) [in Step 4].
Step 8 Evaluate the solution and apply selection process rules in Step 3.
Step 9 Add the food sources to the archive, compare and keep only the non-dominated solutions in the archive.
Step 10 If the solution cannot be improved through scout production period (SPP) the food source is abandoned by its bee and a new food source is randomly initialized by the scout bee.
Step 11 Terminate if the maximum cycle number is reached.

3.3. Levy flights

A recent study by Reynolds and Frye shows that fruit flies or *Drosophila melanogaster*, explore their landscape using a series of straight flight paths punctuated by a sudden 90° turn, leading to a Levy-flight-style intermittent scale-free search pattern. Subsequently, such behavior has been applied to optimization and optimal search, and preliminary results show its promising capability [24].

Levy flights are random walks whose step length is drawn from the Levy distribution.

$$\text{Levy} \sim u = t^{-1-\beta}.(0<\beta<2) \tag{13}$$

Various studies have shown that flight behavior of many animals and insects has demonstrated the typical characteristics of Levy flights [24]. When generating new solutions s_i, a new food source for a bee in sources x_i a Levy flight is performed

$$s_i = x_i + \alpha * \text{Levy}(\beta) \tag{14}$$

where $\alpha > 0$ is the step size which should be related to the scales of the problem of interest. To accommodate the difference between solution qualities, we use

$$\propto = \propto_0 \left(x_i - x_j\right) \tag{15}$$

where $\propto_0$ is a constant, while the term in the bracket corresponds to the difference of two random solutions. Yang [25] discussed in details the scheme of generating step size by Levy flights and summarized as follows:

$$\text{step} = \propto_0 \left(x_i - x_j\right) * \text{Levy}(\beta) \sim \propto_0 \frac{u}{|v|^{1/\beta}} \left(x_i - x_j\right) \tag{16}$$

Table 4
Site facilities and their dimensions of private hospital construction.

No.	Temporary and fixed facilities	Facility type	Dimension (m^2)	Service phase
F1	Steel yard	Non-fixed	25 × 12	1,2
F2	Carpentry	Non-fixed	25 × 12	1,2,3
F3	Mixer machine yard	Non-fixed	20 × 12	1,2
F4	Material laydown area	Non-fixed	25 × 12	1,2,3
F5	Tool shed	Non-fixed	12 × 9	1,2,3
F6	Diesel generator	Non-fixed	10 × 4	1,2,3
F7	Sample room	Fixed	10 × 10	3
F8	Rest room	Fixed	12.5 × 12.5	1,2,3
F9	Contractor office	Fixed	9 × 12	1,2,3
F10	PM office	Fixed	6 × 12	1,2,3
F11	Material hoist	Fixed	5 × 10	2,3
F12	#1 Tower crane	Fixed	5 × 5	1,2
F13	#2 Tower crane	Fixed	5 × 5	1,2
F14	Security hut at site entrance	Fixed	3 × 3	1,2,3
F15	Security hut at site exit	Fixed	3 × 3	1,2,3

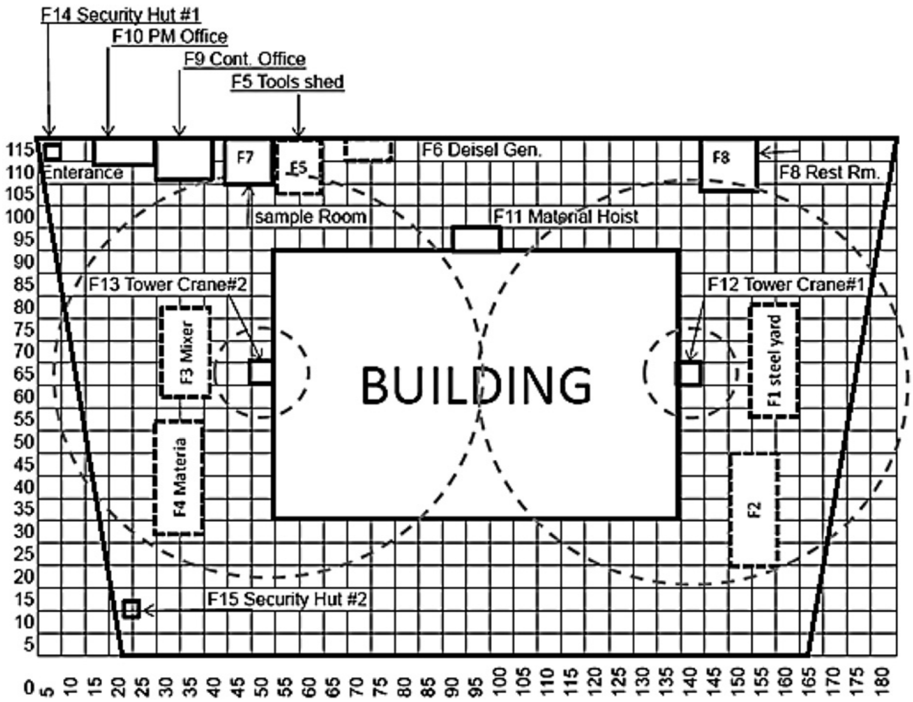

Fig. 11. Original construction site layout prepared by the contractor for design example 2.

where u and v are drawn from normal distributions. That is

$$u \sim N\left(0, \sigma_u^2\right), \;\; v \sim N\left(0, \sigma_v^2\right), \tag{17}$$

with

$$\sigma_u = \left\{ \frac{\Gamma(1+\beta)\sin(\pi\beta/2)}{\Gamma[(1+\beta)]\beta 2^{(\beta-1)/2}} \right\}, \sigma_v = 1. \tag{18}$$

Here Γ is the standard Gamma function which is extension of the factorial function with its argument shifted down by 1, to real and complex numbers. That is if n is a positive integer $\mathbf{\Gamma}(n) = (n-1)!$.

4. Design examples

The multi-objective optimization algorithm developed is applied to determine the optimum site layout problems of two construction projects. The first one is a residential building construction project located in the city of Beijing, China. This example is taken from [3] where optimum site layout problem is solved by using ant colony algorithm. The purpose of considering the same example is to provide an environment for comparing the performance of two algorithms. The second example is the construction project of three story private hospital in the city of Riffa, Bahrain.

