Automation in Construction 89 (2018) 1–12

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

A tri-objective ant colony optimization based model for planning safe construction site layout

Xin Ning[a], Jingyan Qi[a], Chunlin Wu[b,c,*], Wenjuan Wang[d]

[a] School of Investment and Construction Management, Dongbei University of Finance and Economics, Dalian, Liaoning Province, China
[b] School of Economics and Management, Beihang University, Haidian District, Beijing, China
[c] Beijing Key Laboratory of Emergency Support Simulation Technologies for City Operations, Beihang University, Haidian District, Beijing, China
[d] School of Management Science and Engineering, Dongbei University of Finance and Economics, Dalian, Liaoning Province, China

ARTICLE INFO

Keywords:
Construction site layout planning
Ant colony optimization algorithm
Optimization model
Interaction relationship
Safety management

ABSTRACT

Realizing safety improvements in construction site layout planning (CSLP) is vitally important to construction project safety management. Unlike previous studies in which the safety objective is built without detailed risk factors analysis, this study transforms CSLP into a multi-objective optimization (MOO) problem with designing two safety objective functions due to facility safety relationships (potential risks arising from interaction flows) and geographic safety relationship (potential risks arising from hazardous sources) from the holistic interpretation of interaction relationship connecting temporary facilities. Besides, a supplementary cost reduction objective function was also derived as cost is a critical barrier against safety improvement. Subsequently, a tri-objective ant colony optimization based model was developed to solve MOO problem. Finally, a case study is used to verify the proposed model. The study enriches safety implications by considering onsite safety issues from interaction relationship and enhances site safety of CSLP in the pre-construction stage.

1. Introduction

Construction site layout planning (CSLP) is a critical activity that should, ideally, be given full consideration to early in the pre-construction stage of construction projects. Various researchers have discussed the significance of "design for safety" and argued that most accidents or serious risks can be avoided by incorporating more safety considerations into planning schemes [1–4]. It is significantly beneficial and vital to improve construction site safety through better site layout in safety planning, and thus the considerable attention paid to safety planning in the pre-construction stage is critical to improving project safety performance efficiently [5].

CSLP is commonly treated as an optimization problem, and site safety can be realized by designing different objective functions based on safety requirements or considerations (hereafter called "safety objective function"), such as minimizing accidents by optimizing safe locations for tower cranes [6–8], controlling hazardous materials onsite [9, 10], reducing intersections between heavily traveled routes [11], defining the safety zones in term of necessary regulations [12], and reducing the noise pollution onsite [13, 14]. With a specific safety objective function, the generated site layout plan can only fulfil the partial safety requirement mentioned above. In previous researches, limited attention has been paid to designing safety objective functions with full risk factor evaluation involved in the function design. Developing safe construction site layout plans under the partial safety objective function without adequate and further risk factors analysis will result in layout with more risk tendency. Thus, this study was conducted with the objective of designing safety objective functions with full consideration of onsite safety after holistic risk factors analysis associated with site layout.

To find an optimal site layout with defined safety objective functions, CSLP tends to be modeled as a quadratic assignment problem [15, 16]. This problem is commonly solved by genetic algorithm [17–23], ant colony optimization (ACO) algorithm [24–26], artificial bee colony optimization [27], particle swarm optimization (PSO) algorithm [28, 29], harmony search algorithm [30], cutting plane algorithm [31], and simulated annealing algorithm [32]. Among these algorithms, multi-objective optimization with two conflicting or congruent objective functions is solved by determining the dominant relationship between solutions [33, 34] or constructing a weighted sum of all objectives [35–37]. As regards algorithms relying on finding dominance relations between solutions, Yahya and Saka [27] applied enhanced artificial bee algorithm with levy flights to generate site layout plans fulfiling the requirements of safety and cost simultaneously. Xu and Li [38]

* Corresponding author at: School of Economics and Management, Beihang University, Haidian District, Beijing, China.
E-mail address: wuchunlin@buaa.edu.cn (C. Wu).

https://doi.org/10.1016/j.autcon.2018.01.007
Received 16 October 2017; Received in revised form 22 December 2017; Accepted 11 January 2018

developed a multi-objective PSO algorithm to solve the dynamic construction site layout problem considering the total cost of site layout planning, and the possibility of safety and environmental accidents. Ning and Lam [39] proposed a Pareto-based ACO algorithm to find cost and safety tradeoff solutions for an unequal-area site layout problem. As regards the weighted sum method in multi-objective optimization, Singh and Singh [16] developed an improved heuristic approach that employs the weighted sum method to combine multiple objectives (workflow, closeness rating, material handling time, and hazardous movement) into a single objective to generate alternative layouts. Ning et al. [36] used the max-min ant system to handle site layout problems by summarizing the objective functions of safety and cost. The well-known drawback of the latter method is the predetermined weighting coefficients of each objective, as the weighting coefficients do not necessarily correspond directly to the relative importance of the objectives or allow tradeoffs between the objectives to be expressed [40]. The significant advantages of Pareto optimization compared with the weighted sum method are its provision of site managers with several reference solutions and its reflecting of their preference [38]. Therefore, the preferred optimization principle of Pareto optimization theory [34], determining the dominance relation between solutions, is adopted in this paper.

In order to ameliorate the discrepancies discussed above, i.e., the significant limitation of current safety objective functions and deficiency of the weighted sum method in solving multi-objective optimization problems, a tri-objective ACO-based safety model was developed in this study to help construction site planners determine safe site layout plans with more detailed risk factors analysis in the pre-construction stage. More specifically, the layout plans in this study will be significantly enhanced arrangements of the temporary facilities on the construction site considering more safety factors. Finally, the proposed model is applied in the case study to verify its applicability and effectiveness. The findings from the case study is aimed to give constructive suggestions on designing a safe construction site layout plan in a more scientific and reasonable manner.

2. Safety considerations in previous CSLP

In 1997, Anumba and Bishop [41] stated the importance of safety consideration in construction site layout as follows: "… in many cases, site and project managers tend to focus on considerations such as optimizing productivity without adequately taking into account the health and safety implications. This is despite the fact that there is major scope for preventing, or minimizing, the effects of many construction site accidents through appropriate site layout design and organization".

CSLP is a multi-objective decision-making problem, in which optimal site layouts or the best site layout are generated by different algorithms and technologies. During the optimization process, site layout plans are improved continuously considering conflicting or congruent objective functions with the constraints of site condition and resources. In order to design a safety site layout plan, some safety considerations can be realized in the objective functions or by assigning facilities in the preset safety zone.

Ning and Lam [39] designed a safety objective function that minimizes the representative score of safety/environment concerns, which may arise when the two facilities are close to each other, and may affect site workers by increasing the likelihood of accidents, noise, uncomfortable temperature, and pollution. El-Rayes and Khalafallah [11] targeted the safety issue from falling accidents caused by tower cranes, dangerous or hazardous materials, and intersections between heavily travel routes. Abune'meh et al. [9] derived a safe site layout by minimizing the summarization of hazard levels received from hazardous sources such as fires, explosions, thermal flux, and blast waves. In addition to objective functions pertaining to safety issues in optimizing construction site layouts, some safety site spaces or safe distances have also been used as additional site constraints to improve site safety performance and efficiency [42, 43]. A safety zone is an unoccupied and available additional space that is used to accommodate temporary facilities defined by specific rules, regulations, and standards, i.e., the facility space is equal to the sum of the actual dimensions of the facility and the relevant safety zone. In this study, available safe spaces are identified during the assignment of facilities to avoid accidents occurring around potential hazardous sources [12, 44]. To reduce the probability of exposing facilities to potential danger, the safety distance between pairs of facilities is also determined [45, 46].

In previous studies, both the safety objective functions and site space constraints described and recognized the danger to temporary facilities arising from being around hazardous sources. The optimal site layout assigns temporary facilities far away or maintains a necessary distance from the hazardous sources/facilities, such as tower cranes, material hoists, and fuel storage areas. This kind of potential risk coming from being around hazardous sources is related to location. If the location is fixed, regardless of the kind of facilities assigned to the location, their risk arising from the surrounding hazardous sources is constant. In other words, the potential risks considered in previous site layout safety optimization problems were merely dependent on the facilities' positioning. According to El-Rayes and Khalafallah [11], frequent movement of resources (materials, personnel, and equipment) leads to more conflicts or collisions between resources, which can potentially trigger accidents. The transportation of resources between facilities is not related to the facilities' positioning but is highly related to the resources' transportation determined by job demand between the facilities. In order to design a construction site layout with comprehensive risk factors analysis, the movement of resources between the facilities should be considered. In the following section, objective functions are built based on further discussion of risk factor analysis.

3. Optimization objective functions

Reasonable temporary facilities' assignment within a construction site is significantly influenced by the interaction relationship and the distance between the facilities with fulfilment of pre-defined objective functions. As discussed in the previous section, there is insufficient risk factor analysis conducted considering the interaction relationship between the facilities when developing a safety CSLP. It is vital to make good facilities displacement in the construction site for high safety performance in terms of their mutual safety impact on each other. Thus, with interaction relationship analysis to find more risk factor, the tri-objective functions for safety improvements and cost reduction are established.

