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A quantitative safety risk assessment model for construction site layout planning

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ABSTRACT

A good site layout is necessary to provide a safe construction site environment. Previous studies treated construction site layout planning as an optimization problem to achieve high safety performance. However, the optimization problem does not contain holistic risk factor analysis. Risk factors such as the dangers of falling objects, noise pollution and hazardous chemicals tend to be neglected. Moreover, when site managers face different site layout scenarios, no safety risk assessment models are currently available to help them make decisions. Therefore, this paper aims to develop a quantitative safety risk assessment model, including factor identification and classification, factor analysis, and assessment function development, to help site managers evaluate different site layout scenarios more accurately and holistically. In factor identification and classification, the interaction flows between facilities are initially considered as risk factors. Safety/environmental concerns which were not deeply probed into by previous studies are also considered. For the above two risk factor categories, safety risk assessment functions are developed according to the likelihood of accident occurrence and the linear attenuation law respectively. Finally, a case study is used to verify the proposed model. This study interprets how to implement site safety management by means of site facility layout improvement. It enriches occupational safety research by providing a systematic model for assessing site layout plans in a quantitative and more valid manner. The findings help conduct effective site safety management by proper facilities displacement during the preconstruction stage and in turn guarantee construction safety in later stages.

1. Introduction

Construction projects begin with project planning, and good planning is a foundation for delivering successful construction projects (Patrick, 2004). Decisions related to design and/or resource management made at the beginning of a project tend to be more efficient than those made at later stages (Goetsch, 2013). Site space is a type of construction resource that is as important as capital, time, material, labor and equipment (Hegazy and Elbeltagi, 1999). The construction site laying out is an important activity that is done to make good use of site space. A good site layout boosts the effectiveness and efficiency of the subsequent construction work, contributes to the reduction of cost and material travel distance (Said and El-Rayes, 2013), and increases the safety level of the construction site (Sanad et al., 2008). Thus, correct decisions must be made when choosing among different site layout scenarios via valid and systematic safety assessments, so as to improve construction site safety management in both the preconstruction and construction stages.

Malekitabar et al. (2016) revealed that 46.8% of accidents are related to the design chosen for safety and that certain risks can be avoided by making minor changes to a design. Thus, more attention must be paid to safety planning in the preconstruction stage to improve safety management more effectively. Previously, safety researchers tended to conduct safety management during the construction stage and emphasized the important roles that risk factors play in safety performance improvement. These researchers discovered that most accidents are related to inadequate hazard recognition or appraisal and thus are rarely mitigated (Albert et al., 2017, 2014; Haslam et al., 2005; Smith and Carter, 2006). Safety can be improved by finding causations among safety risk factors (Albert et al., 2017; Li et al., 2017; Raviv et al., 2017a,b) and then monitoring and preventing accidents (Isaac and Edrei, 2016; Li et al., 2015). Because of the importance of human factors in construction safety (Cañamares et al., 2017), an increasing number of studies have focused on human-related safety antecedents, such as safety psychology (Pinion et al., 2017), safety climate (Fogarty et al., 2017; Leitão and Greiner, 2017; Zarei et al., 2016), and safety