4.1. Residential building construction project

The proposed MOABC based methodology is used to obtain the solution of the dynamic construction site unequal-area layout problem under multi objective functions in order to demonstrate its efficiency. The performance of the MOABC based method is compared with that of a MMAS-based method which is one of the ant colony optimization (ACO) algorithms [26]. The residential building project is located in the city of Beijing, China. There are four residential buildings (Building 1 and Building 4 are sixty stories high; Building 2 and Building 3 are eighty stories high), site offices and construction operational facilities located within the construction site. Other temporary living facilities are located outside the construction site. The task of the proposed model is to find the corresponding locations for the temporary construction operational facilities in the construction site. The temporary facilities (fixed and non-fixed facilities) and their corresponding dimensions and service phase are shown in Table 2. In Fig. 7, we show the

Table 5
Proximity weights for layout cost for phase 1.

	F1	F2	F3	F4	F5	F6	F8	F9	F10	F12	F13	F14	F15
F1	–	A	U	U	I	E	I	O	U	A	X	I	I
F2	A	–	X	U	I	I	I	O	U	A	X	I	I
F3	U	X	–	A	O	I	O	O	U	X	A	I	I
F4	U	U	A	–	O	U	U	O	U	X	A	E	E
F5	I	I	O	O	–	U	U	U	U	O	O	U	U
F6	E	I	I	U	U	–	O	O	O	E	E	U	U
F8	I	I	O	U	U	O	–	U	U	U	U	U	U
F9	O	O	O	O	U	O	U	–	A	X	X	O	O
F10	U	U	U	U	U	O	U	A	–	X	X	O	O
F12	A	A	X	X	O	E	U	X	X	–	I	U	U
F13	X	X	A	A	O	E	U	X	X	I	–	U	U
F14	I	I	I	E	U	U	U	O	O	U	U	–	O
F15	I	I	I	E	U	U	U	O	O	U	U	O	–

Table 6
Proximity weights for safety and environmental concerns for phase 1.

	F1	F2	F3	F4	F5	F6	F8	F9	F10	F12	F13	F14	F15
F1	–	I	I	I	I	A	A	A	A	O	O	E	E
F2	I	–	O	I	I	A	A	A	A	O	O	E	E
F3	I	O	–	O	O	I	E	A	A	O	O	I	I
F4	I	I	O	–	O	A	E	A	A	E	E	A	A
F5	I	I	O	O	–	I	I	I	I	U	U	O	O
F6	A	A	I	A	I	–	A	A	A	I	I	A	A
F8	A	A	E	E	I	A	–	U	U	I	I	A	A
F9	A	A	A	A	I	A	U	–	U	I	I	E	E
F10	A	A	A	A	I	A	U	U	–	I	I	E	E
F12	O	O	O	E	U	I	I	I	I	–	A	E	E
F13	O	O	O	E	U	I	I	I	I	A	–	E	E
F14	E	E	I	A	O	A	A	E	E	E	E	–	E
F15	E	E	I	A	O	A	A	E	E	E	E	E	–

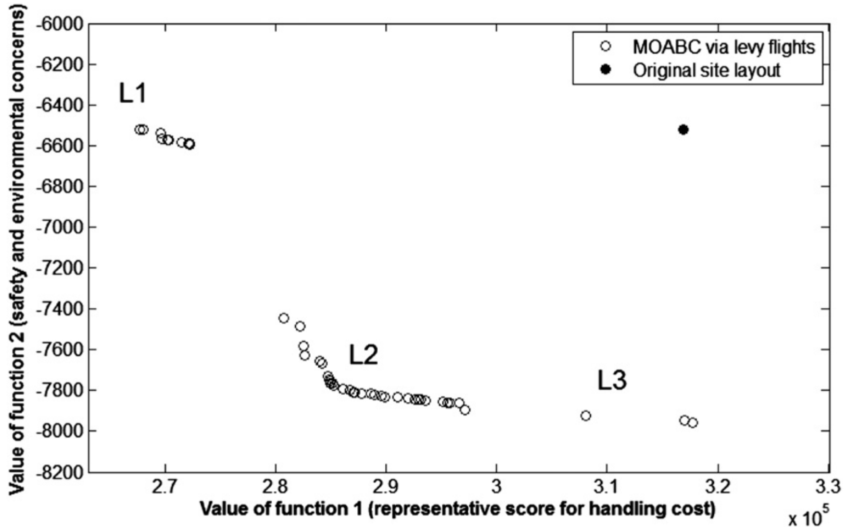

Fig. 12. Pareto front for the CSLP problem of design example 2.

site layout plan used in the original contractor's plan document. The dimensions are measured at scale 1:5. The main works carried out in each construction phase are foundation and underground works (Phase 1), superstructure (Phase 2), finishing works and external works (Phase 3).

The control parameters were set as follows: artificial bee colony size (CS) = 26; maximum cycle number (MCN) = 3000; scout production period (SPP) = 0.1 ∗ D ∗ CS; and modification rate (MR) = 0.8. In this case study there are 8 non-fixed facilities and 5 rectangular facilities, therefore the number of parameters (D) = 8 × 2 + 5 = 21.

4.1.1. Decision variables

(x_i,y_i) are the Cartesian coordinates of the centroid of facility i respectively which are selected as design variables, where $i = 1,2,\ldots,17$. R_i is a binary digit represent representing the orientation of facility i, i.e. $R_i = 0$ if facility i is aligned vertically, and $R_i = 1$ if facility i is aligned horizontally, where $i = 1,2,\ldots,17$.

4.1.2. Objective functions

Minimize the total handling cost of interaction flows between facilities (f_1) and minimize safety hazards/environmental concerns (f_2). The objective functions are mathematically defined as follows:

$$f_1 = \mathrm{Min}\sum_{p=1}^{3}\sum_{i=1}^{17}\sum_{j=1}^{17} C_{ijp} r_{ij} P_{ijp} \tag{19}$$

$$f_2 = \mathrm{Min}\sum_{p=1}^{3}\sum_{i=1}^{17}\sum_{j=1}^{17} \frac{-1}{SE_{ijp}} e_{ij} P_{ijp} \tag{20}$$

4.1.3. Facility closeness relationship

The facilities' closeness relationships for the total relationship C_{ijp} and the safety/Environmental concerns SE_{ijp} in the three phases are shown in Tables A1 to A6.