3.1. Interaction relationship analysis

In a construction site, the facilities participated have interaction relationship with each other. Assume that there are m site facilities that need to be assigned to n free locations ($n \geq m$), a network consisting of facilities and the interaction relationship between them can be depicted as shown in Fig. 1.

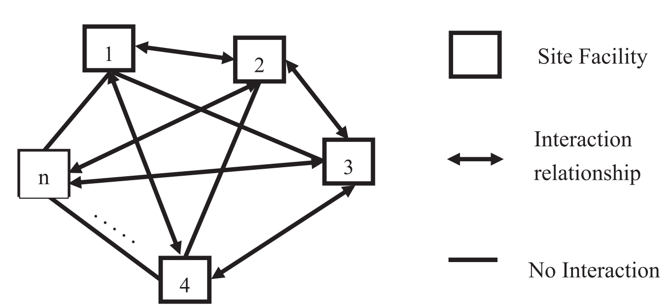

Fig. 1. A network of site facilities.

In Fig. 1, when the facilities are assigned to locations, the distance between them can be derived. For facilities with high potential risk, the surrounding facilities should be assigned further away from them, i.e., the distance to hazardous sources/facilities should be maximized. The potential risk arising from some facilities can be viewed as an interaction relationship, which is related to the safety. In order to establish safety objective functions, the interaction relationship in safety (hereafter called "safety relationship") is analyzed.

Site facilities consist of fixed facilities and mobile facilities. Heavy equipment, e.g., tower cranes are fixed facilities, as the installation fee is high and the location of a tower crane is tightly bound to material magnitude, lifting capability, working range and service-height limitations. The location of a tower crane on a construction site is always frozen and cannot be easily relocated. Material hoists are also fixed on a construction site. In their study of construction site layout involving single facility location problems, Moradi and Bidkhori [47] handled the location problem but not the overall facilities layout problem. Determining the location for haul roads or for heavy-duty equipment such as a tower crane can be considered a single facility location problem [7, 48–51]; thus, a haul road is also a fixed facility in a broad sense. These fixed facilities are always hazardous sources and have a safety interaction relationship with other facilities.

Temporary facilities can produce noise, dust, and hazardous material and can therefore also be hazardous sources. Noise not only causes hearing loss, but also causes high blood pressure, heart disease, and other diseases. In particular, noise can distract people's attention, which is the root cause of various kinds of security incidents [52]. Hazardous materials are often utilized and located on construction sites, exposing construction workers and engineers to safety risks [53, 54]. The dust between stacking facilities and other facilities is harmful to staff and is therefore a potential hazard [55, 56]. For the fixed facilities or dangerous facilities, the potential risk arising from them is only determined by the facilities' occupied location if their positions are frozen in the construction site. In this paper, the dangers arising from heavy-duty equipment, haul road, foundation ditch etc., and temporary facilities producing noise, dust, and hazardous material are dependent on the associated location occupied by the facilities. The potential risk from the hazardous sources varies with the location of the facility and the risk is not related to the categories of the location, called the geographic safety relationship. When different categories of facilities are placed in the same location, the geographic safety relationship is equal.

Further, in the interaction relationships, the interaction flows (resource movement) consisting of quantitative flows of material, personnel, and equipment, are also potential risk factors influencing the safety between the facilities. In Fig. 1, if there are high levels of interaction flows between the facilities, the frequent resource movements on the construction site will increase conflicts or collisions between material, personnel, and equipment. They are the root causes of accidents on the construction site. Conflicts or collisions between materials, personnel, and equipment are dependent on the transportation of resources between the facilities, which is determined by the requirements of construction operations and job demands. In previous studies, the interaction flows between specific pairs of facilities was viewed as constant at specific construction stages. The interaction flows have a negative impact on construction safety. In this paper, the potential risk from interaction flows between the facilities is called the facility safety relationship.

For temporary facilities, dangers arise from two aspects, i.e., 1) geographic safety relationship, and 2) facility safety relationship. The first risk factor is related to the facilities' locations. The potential risks from specific hazardous sources are consistent in fixed locations, and these sources can be placed in different facilities. Regardless of the kind of facilities assigned to a specific location, their geographic safety relationships from the same hazardous sources are equal in terms of safety level. The second risk factor concerns the interaction flows between the facilities, which is determined by construction activities and vary between the diverse facilities. Facility safety relationship is increased with higher job demand between facilities. The safety site layout plan should consider these two safety relationships.

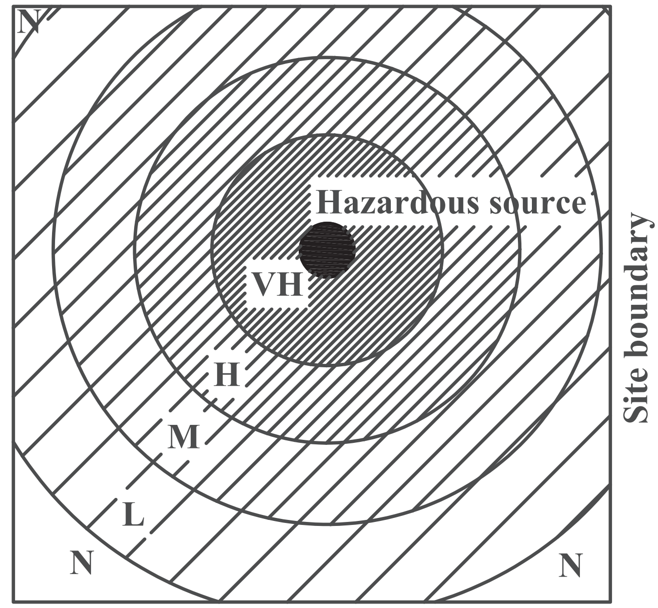

Fig. 2. The risk degrees in dangerous zones of dangerous sources.

3.2. Objective function related to geographic safety relationship

The risk that is influenced by the distance from the danger sources, such as tower cranes, material hoists, road traffic, foundation ditches and hazardous facilities producing noise, dust, and hazardous material, is called the geographic safety relationship. It is reduced when the facilities' locations are far from the hazardous sources. In this paper, the risk degree is used to evaluate the geographic safety relationship arising from hazardous sources. A linear relationship exists between the risk degree and the distance from danger sources such as material hoists, road traffic, foundation ditch, and dangerous facilities [9]. As a linear relationship exists, the risk degree stems from no (N), low (L), medium (M), high (H), or very high (VH) hazard according to the distance from the hazardous sources, as shown in Fig. 2. Risk from noise, dust, and dangerous material may arise when two facilities are close to each other, and may affect site workers by increasing the likelihood of accidents, which can also be evaluated from N, L, M, H, and VH.

According to El-Rayes and Khalafallah [11], a tower crane operation zone can be divided into zone of most danger, caused by falling materials (zone 1), zone of less danger, caused by crane collapse (zone 2), and zone of rare danger (zone 3). In zone 1, there is very high risk of the workforce being exposed to falling objects throughout the workday; the consequence of accidents occurring and the probability are higher than in zones 2 and 3. Thus, the risk degree in zone 1 is set to VH. Correspondingly, the risk degree for zones 2 and 3 are set to M and L, respectively, as there is a lower probability of accidents such as crane collapse and the large distance of zone 3 from the accident points compared to zones 1 and 2. The risk degrees in these three zones are VH, M, and L, respectively, as shown in Fig. 3.

In order to improve the safety level of construction sites, facilities should be assigned to locations far from danger sources in order to minimize the risk degree for all the facilities, as defined in Eq. (1).

$$F_1 = \min \sum_{i=1}^{m} r_{1i} \tag{1}$$

where F_1 is the objective function related to the geographic safety relationship. r_{1i} is the assumed value for the risk degree when facility i

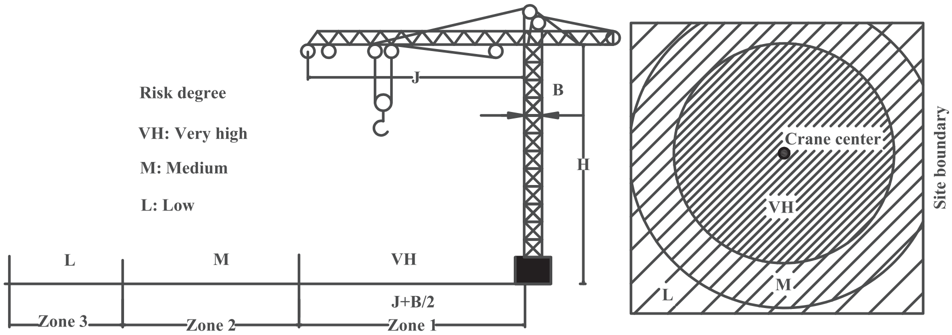

Fig. 3. The risk degrees around the tower crane.

(i = 1, 2, …, m) is assigned to the corresponding dangerous zone with risk degree of VH, H, M, L, or N. Karray et al. [57] divided the interaction relationship into five degrees, i.e., absolutely necessary, especially important, important, ordinary closeness and unimportant, according to the closeness between facilities. They also assigned corresponding assumed values of 243, 81, 27, 9 and 3 to the above five degrees, respectively. In this paper, the component of interaction relationship, i.e., geographic safety relationship, is described in terms of risk degree. Thus, the assumed values for risk degrees VH, H, M, L and N are also set to 243, 81, 27, 9 and 3, respectively. The r_{1i} for each facility is the weighted sum of the risk degree from the different hazardous sources and the weights between them are determined by the negative consequences of each hazardous source if an accident does occur.

3.3. Objective function related to facility safety relationship

Facility safety relationship is the risk arising from the interaction flows, i.e., transportation frequency of resources, or the interactions, among the facilities, including material flow, personnel flow, equipment flow, which can be measured by transportation unit per day, number of employee trips per day, and number of pieces of equipment used between facilities [36, 38, 58].

The higher the frequency of interaction flows between facilities, the more conflicts or collisions can occur between materials, personnel, and equipment. The risk has a positive relationship with the interaction flows. The longer the travel distance for the resources transportation between the facilities, the more crossover and overlapping points are created along this travel route. Thus, crossover or overlapping of the road traffic is dependent on the movement distance between the facilities [11]. There is also a positive relationship between the risk level and distance. In order to improve the safety performance of the construction site layout, the risk due to the facility safety relationship should be minimized, as defined in Eq. (2).

$$F_2 = \min \sum_{i=1}^{m} \sum_{j=1}^{m} \sum_{k=1}^{n} \sum_{l=1}^{n} r_{2ij} d_{kl} \tag{2}$$

Eq. (2) signifies minimization of the site risk level taken by the facility safety relationship when facility i (i = 1, 2, …, m) is assigned to location k (k = 1, 2, …, n) and facility j (j = 1, 2, …, m) is assigned to location l (l = 1, 2, …, n), simultaneously. r_{2ij} is the assumed value for the facility safety relationship considering quantitative flows of material, personnel, and equipment; and d_{kl} is the distance between location k and location l. For different measurement scales for these three quantitative flows, the five assessment levels, VH, H, M, L, and N, are used as in the risk degree in evaluating geographic safety relationship. The assessment rule and assumed value for the five assessment levels are shown in Table 1.

In Table 1, the quantitative flows are evaluated using the five levels in terms of categories range, which is defines in Eq. (3). As there are five assessment levels for quantitative flows, the categories range is uniformly distributed among VH, H, M, L, and N.

Table 1
Five assessment levels for quantitative flows.

Categories range	Assessment level	Assumed value
(80%, 100%)	VH	243
(60%, 80%)	H	81
(40%, 60%)	M	27
(20%, 40%)	L	9
(0, 20%)	N	3

$$\textit{Categories range} = \frac{\textit{value of quantitative flow} - \min \textit{imum value of quantitative flows}}{\max \textit{imum value of quantitative flows} - \min \textit{imum value of quantitative flows}} \times 100\% \tag{3}$$

3.4. Objective function for total resources transportation cost

Construction cost is always an essential criterion for construction management. It is meaningless for a construction project that is completed without budget. According to statistical analysis of construction industry [59], profit margin (the total profit/gross value in construction industry) is around 3.5% (from 3.06% to 3.63%) in recent decade (2007–2016). In an intensely competitive market, it is crucial to save construction cost expenditure for increase profit margin of construction industry. Simultaneously, it is necessary for site manager to conduct efficient safety management without sacrificing the construction cost. Thus, the total resources transportation cost is a supplementary requirement when designing a safety construction site layout.

The total resources transportation cost is determined by the resource flows and the distance between the facilities. In previous studies, the construction resource flows associated with the transportation cost between the facilities consisted of quantitative flows of material, information, personnel and equipment [25, 38, 51, 58]. The information flow can be expressed by the number of communications (oral or reports) between facilities per time unit [36, 38, 58]. With the quantitative flows considering material, information, personnel, equipment, and the distance between the facilities, the site facilities can be assigned to free locations with minimum transportation cost as shown in Eq. (4).

$$F_3 = \min \sum_{i=1}^{m} \sum_{j=1}^{m} \sum_{k=1}^{n} \sum_{l=1}^{n} TC_{ij} d_{kl} \tag{4}$$

where TC_{ij} is the value for quantitative flows, which is derived in light of the rules in Table 1.

4. Tri-objective ACO-based optimization algorithm

4.1. Principle underlying the ACO-based optimization algorithm

In this paper, a construction site layout with high safety performance is designed. Thus, the two objective functions, facility safety relationship and geographic safety relationship, are developed. Further, the total resources transportation cost function is taken into account in the optimization design, so as to achieve safety improvement without sacrificing construction cost. The algorithm should find tradeoff solutions to balance the two safety objectives involved and one total resources transportation cost, which are conflicting or congruent. In the traditional ACO algorithms, the ants choose a branch when they search for food in accordance with the pheromone left on the branch and the length of branch, which is defined as pheromone information and heuristic information, respectively [60]. The amount of pheromone left on the branch is proportional to the quality of the solution found by the ant. In a multi-objective optimization problem with two objective functions [39], there is a set of tradeoff solutions, which differs from single optimization problems. It is difficult to compare the solutions in this set of tradeoff solutions and determine the best one to update the pheromone on that branch. There is no absolutely optimal solution in a multi-objective optimization problem, and the qualities of the solutions are compared in terms of the Pareto dominance relation between them. The pheromone information released by the ants is proportional to the quality of their solutions.

For a min-min problem, the optimization algorithm finds the Pareto-optimal front in the feasible objective space (see Fig. 4). For a tri-objective problem, the feasible solutions and the Pareto-optimal front are in a three-dimensional system of coordinates. For each pair of min-min problems in the tri-objective functions, its feasible solutions and Pareto-optimal front are the projection onto a corresponding two-dimensional space.

In order to find the Pareto dominance relation for our tri-objective problem, we modified the standard ACO algorithm used to solve two objective optimization problems by redefining the parameter λ related to the Pareto dominance relation in three-dimensional space. A tri-objective ACO-based optimization algorithm generates feasible solutions for tri-objective problem, finds the Pareto-optimal front, and places the solutions in an external set, which forms a new search space for ants. Then, the algorithm makes use of local search updating using the Pareto dominance relation and global search to diversify the solutions by finding the sparsest non-dominated solution.

The pseudo-code of the tri-objective optimization algorithm is presented in Table 2.

In Table 2, the two search schemes, local search and global search, are mentioned in Step 11. These two search schemes are the core of the algorithm, and determine the search direction for the ant in each iteration. The following section gives a detailed introduction to these two search schemes.

4.2. Search scheme 1: local search leading by pheromone information communication

In the tri-objective optimization problem, the amount of pheromone information released is based on the quality of the solution, i.e., the

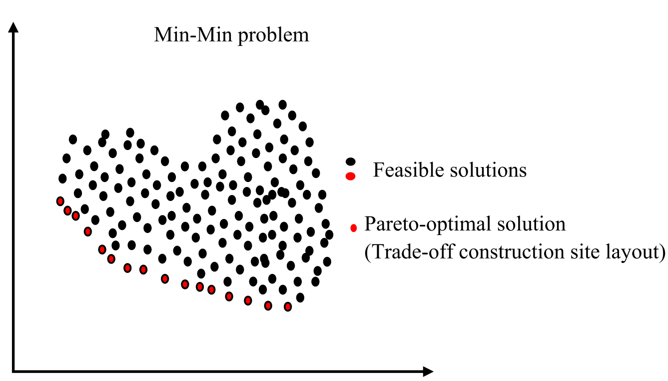

Fig. 4. Pareto-optimal front for min-min problems.

Table 2
The pseudo-code of ACO-based algorithm to find tri-objective optimization problems.

Step	Function
1	Coding the facilities and site location
2	Randomly generating feasible solution with number n
3	Determine the total ant number m
4	Determine the maximum iteration number N
5	Initial the iteration number $t = 1$
6	Calculate the associate value of objective functions
7	Initial external set consisted of all non-dominated feasible solutions
8	For each ant i
9	Set a parameter q_0 between [0, 1].
10	Generate a random variable q, which is uniformly distributed over [0,1]
11	If $q \le q_0$, an ant k determine its searching direction in terms of global search; Otherwise, local search is adopted.
12	Update the iteration number $t = t + 1$
13	If $t < N$, go to step 7
14	Update external non-dominated feasible solutions
15	Output the Pareto-optimal solution

Pareto dominance relation between solutions. Suppose that x_i and x_j are the respective solutions associated with ants i and j, the pheromone information θ_i released by ant i determines the search orientation of ant j, and is defined in Table 3.

In the definition, $i, j = 1, 2, \ldots, m$ and $i \ne j$, λ_1, λ_2, λ_{31}, λ_{32}, and λ_4 are five parameters for pheromone information that depend on the dominance relation between x_i and x_j, and $\lambda_4 > \lambda_{32} > \lambda_{31} > \lambda_2 > \lambda_1$. The search direction of ant j not only pertains to the pheromone information released by ant i, but is also affected by the distance d_{ij} between them. The shorter is the distance between ants i and j, the greater is the probability of ant j following the search direction of ant i. The following probability P_i of ant i is shown in Eq. (5).

$$P_i = \frac{\theta_i \delta_{ij}}{\sum_{i=1}^{m} \theta_i \delta_{ij}}, \quad i \ne j,\ i = 1, 2, \ldots, N \tag{5}$$

where $\delta_{ij} = 1/d_{ij}$.