4.1.4. Overlapping constraints

$$\min\left\{0.5\left(b_i - b_j\right) + h_{ij} - \left|x_i - x_j\right|, 0.5\left(l_i - l_j\right) + v_{ij} - \left|y_i - y_j\right|\right\} \le 0 \tag{21}$$

for $i = 1,2,\ldots,17$ for temporary facilities and $i = 18,19,20,21$ for the four buildings, and $j = 1,2,\ldots,17$ for temporary facilities and $j = 18,19,20,21$ for the four buildings. To maintain a minimum distance of 3 m between buildings under construction and any temporary facilities, h_{ij} and v_{ij} are set to 3/5 for any i or $j = 18,19,20$ or 21.

4.1.5. Site boundary constraints (BC)

$$\mathrm{BC}(1):\ 14 - 1.4\left(x_i - \frac{b_i}{2}\right) - \left(y_i - \frac{l_i}{2}\right) \le 0 \tag{22}$$

$$\mathrm{BC}(2):\ \left(-y_i + \frac{l_i}{2}\right) + 2 \le 0 \tag{23}$$

$$\mathrm{BC}(3):\ -19.25 + 1.25\left(x_i + \frac{b_i}{2}\right) - \left(y_i - \frac{l_i}{2}\right) \le 0 \tag{24}$$

$$\mathrm{BC}(4):\ \left(x_i + \frac{b_i}{2}\right) - 21 \le 0 \tag{25}$$

$$\begin{array}{ll}
\text{if}\ \left(y_i + \frac{l_i}{2}\right) > 24, & \mathrm{BC}(5) = -16 + \left(x_i + \frac{b_i}{2}\right) \le 0 \\
24 \ge \left(y_i + \frac{l_i}{2}\right) \ge 21, & \mathrm{BC}(5) = 3\left(x_i + \frac{b_i}{2} - 17\right) + \left(y_i + \frac{l_i}{2} - 21\right) \le 0 \\
21 \ge \left(y_i + \frac{l_i}{2}\right) \ge 19, & \mathrm{BC}(5) = 2\left(x_i + \frac{b_i}{2} - 17\right) + \left(y_i + \frac{l_i}{2} - 21\right) \le 0 \\
\left(y_i + \frac{l_i}{2}\right) \le 19, & \mathrm{BC}(5) = \frac{4}{3}\left(x_i + \frac{b_i}{2} - 18\right) + \left(y_i + \frac{l_i}{2} - 19\right) \le 0 \\
\mathrm{BC}(6):\ \left(y_i + \frac{l_i}{2}\right) - 25 \le 0 &
\end{array} \tag{26}$$

$$\begin{array}{ll}
\text{if}\ \left(y_i + \frac{l_i}{2}\right) < 14, & \mathrm{BC}(7) = 4 - \left(x_i - \frac{b_i}{2}\right) \le 0 \\
14 \le \left(y_i + \frac{l_i}{2}\right) \le 15, & \mathrm{BC}(7) = 8 - \left(x_i - \frac{b_i}{2}\right) \le 0 \\
\left(y_i + \frac{l_i}{2}\right) > 15, & \mathrm{BC}(7) = 7 - \left(x_i - \frac{b_i}{2}\right) \le 0
\end{array} \tag{27}$$

(x_j,y_j) are positive real numbers; $i = 1,2,\ldots,17$.

Table 7
Three solutions for CSLP problem for case study 2.

Alternative 1			Alternative 2			Alternative 3		
x_i	y_i	R_i	x_i	y_i	R_i	x_i	y_i	R_i
146.387	87.735	0	144.990	78.538	0	165.293	77.782	0
151.585	62.595	0	151.967	52.903	0	153.004	53.378	0
34.600	77.102	1	37.801	74.479	0	37.770	74.779	0
31.136	64.249	1	25.684	74.920	0	25.581	74.685	0
95.368	103.922	1	156.281	4.814	1	156.018	4.846	1
115.504	99.909	0	133.566	95.101	1	168.594	95.482	1

Table 8
Comparison with original site layout of case study 2.

Layout	F1	F2	Δ% for F1	Δ% for F2
Original layout (OL)	316,875	−6523	–	–
L1	267,704	−6519	−15.5	0.1
L2	285,307	−7777	−10.0	−19.2
L3	308,059	−7921	−2.8	−21.4

Note: Δ% for F1 = (F1(L1) − F1(OL)) / F1(OL), Δ% for F2 = (F2(L1) − F2(OL)) / |F2(OL)|.

4.1.6. Tower crane constraints

The two tower cranes have a 45 meter reachable radius. Rebar bending yards (F5), carpentry workshop (F6), #1 material laydown area (F7), and #2 material laydown area (F8), have to be positioned within the reachable radius of one of the two tower cranes.

$$\min\left\{\sqrt{(FCX_i - TX_1)^2 + (FCY_i - TY_1)^2} - \frac{45}{5}, \sqrt{(FCX_i - TX_2)^2 + (FCY_i - TY_2)^2} - \frac{45}{5}\right\} \leq 0;\quad i = 5, 6, 7, 8 \tag{28}$$

4.1.7. Results and discussions

The results of optimal CSLP alternatives (pareto fronts) generated by both Basic-MOABC model and MOABC via Levy flights are presented in Fig. 8. Each point in a pareto line represents the values for the two objective functions of a pareto optimal layout alternative. For comparison and evaluation, the objective functions for the original site layout and a pareto front of MMAS [26] are calculated and shown in Fig. 8 as well. The alternatives generated by MOABC via Levy flights are significantly larger in number than those generated by the Basic-MOABC and MMAS [26]. The pareto front generated by the proposed algorithm is wider in range when it is compared with pareto fronts generated by the Basic-MOABC. For example, with MOABC via Levy flights the values of the first objective function range from 90,983 to 101,039. However, with the Basic-MOABC the values of the first objective function range from 97,203 to 98,194. Similarly, with MOABC via Levy flights, the values of the second objective function range from −709 to −604. However, with the Basic-MOABC, the values of the second objective function range from −612 to −594. The alternatives generated by MOABC via Levy flights are dominating those alternatives generated by the other considered algorithms i.e. they include solutions with better values of both objective functions. Three alternatives from the ninety seven alternatives of MOABC via Levy flights are numerically compared with the original layout in Table 3. Alternative L1, illustrated in Fig. 9, has a 12.5% reduction rate in handling cost, however the safety concern is 11.6% higher than that in the original site layout. Alternative L2, illustrated in Fig. 10, has a 6.2% reduction rate in handling cost at the same level of safety concern as that in the original site layout. Alternative L3 has a 2.8% reduction rate in handling cost and a 3.9% reduction rate in safety concern compared to that in the original site layout. Also shown in Table 3, the MMAS alternative reduces the handling cost by 11.4%, however the minimum safety concern is increased by 22.8%.