4.3. Search scheme 2: global search leading by the shared function

There is a long travel path with less pheromone information in the optimal solution; thus, resulting in the ant deviating from the optimal search direction. Meanwhile, the pheromone communication process requires a long time to establish and the diversity of the ant colony cannot be maintained. The advantage of the algorithm is that it biases the ant choice in accordance with global optimum search history. Specifically, an external set BP is used to keep all non-dominated solutions found during the run of the algorithm.

To improve the diversity of solutions and the global optimization search capability, share functions and niche radium are introduced. Share functions represent the degree of similarity between non-dominated solutions, which can improve the distribution of non-dominated

Table 3
The pheromone information θ_i released by the ant i.

θ_i	Pareto dominance relationship between solutions
λ_1	If x_i is the non-feasible solution;
λ_2	If x_i, x_j are the feasible solutions and solution x_j dominants x_i;
λ31	If x_i, x_j are the feasible solutions and x_i, x_j is non constrained dominated relation with one function value in x_i dominates x_j, the other two function values in x_i non-dominants x_j;
λ32	If x_i, x_j are the feasible solutions and x_i, x_j is non constrained dominated relation with two function values in x_i dominate x_j, one function value in x_i non-dominates x_j;
λ_4	If x_i, x_j are the feasible solutions and solutions x_i dominants x_j.

solutions and help to find the sparsest non-dominated solution i in the external set BP to maintain the diversity of solutions.

Assume that there are non-dominated solutions $x = (x_1, x_2, \ldots, x_s)$ in the set BP, the distance Fd_{ij} between the objective functions of x_j to the other non-dominated solutions x_j can be calculated using the following Eq. (6):

$$Fd_{ij} = \sqrt{\sum_{m=1}^{n} (F_m(x_i) - F_m(x_j))^2} \tag{6}$$

where n is the number of objectives and $i = 1, 2, \ldots, s$, $j = 1, 2, \ldots, s$, $i \neq j$.

Share functions $sh[Fd(x_i, x_j)]$ are reducing functions associated with distance, i.e., the non-dominated self-shared function value for x_i is one, and the shared function value between x_i and other non-dominated solutions is less than one. The shared function is defined by Eq. (7).

$$Sh[Fd(x_i, x_j)] = \begin{Bmatrix} 1 - Fd(x_i, x_j)/\sigma_{share}, \ Fd_{ij} < \sigma_{share} \\ 0, \ Fd(x_i, x_j) > \sigma_{share} \end{Bmatrix} \tag{7}$$

where σ_{share} is the niching radius. The niche of the non-dominated solution is given by Eq. (8).

$$niche(i) = \sum_{j=1}^{s} Sh[Fd(x_i, x_j)], \ i = 1, 2, \ldots, s, \quad i \neq j. \tag{8}$$

The smallest $niche(i)$ of the non-dominated solution i determines the search direction of the ants.

With the development of three objective functions, i.e., geographic safety relationship (F_1) and facility safety relationship (F_2), and the total resources transportation cost (F_3), illustration of the proposed tri-objective ACO-based algorithm, the optimization model is established. In order to verify applicability and effectiveness of the model, a case study is conducted. In light of the results of the case study, a constructive suggestion to improve site safety performance will be provided.

5. Case study

The case study is used to verify the proposed a tri-objective ACO-based model. With the case study, the model can be realized to produce the final optimal results (construction site layout) by appropriate parameters setting. With the case study, the application process can be realized in reality. Most important, with the results analysis, the impact of facilities layout in the construction site on the safety and cost can be figured out. Based on the impact, the suggestion on how to arrange the site temporary facilities will be given to site manager for safety performance improvement and cost reduction.

5.1. Case description

The facilities associated with the construction site are listed in Table 4.

There are thirteen temporary facilities located on the construction site. Five of the facilities, a field office, security hut, two material hoists, and a tower crane, are frozen in their locations and are therefore called fixed facilities. The security hut and the field office are located next to the site entrance for site security and supervision. The material hoists are used to transport construction material and labor to the building's superstructure. The tower crane is structured to service two building's material transportation. The remaining eight facilities are free facilities, and are assigned to free locations with optimization by the proposed algorithm.

5.2. Site mapping and facility representations

In this paper, the site locations are defined in terms of the coordination of the grids and the distances between the facilities can be defined once they are assigned. Each facility is represented by a collection of grid units, whose sum fulfils the requirements of the facility areas [61]. In this case study, there are two facilities with areas 25 m^2 and 50 m^2, the greatest common divisor is 25 m^2. Thus, the total construction site is divided into grid units with an area of 25 m^2 (5 m × 5 m) and the facilities can be represented by the allocation of their respective units. For example, inflammable materials storage and tool shed can be represented by one grid unit and two grid units, respectively.

Table 4
Temporary facilities located in the construction site.

Facility no.	Facilities	Area (m^2)	Status
TF1	Inflammable materials storage	25	Free
TF2	Fire equipment storage	25	Free
TF 3	Equipment maintenance plant	25	Free
TF 4	Reba bending yard	100	Free
TF 5	Carpentry workshop	100	Free
TF 6	Material laydown area	100	Free
TF 7	Tool shed	50	Free
TF 8	Labor hut	25	Free
TF 9	Field office	50	Fixed
TF 10	Security hut	25	Fixed
TF 11	1# material hoist	25	Fixed
TF 12	2# material hoist	25	Fixed
TF 13	Tower crane	50	Fixed

In Fig. 5, the grey grids represented by the number "0" are occupied by the facilities, which mean that these site locations are not available for assignment to other facilities. Conversely, the white grids represented by the number "1" are available for assignment. The grid in row i and column j, the grid in row i and column $j + 2$, and the grid in row $i + 1$ and column $j + 2$ are transformed into "0" in matrix (i, j), "0" in matrix $(i, j + 2)$, and "0" in matrix $(i + 1, j + 2)$, accordingly. Facilities for inflammable materials storage and tool shed can be assigned to the white grids via the optimization model (please see Fig. 5 for example).

5.3. Definition of facility distance

The facility distance defined in this study is the Euclidean distance between the gravity center of facility (GCF). The grid can be represented as $(X_i, Y_i) = (grid\ row, grid\ column)$, and the gravity center of the grid (GCG) can be calculated by Eq. (9).

$$GCG = (GX_i, GY_i) = (X_i - 0.5, Y - 0.5) = (grid\ row - 0.5, grid\ column - 0.5) \tag{9}$$

The Euclidean distance between grid i, j can be determined by Eq. (10).

$$Euclidean\ distance = \sqrt{(GX_i - GX_j)^2 + (GY_i - GY_j)^2} \tag{10}$$

After determining the GCG, the GCF can be calculated as below by the coordination defined in Eq. (11).

$$GCF = (FX_i, FY_j) = \left(\frac{Sum\ of\ grid\ gravity\ GX_i}{grid\ units}, \frac{Sum\ of\ grid\ gravity\ GY_i}{grid\ units} \right) \tag{11}$$

Then, the distance can be determined in Eq. (12).

$$d_{ij} = \sqrt{(FX_i - FX_j)^2 + (FY_i - FY_j)^2} \tag{12}$$

5.4. Results of case study

The ACO-based optimization algorithm determines construction site layout alternatives (optimal solutions) to satisfy facilities geographic

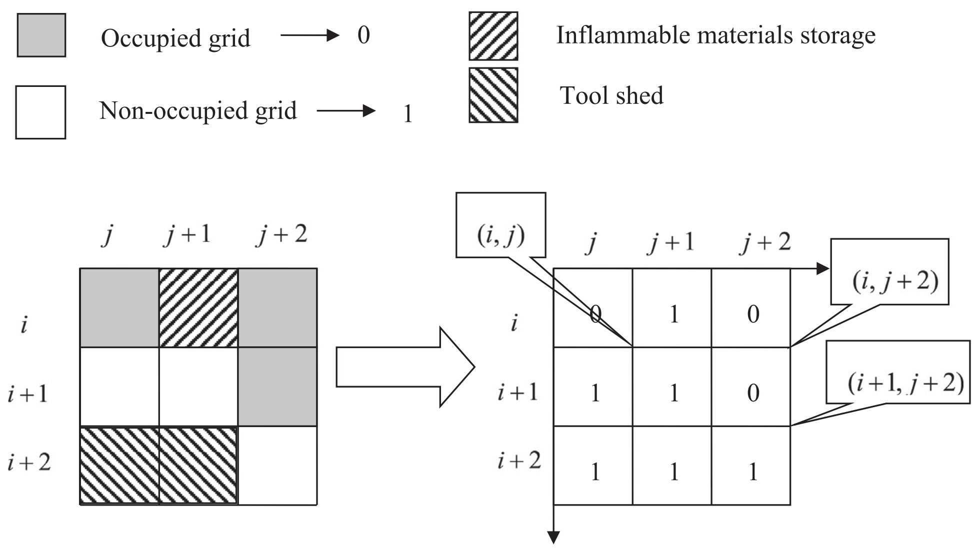

Fig. 5. The method to represent site grid.

safety relationship (F_1), facility safety relationship (F_2), and total resources transportation cost (F_3). The key parameter, the pheromone information of λ_1, λ_2, λ_{31}, λ_{32}, λ_4 were set to 0.01, 0.1, 2, 3, and 5, respectively. The feasible solutions with number of n and total number m are set to 200 and 10 respectively. The Pareto-optimal solutions found for the case study are shown in Fig. 6.

For a multi-objective optimization problem, many Pareto-optimal solutions are usually generated. This is because the multiple objectives are usually conflicting; thus, one optimal solution cannot fulfil the requirements for all the objectives. In mathematics, one solution cannot dominate the remaining solutions. The solution may achieve the minimum value for two objectives but cannot guarantee the remaining objective's minimum value. Consequently, six Pareto-optimal solutions were found by the algorithm. The more choices there are for site managers, the more time is consumed and bias is introduced into their decision-making. In fact, the requirements for safety and cost vary for different projects and site layout design is highly related to the user's preference. In order to clarify the requirements for the safety and cost goals in this specific project, we invited site managers to state the importance of the three objective functions to help them focus on the quality of the construction site layout plans for further decision-making. A nine-point rating scale and analytic hierarchy process (AHP) were then employed to determine the weights between the three objective functions. The weights for F_1, F_2, and F_3 were 0.43, 0.31, and 0.26, respectively. Considering the importance of the weights between the objective functions, the results for the former three construction site layout alternatives with the minimum weighted sum values are presented in Table 5 and Fig. 7.

With the optimal results, the schematic layout drawing for each of P1, P2, and P3 are displayed in detail in Figs. 8 to 10, respectively.

The optimal construction site layouts of P1, P2, and P3 were generated to minimize the risk caused by the geographic safety relationship (F_1) and facility safety relationship (F_2), and reduce the total resources transportation cost (F_3). F_1 is determined by the risk degree of the surrounding hazardous facilities. F_2 is determined by the interaction flows for materials, equipment, and personnel, and the distance between the facilities. F_3 is determined by the interaction flows for materials, equipment, and personnel and the information and the distance

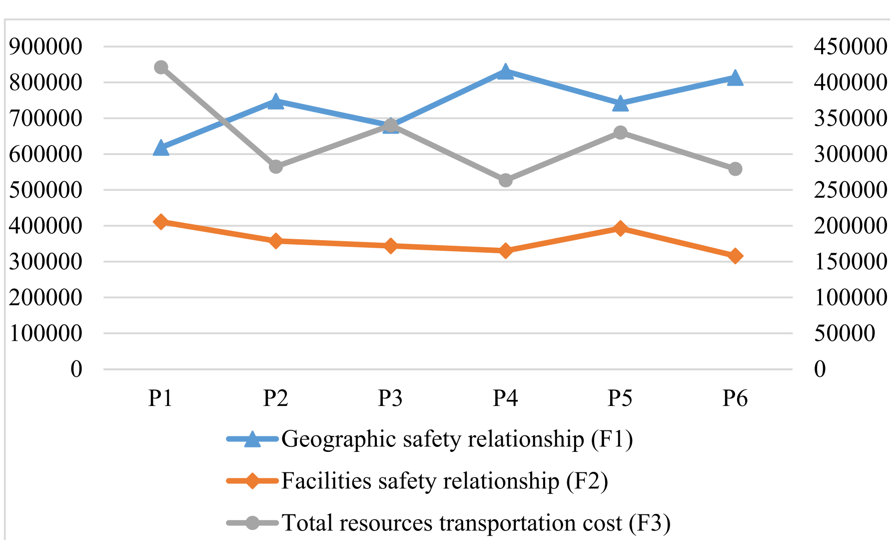

Fig. 6. Pareto-optimal front for the case study.

Table 5
The optimal results for the six construction site layout alternatives.

Objective function	P1	P2	P3	P4	P5	P6
F1	618,654.2	747,873.5	679,986.7	831,255.5	742,072.1	813,656.8
F2	205,617.7	178,913.3	171,976.0	165,229.2	196,414.8	158,023.2
F3	421,227.4	282,551.0	340,169.7	263,599.7	330,156.9	279,424.3
Weighted sum	439,281.9	450,512.0	434,151.0	477,196.8	465,820.4	471,509.9

between the facilities. From the description in Fig. 7, it is clear that the three objectives are conflicting; hence, there is no best and unique solution for the construction site layout.

5.5. Discussion of case study results

Among the three site layout alternatives, construction site layout P1 in Fig. 8 has a minimum value of 618,654.2 for geography safety relationship. In P1, the temporary facilities are assigned far away from TF13 (tower crane), TF11 (1# material hoist) and TF12 (2# material hoist); the risk degrees are lower if the facilities are located in the specific lower safety zone. In particular, for TF8 (labor hut), which is placed away from the dangerous facilities, the safety and health of laborers are improved. The labor hut is assigned to the left of building #2 and adjacent to the haul road, which effectively avoids potential risks from the tower crane. The temporary facilities are located relatively separately, the distance between the facilities are great; thus, the risk due to facility safety relationship is 205,617.7, which is the maximum value among the three construction site layout alternatives. Correspondingly, the total resources transportation cost has the highest value of 421,227.4 for the disperse distribution of the facilities.

Comparing the layouts of P1 (see Fig. 8) and P3 (see Fig. 10), the distribution of temporary facilities is more decentralized in P1 than in P3; thus, the value of 171,976.0 for facility safety relationship in P3 is lower than that of 205,617.7 in P1. TF4 (rebar bending yard) and TF5 (carpentry workshop) are far away from TF6 (material laydown area) in P1, which increases material handling cost and the value for resources transportation cost in P1 is higher than that in P3. Meanwhile, TF7 (tool shed) is arranged around TF11 (material hoist #1) and TF13 (tower crane) in P3 such that the risk degree from dangerous facilities is relatively high. TF5 (carpentry workshop) and TF6 (material laydown area) are arranged next to the facilities of TF3 (equipment maintenance plant) and TF8 (labor hut) in P3 such that the noise pollution for them is relatively high. The shorter the distance is between the facilities, the higher is the noise level. The location of TF1 (Inflammable materials storage) in P3 is more reasonable than that in P1, in which TF1 is placed around TF3, TF5, and TF8. Therefore, the risk arising from hazardous materials is lower in P3 than in P1. Correspondingly, the geographic safety relationship is increased from 618,654.2 in P1 to 679,986.7 in P3. However, transportation cost in P3 is decreased because there is a shorter distance between TF5 and TF6. Thus, the total resources transportation cost is relatively lower in layout P3 with a value of 340,169.7. In addition, it is proper arrangement in P3 for TF8 to be close to TF5 and TF6 when considering construction productivity. From the above discussion and analysis, it is clear that layout alternative P3 with the minimum weighted sum is superior to layout alternative P1 for site managers.

For layout alternatives P2 (see Fig. 9) and P3 (see Fig. 10), the facilities are not distributed but are arranged compactly on the construction site. TF4 (rebar bending yard), TF5 (carpentry workshop), and TF6 (material laydown area) in P2 are closer to dangerous facilities than they are in P3. In particular, TF4 and TF6 are assigned in the danger zone of TF11 (material hoist #1), and TF5 is adjacent to TF13 (tower crane); the risk degree caused by the tower crane and material hoist are high. The location occupied by TF8 (labor hut) in P2 is faced with various danger sources, such as TF1 (Inflammable materials storage), TF4, and TF13, which will increase the risk degree for personnel safety and health related to noise pollution and hazardous materials. Thus, it is obvious that P3 has a maximum value of 747,873.5 for geography safety relationship. On the other hand, there is frequent transportation of resources among TF4 (rebar bending yard), TF5 (carpentry workshop), and TF6 (material laydown area). However, TF5 and TF6 in P2 are arranged separately on both sides of TF11, which will increase the possibility of accident between the two facilities and severely decrease productivity. Conversely, TF5 is close to TF6 in P3, which contributes to a reduction in the facility safety relationship from 178,913.3 in P2 to 171,976.0 in P3 and improves construction productivity simultaneously. Resources transportation cost with a value of 340,169.7 is higher in P3 than in P2 because the distance between the facilities is greater, such as TF4, TF6 and TF7, TF8. Because the

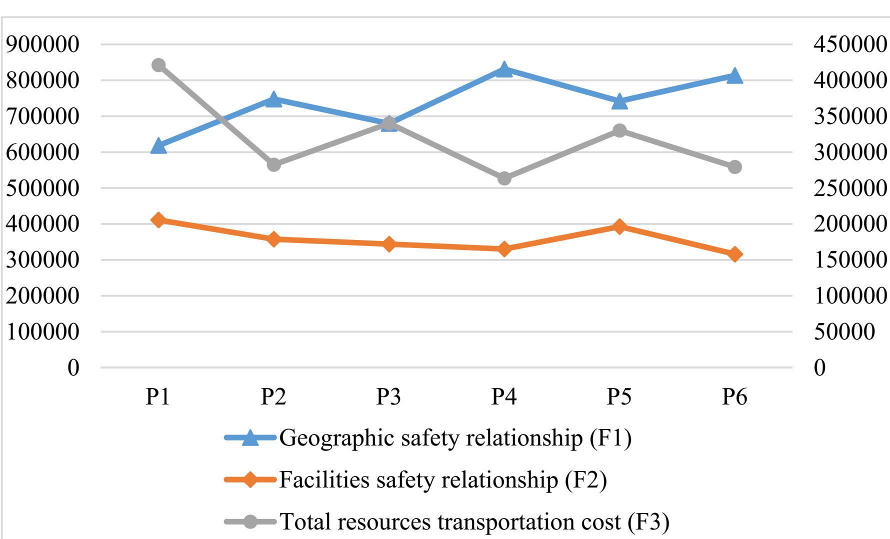

Fig. 7. The results comparison for the six construction site layout alternatives.