4.2. Private hospital construction project

A private hospital project that is located in the city of Riffa, Bahrain is considered as a second case study. The building is three stories high. Site offices and construction operational facilities are located within the construction site. Other temporary living facilities are located outside the construction site. The task of the proposed model is to find the corresponding locations for the temporary construction operational facilities in the construction site. The temporary facilities (fixed and non-fixed facilities) and their corresponding dimensions and service phase are shown in Table 4. Fig. 11 shows the site layout plan used in the original contractor's plan document. The main works carried out in each construction phase are foundation and underground works (Phase 1), superstructure (Phase 2), and finishing works and external works (Phase 3).

The control parameters were set as follows: artificial bee colony size (CS) = 50; maximum cycle number (MCN) = 1500; scout production period (SPP) = 0.1 ∗ D ∗ CS; and modification rate (MR) = 0.8.In this case study there are 6 non-fixed rectangular facilities, therefore the number of parameters (D) = 6 × 2 + 6 = 18.

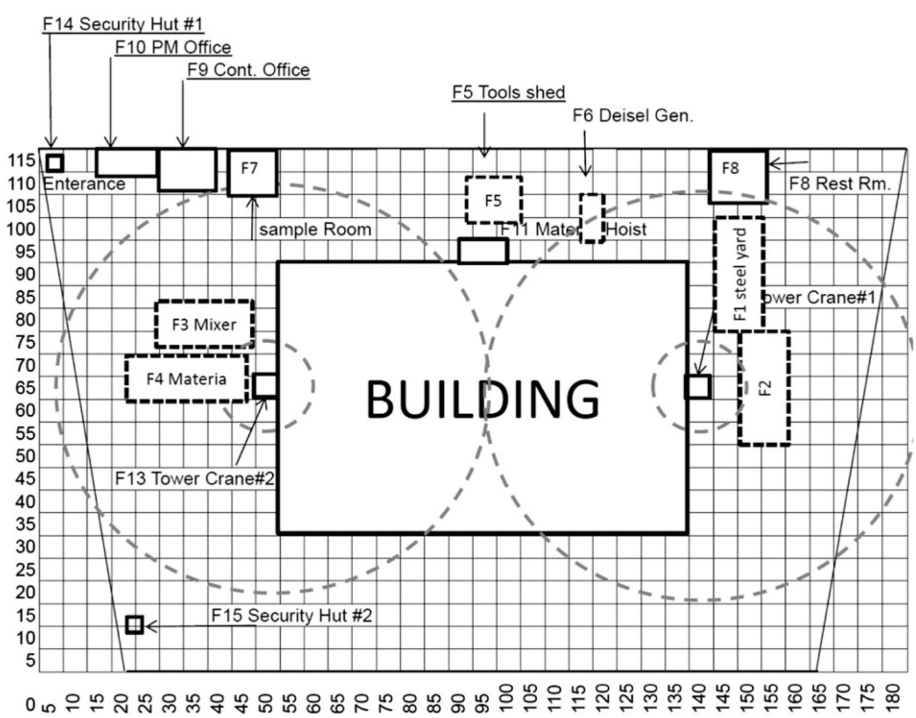

Fig. 13. Construction site layout alternative L1 for case study 2.

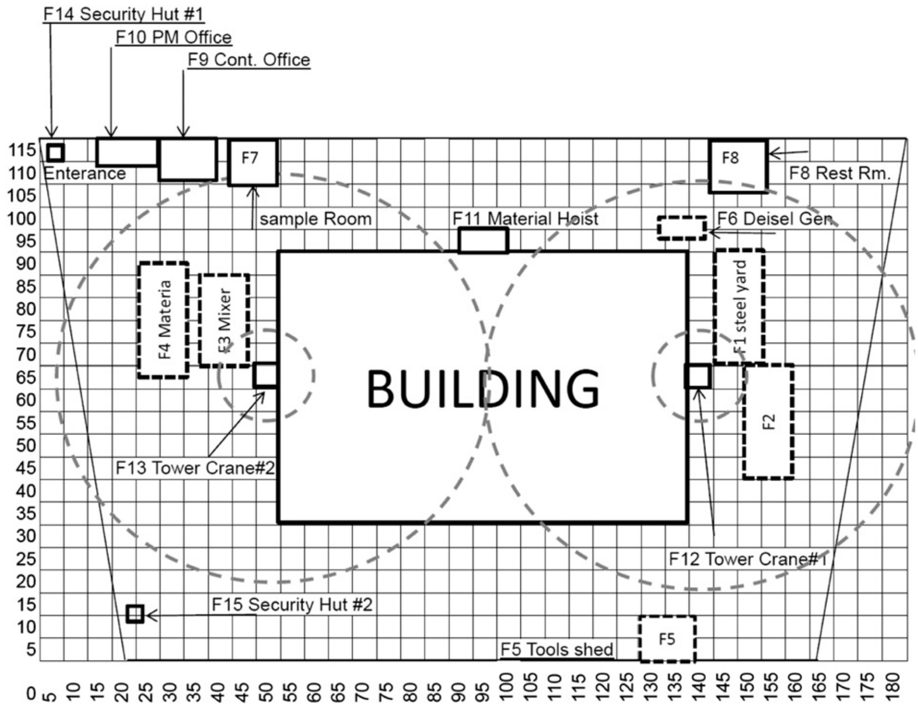

Fig. 14. Construction site layout alternative L2 for case study 2.

4.2.1. Decision variables

(x_i,y_i) represent the Cartesian coordinates of the centroid of facility i which are selected as design variables, where $i = 1,2,\ldots,15$. R_i is a binary digit representing the orientation of facility i, i.e. $R_i = 0$ if facility i is aligned vertically, and $R_i = 1$ if facility i aligned horizontally, where $i = 1,2,\ldots,15$.

4.2.2. Objective functions

Minimize the total handling cost of interaction flows between facilities (f_1) and minimize safety hazards/environmental concerns (f_2). The objective functions are mathematically defined as follows:

$$f_1 = Min\sum_{p=1}^{3}\sum_{i=1}^{15}\sum_{j=1}^{15} C_{ijp} r_{ij} P_{ijp} \tag{29}$$

$$f_2 = Min\sum_{p=1}^{3}\sum_{i=1}^{15}\sum_{j=1}^{15} \frac{-1}{SE_{ijp}} e_{ij} P_{ijp}. \tag{30}$$

4.2.3. Facility closeness relationship

Based on input from the project manager, the proximity weight matrices were developed. Table 5 presents proximity weights for layout cost for phase 1. Table 6 presents proximity weights for safety and environmental concerns for phase 1. The values for the proximity weights follow the six-value scale previously presented in Table 1. These matrices were then transformed into their quantitative equivalents before being input to the automated system.

The facilities' closeness relationships for the layout cost relationship C_{ijp} and the safety/environmental concerns SE_{ijp} in the three phases are recorded in Appendix B.

4.2.4. Overlapping constraints

$$\min\left\{0.5\left(b_i + b_j\right) + h_{ij} - \left|x_i - x_j\right|, 0.5\left(l_i + l_j\right) + v_{ij} - \left|y_i - y_j\right|\right\} \le 0 \tag{31}$$

for $i = 1,2,\ldots,15$ for temporary facilities and $i = 16$ for the building. Similarly $j = 1,2,\ldots,15$ for temporary facilities and $j = 16$ for the buildings. To maintain a minimum distance of 3 m between the building under construction and any temporary non-fixed facilities, h_{ij} and v_{ij} are set to 3 for any i or $j = 16$.

4.2.5. Site boundary constrains (BC)

$$BC(1) : 115 - 6.571\left(x_i - \frac{b_i}{2}\right) - \left(y_i - \frac{l_i}{2}\right) \le 0 \tag{32}$$

$$BC(2) : \left(-y_i + \frac{l_i}{2}\right) \le 0 \tag{33}$$

$$BC(3) : -1067.625 + 6.571\left(x_i + \frac{b_i}{2}\right) - \left(y_i - \frac{l_i}{2}\right) \le 0 \tag{34}$$

$$BC(6) : \left(y_i + \frac{l_i}{2}\right) - 115 \le 0 \tag{35}$$

(x_j,y_j) are positive real numbers; $i = 1,2,\ldots,6$.

4.2.6. Tower crane constraints

In the site there are two tower cranes (F12 and F13) which have a 45 meter reachable radius. Steel yards (F1) and carpentry workshop (F2) have to be positioned within the reachable radius of (F12), where the mixer machine yard (F3) and material laydown area (F4) have to be positioned within the reachable radius of (F13). Accordingly, the tower crane constraints are represented as follows.

For Tower crane no. 1 (F12):

$$\sqrt{(FCX_i - TX_1)^2 + (FCY_i - TY_1)^2} - 45 \le 0 \quad i = 1, 2. \tag{36}$$

For Tower crane no. 2 (F13):

$$\sqrt{(FCX_i - TX_2)^2 + (FCY_i - TY_2)^2} - 45 \le 0 \quad i = 3, 4. \tag{37}$$

4.2.7. Results and discussions

The results of optimal CSLP alternatives (pareto fronts) generated by MOABC via Levy flights are presented in Fig. 12. Each point in a pareto

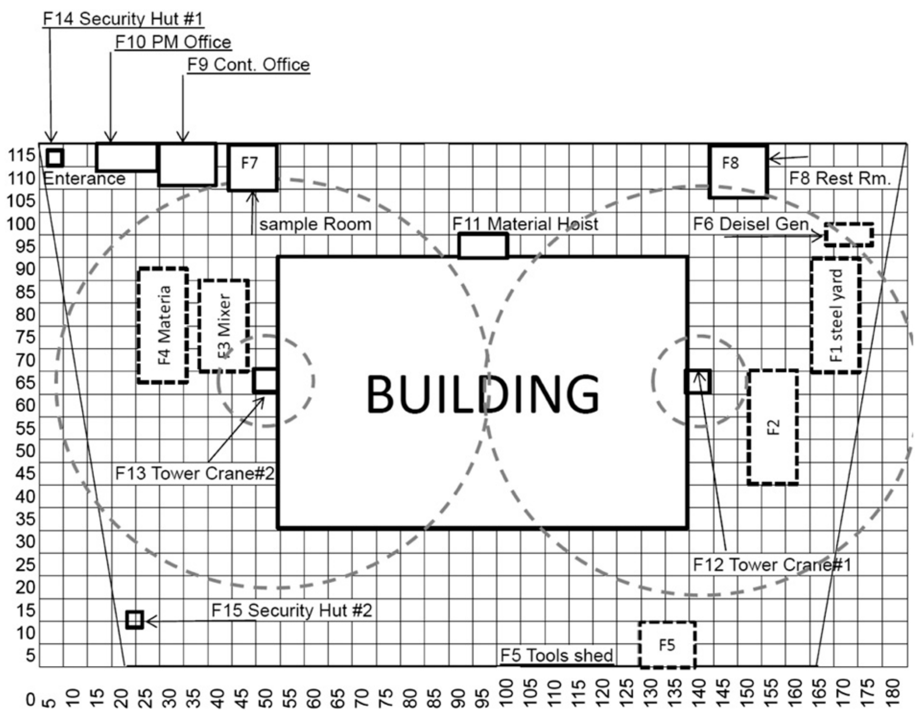

Fig. 15. Construction site layout alternative L3 for case study 2.

line represents the values for the two objective functions of a pareto optimal layout alternative. For comparison and evaluation, the objective functions for the original site layout are calculated and shown in the same figure as well. The alternatives generated by MOABC via Levy flights are large in number, wide in range, and dominate the original layout. Three alternatives from the 46 alternatives of MOABC via Levy flights are numerically compared with the original layout in Tables 7 and 8. Alternative L1, illustrated in Fig. 13, has a 15.5% reduction rate in handling cost, and the safety concern is slightly increased by just 0.1% higher than that in the original site layout. Alternative L2, illustrated in Fig. 14, has a 10.0% reduction rate in handling cost and a 19.1% reduction rate in safety concern compared to that of the original site layout. Alternative L3, illustrated in Fig. 15, has a 2.8% reduction rate in handling cost and a 21.4% reduction rate in safety concern compared to that of the original site layout.