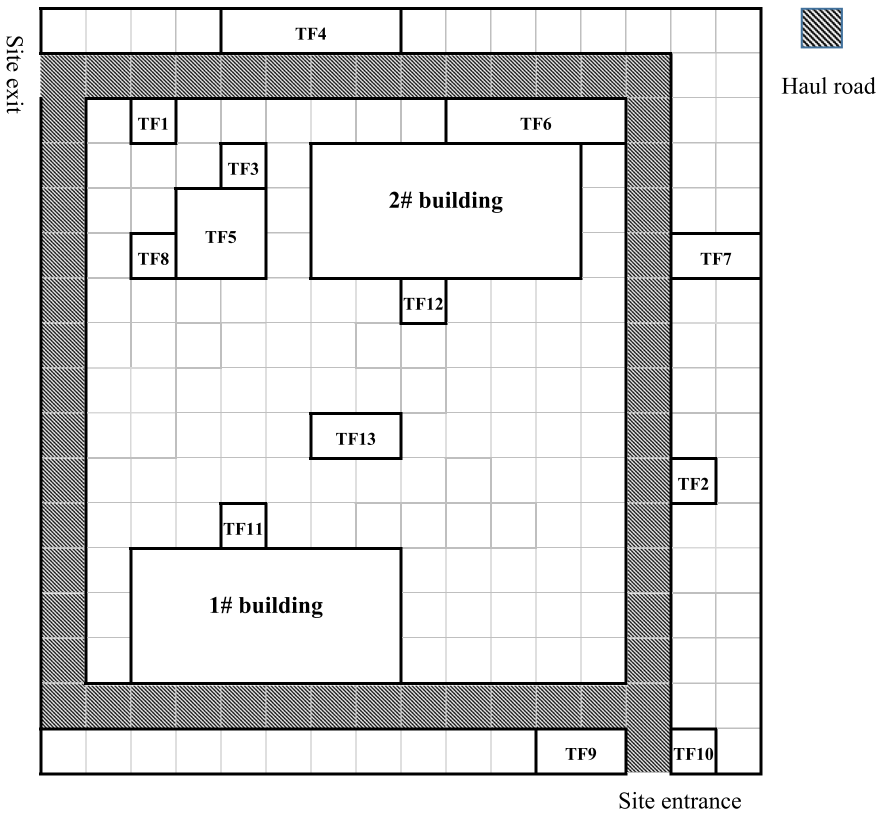

Fig. 8. Schematic layout drawing for P1.

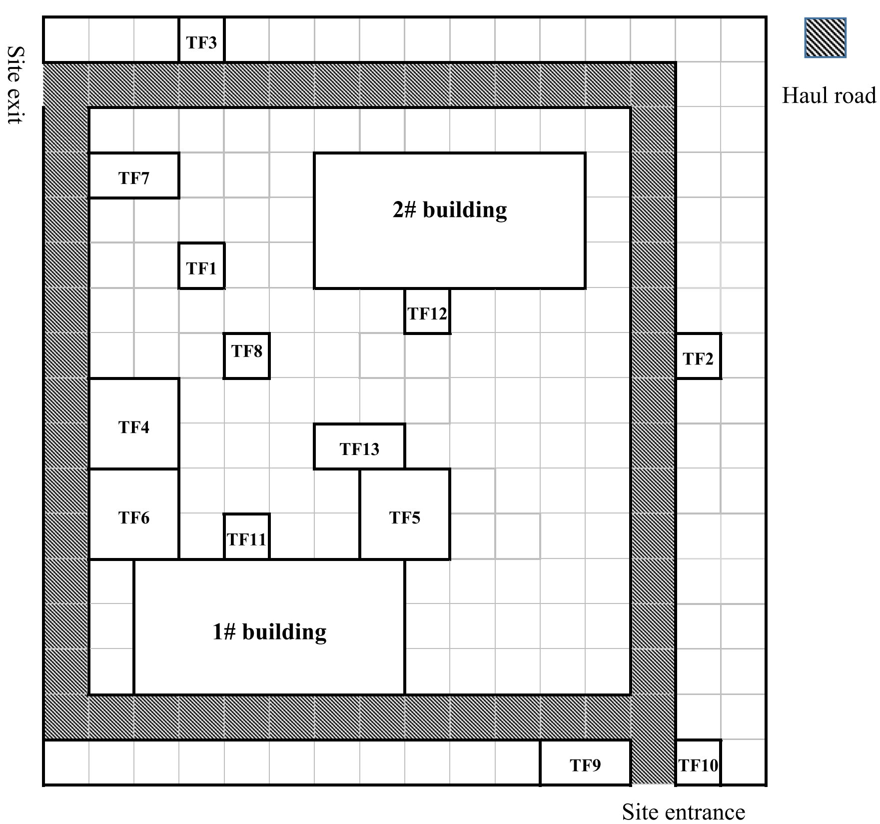

Fig. 9. Schematic layout drawing for P2.

geographic safety relationship and facility safety relationship are more important with higher weights, the layout alternative in P3 is a more reasonable layout selection for site managers compared to layout alternative P2.

The three objectives are conflicting. Thus, the best site layout cannot fulfil the requirement of the three objectives simultaneously. The ultimately selected construction site layout is a tradeoff solution, i.e., construction site layout alternative P3.

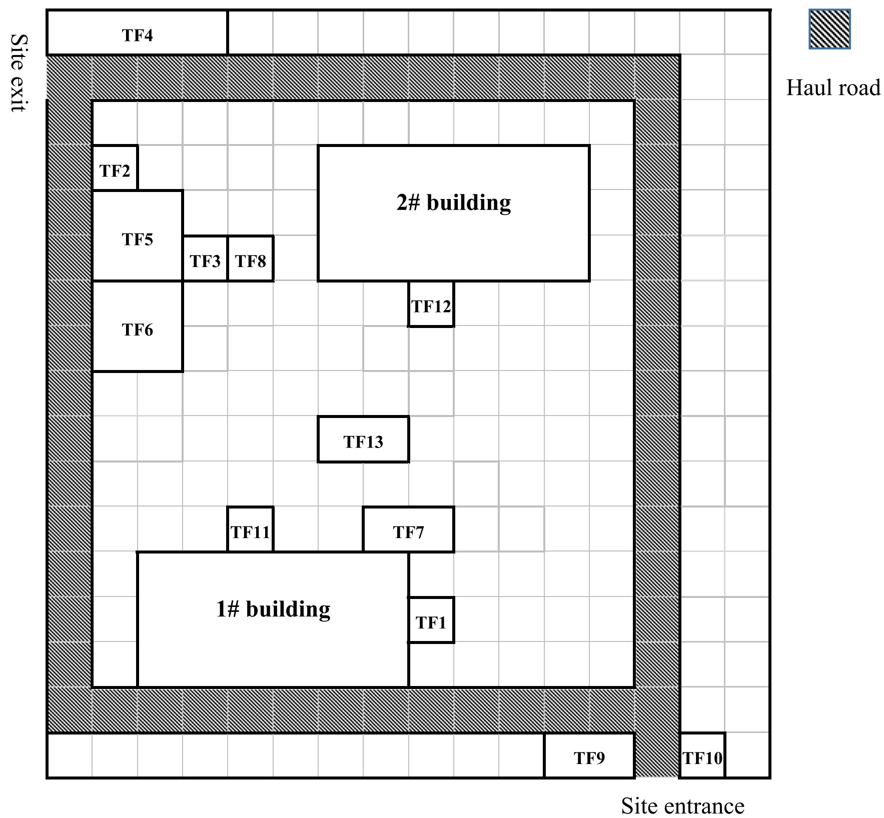

Fig. 10. Schematic layout drawing for P3.

6. Discussion

6.1. Theoretical and practical implications

This study contributes to the current construction safety theory by revealing the importance of interaction flows for improving the safety performance in CSLP, and innovatively presenting the two safety objective functions pertaining to the interaction relationship between the facilities. It goes deep into safety planning in the construction site layout by providing deep analysis on the interaction relationship, which is the key factor to determine the facilities' distribution on construction sites. In order to solve the multi-objective optimization problem, a novel tri-objective ACO-based optimization model is proposed. This algorithm makes use of Pareto optimization by determining the dominance relation between the solutions, which is the key parameter leading the algorithm's search direction. The superiority of this algorithm is independent of the predetermined weighting coefficients of each objective and the final solution is diversified to offer more site layout alternatives for decision-making. In other words, this study enriches the approaches to safety optimization problems in CSLP by developing a tri-objective ACO-based model for designing a safe construction site layout in a systematic and numerical manner.

From a practical perspective, this study provides many site layout alternatives for decision-making. The site manager in the project can select the final site layout plan in terms of their personal preference or the project requirements. It assists site managers to avoid busy resources movement in construction sites by better resources planning. The facilities with higher resources movement between them should be located closer to each other such that the resources transportation cost can be reduced simultaneously. For reducing the risk brought by the geographic safety relationship, the facilities should be assigned far away from danger sources, such as tower cranes, haul roads, and material hoists. On a congested construction site, it is better to assign temporary facilities around the heavy equipment, i.e., tower crane, material hoist, which usually have a high material transportation rate with most of the facilities as temporary facilities. Such an arrangement minimizes transportation cost and the safety level owing to interaction flows and facilitates the construction operations. However, the geographic safety relationship increases correspondingly with the closer distances between the majorities of the temporary facilities. In order to reduce the geographic safety relationship, non-productivity facilities, such as labor hut and inflammable materials storage areas, which have lower interaction flows between the heavy facilities should be placed far away from them.