5. Conclusions

In this article, a multi objective decision making model for dynamic construction site layout planning problem is proposed which makes use of novel MOABC via Levy flights algorithm. The performance of the proposed CSLP model based on multi objective artificial bee colony via Levy flights (MOABC via Levy flights) is compared with Basic-MOABC model, max–min Ant system (MMAS) model, and the original construction site layout of the studied problem. Results show that MOABC via Levy flights performs better than the mentioned algorithms. Using Levy flight by employed bees has improved the efficiency of MOABC algorithm as it contains balanced combination of a local random search of onlooker bees and the global explorative random search of employed bees. The main contributions of this paper are as follows: firstly, alternatives generated by the proposed CSLP model are more practical due to its feature of measuring traveling distances in a manner that represents the actual situation more realistically. Secondly, the proposed algorithm allows vertical and horizontal alignment of temporary facilities. Thirdly, it considers the CSLP problem as a continuous search problem rather than a simplified assignment problem. Finally, it gives the option to maintain minimum distances between the facilities and between facilities and buildings. The proposed model was successfully applied to practical case studies and proved to be robust and efficient.

Appendix A

Table A1
The facility relationship weights representing total handling cost in phase 1.

	F2	F3	F4	F5	F6	F7	F8	F9	F10	F15	F16	F17
F2	0	7.23	7.07	9	9.52	22.96	11.45	7.88	6.73	11.92	17.02	17.02
F3	7.23	0	13.05	9.99	13.15	10.57	10.57	10.98	10.98	13.59	15.91	15.91
F4	7.07	13.05	0	10.98	11.92	9.16	12.77	17.78	17.78	12.41	11.37	11.37
F5	9	9.99	10.98	0	9.66	20.86	20.86	12.77	16.55	11.92	12.41	12.41
F6	9.52	13.15	11.92	9.66	0	20.86	20.86	13.15	12.41	11.37	9.66	9.66
F7	22.96	10.57	9.16	20.86	20.86	0	6.39	13.59	11.37	8.01	13.15	13.15
F8	11.45	10.57	12.77	20.86	20.86	6.39	0	13.59	15.91	9.99	13.15	13.15
F9	7.88	10.98	17.78	12.77	13.15	13.59	13.59	0	13.59	10.54	11	11
F10	6.73	10.98	17.78	16.55	12.41	11.37	15.91	13.59	0	15.92	16.26	16.26
F15	11.92	13.59	12.41	11.92	11.37	8.01	9.99	10.54	15.92	0	18.59	18.59
F16	17.02	15.91	11.37	12.41	9.66	13.15	13.15	11	16.26	18.59	0	14.59
F17	17.02	15.91	11.37	12.41	9.66	13.15	13.15	11	16.26	18.59	14.59	0

Table A2
The facility relationship weights representing safety concerns in phase 1.

	F2	F3	F4	F5	F6	F7	F8	F9	F10	F15	F16	F17
F2	0	4.95	4.95	6.75	14.85	24.3	13.5	5.85	2.1	16.2	20.25	20.25
F3	4.95	0	17.55	2.1	16.2	8.1	8.1	6.3	6.3	5.4	14.85	14.85
F4	4.95	17.55	0	18.9	16.2	1.8	14.85	7.65	7.65	16.2	14.85	14.85
F5	6.75	2.1	18.9	0	18.9	1.65	1.65	14.85	2.1	16.2	16.2	16.2
F6	14.85	16.2	16.2	18.9	0	1.65	1.65	16.2	16.2	14.85	18.9	18.9
F7	24.3	8.1	1.8	1.65	1.65	0	8.1	16.2	14.85	6.3	5.4	5.4
F8	13.5	8.1	14.85	1.65	1.65	8.1	0	16.2	14.85	2.1	5.4	5.4
F9	5.85	6.3	7.65	14.85	16.2	16.2	16.2	0	16.2	6.75	7.65	7.65
F10	2.1	6.3	7.65	2.1	16.2	14.85	14.85	16.2	0	16.2	16.2	16.2
F15	16.2	5.4	16.2	16.2	14.85	6.3	2.1	6.75	16.2	0	7.65	7.65
F16	20.25	14.85	14.85	16.2	18.9	5.4	5.4	7.65	16.2	7.65	0	5.85
F17	20.25	14.85	14.85	16.2	18.9	5.4	5.4	7.65	16.2	7.65	5.85	0

Table A3
The facility relationship weights representing total handling cost in phase 2.

	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17
F2	0	15.47	18.2	16.11	10.38	22.4	15.47	18.49	15.29	26.54	13.34	15	15.26	13.41	13.15	13.15
F3	15.47	0	14.58	21	14.02	10.57	10.57	20.6	21	21.13	18.54	17.77	23.17	9.67	10.63	10.63
F4	18.2	14.58	0	13.41	11.92	10.6	11	17.78	17.78	10.55	10.55	10.55	10.55	8.2	11.92	11.92
F5	16.11	21	13.41	0	12.47	20.86	20.86	12.11	13.15	13.79	15.33	15.26	15.94	12.85	10.26	10.26
F6	10.38	14.02	11.92	12.47	0	16.93	16.93	8.2	11.92	13.09	9.67	10.63	8.2	21	12.62	12.62
F7	22.4	10.57	10.6	20.86	16.93	0	6.39	21.18	21.18	21.18	21.18	21.18	21.18	13.41	13.15	13.15
F8	15.47	10.57	11	20.86	16.93	6.39	0	21.18	21.18	21.18	21.18	21.18	21.18	11	14.02	14.02
F9	18.49	20.6	17.78	12.11	8.2	21.18	21.18	0	21	21	21	21	21	13.41	13.15	13.15
F10	15.29	21	17.78	13.15	11.92	21.18	21.18	21	0	21	21	21	21	15.92	17.17	17.17
F11	26.54	21.13	10.55	13.79	13.09	21.18	21.18	21	21	0	21	21	21	13.15	17.53	17.53
F12	13.34	18.54	10.55	15.33	9.67	21.18	21.18	21	21	21	0	21	21	13.41	10.38	10.38
F13	15	17.77	10.55	15.26	10.63	21.18	21.18	21	21	21	21	0	21	11.17	14.02	14.02
F14	15.26	23.17	10.55	15.94	8.2	21.18	21.18	21	21	21	21	21	0	12.04	10.38	10.38
F15	13.41	9.67	8.2	12.85	21	13.41	11	13.41	15.92	13.15	13.41	11.17	12.04	0	18.59	18.59
F16	13.15	10.63	11.92	10.26	12.62	13.15	14.02	13.15	17.17	17.53	10.38	14.02	10.38	18.59	0	14.38
F17	13.15	10.63	11.92	10.26	12.62	13.15	14.02	13.15	17.17	17.53	10.38	14.02	10.38	18.59	14.38	0

Table A4
The facility relationship weights representing safety concerns in phase 2.