6.2. Limitations and recommendations

This paper analyzed risk factors from the viewpoint of the interaction relationship between facilities, which is the connection that links all the temporary facilities on the overall construction site. Based on the risk factors analysis, objective functions were established to improve the safety level on the construction site. This is limited to describing the other risk factors, such as space conflicts for all onsite equipment and the moving vehicle. In order to solve a tri-objective optimization problem, an improved ACO-based optimization model combined with Pareto optimization theory was adopted. The parameters involved were constants and were not tested or analyzed to derive the optimal parameter settings for the algorithm.

It is recommended that the risk factors be analyzed from the viewpoint of space utilization and thus to incorporate space accessibility, ease of space expansion, etc. into the safety objective function. With the defined objective function for space safety, such as collisions between the heavy equipment will tend to be prevented and the construction operations during the construction process will be smooth [62]. Concerning the impact of different parameter settings on the search efficiency of the algorithm, future research should emphasize parameter analysis to derive the best parameter settings.

7. Conclusion

As an important part of the safety objective function in designing construction site layout plans, this paper established an optimization model which incorporates partial safety considerations mentioned in previous studies into two safety objective functions constructed based on facility safety relationship and geographic safety relationship. Since construction cost is the basic and very important requirement for construction management, an additional objective function related to cost was also established as a supplementary objective for CSLP. The resulting tri-objective optimization problem was solved via Pareto-based ACO algorithm, which is used to find tradeoff solutions (optimal construction site layouts) according to the dominance relation between solutions. Finally, a residential building was used as a case study to illustrate the applicability and feasibility of the proposed model. The results show that the objective function related to interaction relationship is congruent with resources transportation cost and have a conflicting relationship with the objective function related to geographic safety relationship.

In summary, this study conducted safety improvements in the CSLP to establish a tri-objective ACO-based optimization model to generate site plans. In the model, bi-objective functions for safety are initially built on the basis of interaction relationship analysis, which revealed the importance of the interaction relationship on the safety improvement. The optimization algorithm combining Pareto optimization theory with ACO proposed in this study can be expanded to solve other multi-objective optimization problems in construction management. Meanwhile, this study offers a reasonable and scientific method to design a safe construction site layout, and give constructive suggestions to site managers when they face decision-making on how to organize temporary facilities in construction sites.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant Nos. 71501029 and 71601036) and Program for Excellent Talents in Dongbei University of Finance and Economics 2017 (Grant No. 2017216).

References

[1] J. Hinze, F. Wiegand, Role of designers in construction worker safety, J. Constr. Eng. Manag. 118 (4) (1992) 677–684, http://dx.doi.org/10.1061/(ASCE)0733-9364(1992)118:4(677).
[2] M. Behm, Linking construction fatalities to the design for construction safety concept, Saf. Sci. 43 (2005) 589–611, http://dx.doi.org/10.1016/j.ssci.2005.04.002.
[3] M. Weinstein, J.A. Gambatese, Can design improve construction safety? Assessing the impact of a collaborative safety-in-design process, J. Constr. Eng. Manag. 131 (10) (2005) 1125–1134, http://dx.doi.org/10.1061/(ASCE)0733-9364(2005)131:10(1125).
[4] X.H. Yu, C.Q. Li, G.M. Zhang, Impediments to Implementing Design for Construction Safety, Springer, Berlin, Heidelberg, 978-3-662-46993-4, 2015.
[5] A.L.E. Teo, G. Ofori, I.K. Tjandra, H. Kim, Design for safety: theoretical framework of the safety aspect of BIM system to determine the safety index, Constr. Econ. Build. 16 (4) (2016) 1–18, http://dx.doi.org/10.5130/AJCEB.v16i4.4873.
[6] P. Zhang, F.C. Harris, P.O. Olomolaiye, G.D. Holt, Location optimization for a group of tower cranes, J. Constr. Eng. Manag. 125 (2) (1999) 115–122, http://dx.doi.org/10.1061/(ASCE)0733-9364(1999)125:2(115).
[7] C.M. Tam, K.L. Tong, GA-ANN model for optimizing the locations of tower crane and supply points for high-rise public housing construction, Constr. Manag. Econ. 21 (2003) 257–266, http://dx.doi.org/10.1080/0144619032000049665.
[8] M.A. Abdelmegid, K.M. Shawki, H. Abdel-Khalek, GA optimization model for solving tower crane location problem in construction sites, Alex. Eng. J. 54 (3) (2015) 519–526, http://dx.doi.org/10.1016/j.aej.2015.05.011.
[9] M. Abune'meh, R.E. Meouch, I. Hijaze, A. Mebarki, I. Shahrour, Optimal construction site layout based on risk spatial variability, Autom. Constr. 70 (2016) 167–177, http://dx.doi.org/10.1016/j.autcon.2016.06.014.
[10] J. Xu, S. Zhao, Z. Li, Z. Zeng, Bi-level construction site layout optimization based on hazardous-material transportation, J. Infrastruct. Syst. 22 (3) (2016) 04016014, , http://dx.doi.org/10.1061/(ASCE)IS.1943-555X.0000303.
[11] K. El-Rayes, A. Khalafallah, Trade-off between safety and cost in planning construction site layouts, J. Constr. Eng. Manag. 131 (11) (2005) 1186–1195, http://dx.doi.org/10.1061/(ASCE)0733-9364(2005)131:11(1186).
[12] E. Elbeltagi, T. Hegazy, A. Eldosouky, Dynamic layout of construction temporary facilities considering safety, J. Constr. Eng. Manag. 130 (4) (2004) 534–541, http://dx.doi.org/10.1061/(ASCE)0733-9364(2004)130:4(534).
[13] A.W.A. Hammad, A. Akbarnezhad, D. Rey, A multi-objective mixed integer nonlinear programming model for construction site layout planning to minimise noise pollution and transport costs, Autom. Constr. 61 (2016) 73–85, http://dx.doi.org/10.1016/j.autcon.2015.10.010.
[14] M.J. Ballesteros, M.D. Fernández, S. Quintana, J.A. Ballesteros, I. González, Noise emission evolution on construction sites. Measurement for controlling and assessing its impact on the people and on the environment, Build. Environ. 45 (2010) 711–717, http://dx.doi.org/10.1016/j.buildenv.2009.08.011.
[15] A.M. Adrian, A. Utamima, K.J. Wang, A comparative study of GA, PSO and ACO for solving construction site layout optimization, KSCE J. Civ. Eng. 19 (3) (2015) 520–527, http://dx.doi.org/10.1007/s12205-013-1467-6.
[16] S.P. Singh, V.K. Singh, An improved heuristic approach for multi-objective facility layout problem, Eur. J. Oper. Res. 48 (4) (2010) 1171–1194, http://dx.doi.org/10.1080/00207540802534731.
[17] F.G. Paes, A.A. Pessoa, T. Vidal, A hybrid genetic algorithm with decomposition phases for the unequal area facility layout problem, Eur. J. Oper. Res. 256 (2017) 742–756, http://dx.doi.org/10.1016/j.ejor.2016.07.022.
[18] I.N. Papadaki, A.P. Chassiakos, Multi-objective construction site layout planning using genetic algorithms, Proc. Eng. 164 (2016) 20–27, http://dx.doi.org/10.1016/j.proeng.2016.11.587.
[19] C. Wong, I. Fung, C.M. Tam, Comparison of using mixed-integer programming and genetic algorithms for construction site facility layout planning, J. Constr. Eng. Manag. 136 (10) (2010) 1116–1128, http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000214.
[20] M.J. Mawdesley, S.H. Al-jibouri, H. Yang, Genetic algorithms for construction site layout in project planning, J. Constr. Eng. Manag. 128 (5) (2002) 418–426, http://dx.doi.org/10.1061/(ASCE)0733-9364(2002)128:5(418).
[21] H. Said, K. El-Rayes, Optimal utilization of interior building spaces for material procurement and storage in congested construction sites, Autom. Constr. 31 (3) (2013) 292–306, http://dx.doi.org/10.1016/j.autcon.2012.12.010.
[22] S.R. Razavialavi, S. Abourizk, Site layout and construction plan optimization using an integrated genetic algorithm simulation framework, J. Comput. Civ. Eng. 31 (4) (2017) 04017011, , http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000653.
[23] P.P. Zouein, H. Harmanani, A. Hajar, Genetic algorithm for solving site layout problem with unequal-size and constrained facilities, J. Comput. Civ. Eng. 16 (2) (2002) 143–151, http://dx.doi.org/10.1061/(ASCE)0887-3801(2002)16:2(143).
[24] G. Calis, O. Yuksel, An improved ant colony optimization algorithm for construction site layout problems, J. Build. Constr. Plann. Res. 3 (2015) 221–232, http://dx.doi.org/10.4236/jbcpr.2015.34022.
[25] K.C. Lam, X. Ning, T. Ng, The application of the ant colony optimization algorithm to the construction site layout planning problem, Constr. Manag. Econ. 25 (4) (2007) 359–374, http://dx.doi.org/10.1080/01446190600972870.
[26] K.Y. Wong, P.C. See, A hybrid ant colony optimization algorithm for solving facility layout problems formulated as quadratic assignment problems, Eng. Comput. 27 (1) (2010) 117–128, http://dx.doi.org/10.1108/02644401011008559.
[27] M. Yahya, M.P. Saka, Construction site layout planning using multi-objective artificial bee colony algorithm with Levy flights, Autom. Constr. 38 (2014) 14–29, http://dx.doi.org/10.1016/j.autcon.2013.11.001.
[28] H. Zhang, J.Y. Wang, Particle swarm optimization for construction site unequal-area layout, J. Constr. Eng. Manag. 134 (9) (2008) 739–748, http://dx.doi.org/10.1061/(ASCE)0733-9364(2008)134:9(739).
[29] J.P. Xu, X.L. Song, Suggestions for temporary construction facilities' layout problems in large-scale construction projects, J. Constr. Eng. Manag. 140 (5) (2014) 06014001, , http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000841.
[30] R. Gholizadeh, G.G. Amiri, B. Mohebi, An alternative approach to a harmony search algorithm for a construction site layout problem, Can. J. Civ. Eng. 37 (12) (2010) 1560–1571, http://dx.doi.org/10.1139/L10-084.
[31] A.W.A. Hammad, D. Rey, A. Akbarnezhad, A cutting plane algorithm for the site layout planning problem with travel barriers, Comput. Oper. Res. 82 (2017) 36–51, http://dx.doi.org/10.1016/j.cor.2017.01.005.
[32] S.P. Singh, R.R.K. Sharma, Two-level modified simulated annealing based approach for solving facility layout problem, Int. J. Prod. Res. 46 (13) (2008) 3563–3582, http://dx.doi.org/10.1080/00207540601178557.
[33] Z.M. Li, W.J. Shen, J.P. Xu, B.J. Lev, Bilevel and multi-objective dynamic construction site layout and security planning, Autom. Constr. 57 (2015) 1–16, http://dx.doi.org/10.1016/j.autcon.2015.04.011.
[34] K. Deb, Multi-objective Optimization Using Evolutionary Algorithms, John Wiley & Sons, Ltd., England, 0-471-87339-X, 2001.
[35] J.P. Xu, X.L. Song, Multi-objective dynamic layout problem for temporary construction facilities with unequal-area departments under fuzzy random environment, Knowl.-Based Syst. 81 (2015) 30–45, http://dx.doi.org/10.1016/j.knosys.2015.02.001.
[36] X. Ning, K.C. Lam, M.C.K. Lam, Dynamic construction site layout planning using max-min ant system, Autom. Constr. 19 (2010) 55–65, http://dx.doi.org/10.1016/j.autcon.2009.09.002.
[37] X. Ning, K.C. Lam, M.C.K. Lam, A decision-making system for construction site layout planning, Autom. Constr. 20 (2011) 459–473, http://dx.doi.org/10.1016/j.autcon.2010.11.014.
[38] J.P. Xu, Z.M. Li, Multi-objective dynamic construction site layout planning in fuzzy random environment, Autom. Constr. 27 (2012) 155–169, http://dx.doi.org/10.1016/j.autcon.2012.05.017.
[39] X. Ning, K.C. Lam, Cost-safety trade-off in unequal-area construction site layout planning, Autom. Constr. 32 (2013) 96–103, http://dx.doi.org/10.1016/j.autcon.

2013.01.011.
[40] L.S.D. Oliveira, S.F.P. Saramago, Multiobjective optimization techniques applied to engineering problems, J. Braz. Soc. Mech. Sci. Eng. 32 (1) (2010) 94–105, http://dx.doi.org/10.1590/S1678-58782010000100012.
[41] C. Anumba, G. Bishop, Importance of safety considerations in site layout and organization, Can. J. Civ. Eng. 24 (1997) 229–236, http://dx.doi.org/10.1139/l96-100.
[42] S.S. Kumar, J.C.P. Cheng, A BIM-based automated site layout planning framework for congested construction sites, Autom. Constr. 59 (2015) 24–37, http://dx.doi.org/10.1016/j.autcon.2015.07.008.
[43] D. Dagan, S. Isaac, Planning safe distances between workers on construction sites, Autom. Constr. 50 (2015) 64–71, http://dx.doi.org/10.1016/j.autcon.2014.12.008.
[44] J.C. Lin, C.E. Yang, W.H. Hung, S.C. Kang, Accessibility evaluation system for site layout planning - a tractor trailer example, Vis. Eng. 1 (1) (2013) 1–11, http://dx.doi.org/10.1186/2213-7459-1-12.
[45] C. Huang, C.K. Wong, Optimisation of site layout planning for multiple construction stages with safety considerations and requirements, Autom. Constr. 53 (2015) 58–68, http://dx.doi.org/10.1016/j.autcon.2015.03.005.
[46] H. Neghabi, F.G. Tari, A new concept of adjacency for concurrent consideration of economic and safety aspects in design of facility layout problems, J. Loss Prev. Process Ind. 40 (2016) 603–614, http://dx.doi.org/10.1016/j.jlp.2016.02.010.
[47] E. Moradi, M. Bidkhori, Single Facility Location Problem, Heidelberg, Berlin, (2009) 978-3-7908-2150-5, pp. 37–68.
[48] L.C. Lien, M.Y. Cheng, Particle bee algorithm for tower crane layout with material quantity supply and demand optimization, Autom. Constr. 45 (2014) 25–32, http://dx.doi.org/10.1016/j.autcon.2014.05.002.
[49] A.R. Soltani, T. Fernando, A fuzzy based multi-objective path planning of construction sites, Autom. Constr. 13 (6) (2004) 717–734, http://dx.doi.org/10.1016/j.autcon.2004.04.012.
[50] A.R. Soltani, H. Tawfik, J.Y. Goulermas, T. Fernando, Path planning in construction sites: performance evaluation of the Dijkstra, A *, and GA search algorithms, Adv. Eng. Inform. 16 (4) (2002) 291–303, http://dx.doi.org/10.1016/j.autcon.2004.04.012.
[51] M. Andayesh, F. Sadeghpour, A comparative study of different approaches for finding the shortest path on construction sites, Creative Construction Conference, 2014 2014, pp. 33–41, , http://dx.doi.org/10.1016/j.proeng.2014.10.526.
[52] M.D. Fernández, S. Quintana, N. Chavarría, J.A. Ballesteros, Noise exposure of workers of the construction sector, Appl. Acoust. 70 (2009) 753–760, http://dx.doi.org/10.1016/j.apacoust.2008.07.014.
[53] A. ElSafty, A. ElSafty, M. Malek, Construction safety and occupational health education in Egypt, the EU, and US firms, Open J. Civ. Eng. 2 (2012) 174–182, http://dx.doi.org/10.4236/ojce.2012.23023.
[54] R.D. Woodson, Construction Hazardous Materials Compliance Guide: Asbestos Detection, Abatement and Inspection Procedures, Butterworth-Heinemann, UK, 0124158412, 2012.
[55] E.F. Mølgaard, H. Harald, T. Finn, B. Charlotte, K. Lilli, Chronic lower respiratory diseases among demolition and cement workers: a population-based register study, BMJ Open 3 (1) (2013) 1–4, http://dx.doi.org/10.1136/bmjopen-2012-001938.
[56] F. Tüchsen, H. Hannerz, E.F. Mølgaard, C. Brauer, L. Kirkeskov, Time trend in hospitalised chronic lower respiratory diseases among danish building and construction workers, 1981–2009: a cohort study, BMJ Open 2 (6) (2012) 1–6, http://dx.doi.org/10.1136/bmjopen-2012-001761.
[57] F. Karray, E. Zaneldin, T. Hegazy, A.H.M. Shabeeb, Tools of soft computing as applied to the problem of facilities layout planning, IEEE Trans. Fuzzy Syst. 8 (4) (2000) 367–379, http://dx.doi.org/10.1109/91.868944.
[58] K.C. Lam, C.M. Tang, W.C. Lee, Application of the entropy technique and genetic algorithms to construction site layout planning of medium-size projects, Constr. Manag. Econ. 23 (2) (2005) 127–145, http://dx.doi.org/10.1080/0144619042000202834.
[59] Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD), Statistical analysis of construction industry development (2016), Beijing, China, http://www.mohurd.gov.cn/xytj/tjzljsxytjgb/xjxxqt/w02017052321346623070743428.pdf, (2017) , Accessed date: 21 November 2017.
[60] M. Dorigo, T. Stützle, Ant Colony Optimization, MIT Press, London, 2004 (ISBN: 978-0-662-04219-2).
[61] C. Huang, C.K. Wong, Discretized cell modeling for optimal facility layout plans of unequal and irregular facilities, J. Constr. Eng. Manag. 143 (1) (2016) 04016082, , http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0001206.
[62] M.J. Skibniewski, Information technology applications in construction safety assurance, J. Civ. Eng. Manag. 20 (6) (2014) 778–794, http://dx.doi.org/10.3846/13923730.2014.987693.