	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17
F2	0	21.6	7.65	4.95	5.4	8.55	21.6	22.95	14.85	5.4	9	7.2	7.65	14.85	16.2	16.2
F3	21.6	0	25.65	7.2	22.95	8.1	8.1	8.55	7.2	7.65	4.95	1.8	9	21.6	22.95	22.95
F4	7.65	25.65	0	14.85	16.2	8.55	21.6	7.65	7.65	5.85	5.85	5.85	5.85	14.85	16.2	16.2
F5	4.95	7.2	14.85	0	27	1.65	1.65	1.65	1.8	8.55	7.2	7.65	4.95	16.2	25.65	25.65
F6	5.4	22.95	16.2	27	0	1.65	1.65	14.85	16.2	25.65	21.6	22.95	14.85	81	25.65	25.65
F7	8.55	8.1	8.55	1.65	1.65	0	8.1	7.65	7.65	7.65	7.65	7.65	7.65	14.85	5.4	5.4
F8	21.6	8.1	21.6	1.65	1.65	8.1	0	7.65	7.65	7.65	7.65	7.65	7.65	7.2	22.95	22.95
F9	22.95	8.55	7.65	1.65	14.85	7.65	7.65	0	81	81	81	81	81	14.85	5.4	5.4
F10	14.85	7.2	7.65	1.8	16.2	7.65	7.65	81	0	81	81	81	81	16.2	27	27
F11	5.4	7.65	5.85	8.55	25.65	7.65	7.65	81	81	0	81	81	81	5.4	25.65	25.65
F12	9	4.95	5.85	7.2	21.6	7.65	7.65	81	81	81	0	81	81	14.85	5.4	5.4
F13	7.2	1.8	5.85	7.65	22.95	7.65	7.65	81	81	81	81	0	81	21.6	22.95	22.95
F14	7.65	9	5.85	4.95	14.85	7.65	7.65	81	81	81	81	81	0	4.95	1.8	1.8
F15	14.85	21.6	14.85	16.2	81	14.85	7.2	14.85	16.2	5.4	14.85	21.6	4.95	0	7.65	7.65
F16	16.2	22.95	16.2	25.65	25.65	5.4	22.95	5.4	27	25.65	5.4	22.95	1.8	7.65	0	6.3
F17	16.2	22.95	16.2	25.65	25.65	5.4	22.95	5.4	27	25.65	5.4	22.95	1.8	7.65	6.3	0

Table A5
The facility relationship weights representing total handling cost in phase 3.

	F1	F2	F3	F4	F6	F7	F8	F11	F12	F13	F14	F15	F16	F17
F1	0	8.54	17.16	10.05	17.16	17.16	17.16	14.1	17.53	17	17.9	14.1	14.1	14.1
F2	8.54	0	15.31	15.78	24.7	17.16	17.16	13.32	14.87	15	15	14.1	18.48	18.48
F3	17.16	15.31	0	9.52	17.16	10.57	10.57	8.23	10	18	18	13.67	5.9	5.9
F4	10.05	15.78	9.52	0	11.92	17.16	17.16	10.55	10.55	10.55	10.55	13.67	5.94	5.94
F6	17.16	24.7	17.16	11.92	0	20.86	20.86	17.16	17.16	17.16	17.16	17.16	17.16	17.16
F7	17.16	17.16	10.57	17.16	20.86	0	6.39	21.18	21.18	21.18	21.18	17.16	17.16	17.16
F8	17.16	17.16	10.57	17.16	20.86	6.39	0	21.18	21.18	21.18	21.18	14.23	14.41	14.41
F11	14.1	13.32	8.23	10.55	17.16	21.18	21.18	0	21	21	21	14.23	17.4	17.4
F12	17.53	14.87	10	10.55	17.16	21.18	21.18	21	0	21	21	14.23	17.4	17.4
F13	17	15	18	10.55	17.16	21.18	21.18	21	21	0	21	14.23	17.4	17.4
F14	17.9	15	18	10.55	17.16	21.18	21.18	21	21	21	0	14.23	17.4	17.4
F15	14.1	14.1	13.67	13.67	17.16	17.16	14.23	14.23	14.23	14.23	14.23	0	18.59	18.59
F16	14.1	18.48	5.9	5.94	17.16	17.16	14.41	17.4	17.4	17.4	17.4	18.59	0	18.32
F17	14.1	18.48	5.9	5.94	17.16	17.16	14.41	17.4	17.4	17.4	17.4	18.59	18.32	0

Table A6
The facility relationship weights representing safety concerns in phase 3.

	F1	F2	F3	F4	F6	F7	F8	F11	F12	F13	F14	F15	F16	F17
F1	0	2.1	22.95	6.75	22.95	22.95	22.95	7.65	6.75	5.4	6.3	7.65	7.65	7.65
F2	2.1	0	22.95	2.4	24.3	22.95	22.95	4.95	2.1	22.95	22.95	22.95	20.25	20.25
F3	22.95	22.95	0	16.2	22.95	8.1	8.1	6.3	22.95	22.95	22.95	6.75	5.85	5.85
F4	6.75	2.4	16.2	0	16.2	22.95	22.95	5.85	5.85	5.85	5.85	6.75	5.85	5.85
F6	22.95	24.3	22.95	16.2	0	1.65	1.65	22.95	22.95	22.95	22.95	22.95	22.95	22.95
F7	22.95	22.95	8.1	22.95	1.65	0	8.1	7.65	7.65	7.65	7.65	22.95	22.95	22.95
F8	22.95	22.95	8.1	22.95	1.65	8.1	0	7.65	7.65	7.65	7.65	16.2	18.9	18.9
F11	7.65	4.95	6.3	5.85	22.95	7.65	7.65	0	81	81	81	16.2	44.55	44.55
F12	6.75	2.1	22.95	5.85	22.95	7.65	7.65	81	0	81	81	16.2	44.55	44.55
F13	5.4	22.95	22.95	5.85	22.95	7.65	7.65	81	81	0	81	16.2	44.55	44.55
F14	6.3	22.95	22.95	5.85	22.95	7.65	7.65	81	81	81	0	16.2	44.55	44.55
F15	7.65	22.95	6.75	6.75	22.95	22.95	16.2	16.2	16.2	16.2	16.2	0	7.65	7.65
F16	7.65	20.25	5.85	5.85	22.95	22.95	18.9	44.55	44.55	44.55	44.55	7.65	0	6.3
F17	7.65	20.25	5.85	5.85	22.95	22.95	18.9	44.55	44.55	44.55	44.55	7.65	6.3	0

Appendix B

Table B1
The facility relationship weights representing total handling cost in phase 1.

	F1	F2	F3	F4	F5	F6	F8	F9	F10	F12	F13	F14	F15
F1	0	81	1	1	9	27	9	3	1	81	0	9	9
F2	81	0	0	1	9	9	9	3	1	81	0	9	9
F3	1	0	0	81	3	9	3	3	1	0	81	9	9
F4	1	1	81	0	3	1	1	3	1	0	81	27	27
F5	9	9	3	3	0	1	1	1	1	3	3	1	1
F6	27	9	9	1	1	0	3	3	3	27	27	1	1
F8	9	9	3	1	1	3	0	1	1	1	1	1	1
F9	3	3	3	3	1	3	1	0	81	0	0	3	3
F10	1	1	1	1	1	3	1	81	0	0	0	3	3
F12	81	81	0	0	3	27	1	0	0	0	9	1	1
F13	0	0	81	81	3	27	1	0	0	9	0	1	1
F14	9	9	9	27	1	1	1	3	3	1	1	0	3
F15	9	9	9	27	1	1	1	3	3	1	1	3	0

Table B2
The facility relationship weights representing safety concerns in phase 1.

	F1	F2	F3	F4	F5	F6	F8	F9	F10	F12	F13	F14	F15
F1	0	9	9	9	9	81	81	81	81	3	3	27	27
F2	9	0	3	9	9	81	81	81	81	3	3	27	27
F3	9	3	0	3	3	9	27	81	81	3	3	9	9
F4	9	9	3	0	3	81	27	81	81	27	27	81	81
F5	9	9	3	3	0	9	9	9	9	1	1	3	3
F6	81	81	9	81	9	0	81	81	81	9	9	81	81
F8	81	81	27	27	9	81	0	1	1	9	9	81	81
F9	81	81	81	81	9	81	1	0	1	9	9	27	27
F10	81	81	81	81	9	81	1	1	0	9	9	27	27
F12	3	3	3	27	1	9	9	9	9	0	81	27	27
F13	3	3	3	27	1	9	9	9	9	81	0	27	27
F14	27	27	9	81	3	81	81	27	27	27	27	0	27
F15	27	27	9	81	3	81	81	27	27	27	27	27	0

Table B3
The facility relationship weights representing total handling cost in phase 2.

	F1	F2	F3	F4	F5	F6	F8	F9	F10	F11	F12	F13	F14	F15
F1	0	81	1	3	27	27	9	3	1	1	81	0	9	9
F2	81	0	0	3	9	9	9	3	1	3	81	0	9	9
F3	1	0	0	81	3	9	3	3	1	9	0	81	9	9
F4	3	3	81	0	3	1	1	3	1	27	0	81	27	27
F5	27	9	3	3	0	1	1	1	1	9	3	3	1	1
F6	27	9	9	1	1	0	3	3	3	27	27	27	1	1
F8	9	9	3	1	1	3	0	1	1	27	1	1	1	1
F9	3	3	3	3	1	3	1	0	81	3	0	0	3	3
F10	1	1	1	1	1	3	1	81	0	3	0	0	3	3
F11	1	3	9	27	9	27	27	3	3	0	9	9	1	1
F12	81	81	0	0	3	27	1	0	0	9	0	9	1	1
F13	0	0	81	81	3	27	1	0	0	9	9	0	1	1
F14	9	9	9	27	1	1	1	3	3	1	1	1	0	3
F15	9	9	9	27	1	1	1	3	3	1	1	1	3	0

Table B4
The facility relationship weights representing safety concerns in phase 2.

	F1	F2	F3	F4	F5	F6	F8	F9	F10	F11	F12	F13	F14	F15
F1	0	9	9	9	9	81	81	81	81	9	3	3	27	27
F2	9	0	3	9	9	81	81	81	81	9	3	3	27	27
F3	9	3	0	3	3	9	27	81	81	9	3	3	9	9
F4	9	9	3	0	3	81	27	81	81	9	27	27	81	81
F5	9	9	3	3	0	9	9	9	9	9	1	1	3	3
F6	81	81	9	81	9	0	81	81	81	9	9	9	81	81
F8	81	81	27	27	9	81	0	1	1	27	9	9	81	81
F9	81	81	81	81	9	81	1	0	1	81	9	9	27	27
F10	81	81	81	81	9	81	1	1	0	81	9	9	27	27
F11	9	9	9	9	9	9	27	81	81	0	27	27	27	27
F12	3	3	3	27	1	9	9	9	9	27	0	81	27	27
F13	3	3	3	27	1	9	9	9	9	27	81	0	27	27
F14	27	27	9	81	3	81	81	27	27	27	27	27	0	27
F15	27	27	9	81	3	81	81	27	27	27	27	27	27	0

Table B5
The facility relationship weights representing total handling cost in phase 3.

	F2	F4	F5	F6	F7	F8	F9	F10	F11	F14	F15
F2	0	1	3	3	1	9	1	1	9	9	9
F4	1	0	1	1	9	3	3	1	81	27	27
F5	3	1	0	1	3	1	1	1	27	1	1
F6	3	1	1	0	3	3	3	3	27	1	1
F7	1	9	3	3	0	1	81	81	3	81	3
F8	9	3	1	3	1	0	1	1	27	1	1
F9	1	3	1	3	81	1	0	81	9	3	3
F10	1	1	1	3	81	1	81	0	9	3	3
F11	9	81	27	27	3	27	9	9	0	9	9
F14	9	27	1	1	81	1	3	3	9	0	3
F15	9	27	1	1	3	1	3	3	9	3	0

Table B6
The facility relationship weights representing safety concerns in phase 3.

	F2	F4	F5	F6	F7	F8	F9	F10	F11	F14	F15
F2	0	9	27	81	1	81	81	81	9	27	27
F4	9	0	1	81	3	9	81	81	9	81	81
F5	27	1	0	9	1	9	9	9	9	3	3
F6	81	81	9	0	9	81	81	81	9	81	81
F7	1	3	1	9	0	1	1	1	1	1	1
F8	81	9	9	81	1	0	1	1	1	81	81
F9	81	81	9	81	1	1	0	1	9	1	1
F10	81	81	9	81	1	1	1	0	9	1	1
F11	9	9	9	9	1	1	9	9	0	9	9
F14	27	81	3	81	1	81	1	1	9	0	27
F15	27	81	3	81	1	81	1	1	9	27	0

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