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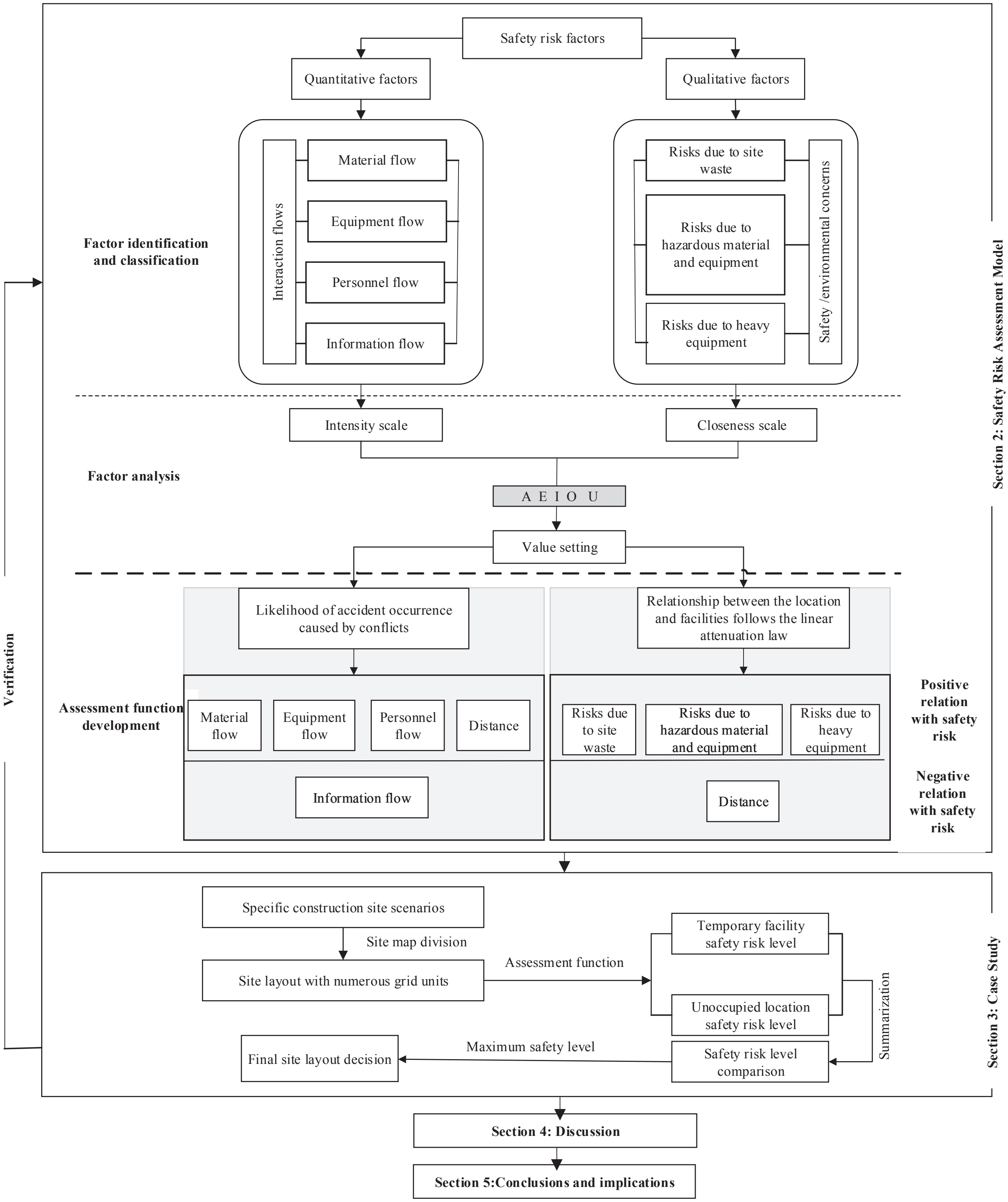

Fig. 1. Research flowchart of the paper.

leadership (Wu et al., 2015; Wu et al., 2017). Their goals have been to probe the relationships between human factors and safety performance, construct safe environments and thus avoid accidents. Based on these studies, this paper considers the design of construction site layouts containing higher safety levels via a systematic safety risk factor identification, classification and analysis and focuses on analyzing the relationship between risk factors and safety level in construction site layouts to build a safety risk assessment model that can assist site managers during the decision-making process.

A construction site layout is developed during the project planning phase, i.e. the preconstruction stage. Similar to a manufacturing plant, a construction site is used to produce an engineering product (e.g., buildings, roads, bridges, and railways). The laborers, machinery, materials and other resources are all located at the construction site. Site layout planning is critical to construction safety performance, as the disorderly placement of construction resources increases the likelihood of accidents. The highly frequent transportation of materials and laborers between facilities, such as fabrication shops, material laydown areas, and heavy equipment storage areas, also causes accidents at a construction site. Construction site layout planning must place facilities in the correct sequences and locations to increase the safety level of a construction site.

However, little attention has been paid to the safety assessment of a construction site layout. Previous studies considered site layout planning to be an optimization problem, which consists of a safety objective function and site safety zones identification in terms of the safety requirements and their fulfillment (Huang and Wong, 2015; Isaac and Edrei, 2016; Khalafallah and El-Rayes, 2006; Sanad et al., 2008). Regarding the safety objective function, the safety requirement is considered as one objective function with cost reduction in the multi-objective optimization problem (El-Rayes and Khalafallah, 2005; Ning and Lam, 2013). This type of problem requires a cost-safety trade-off to be established for the site layout plan. Cost is the initial requirement for construction management, and cost and safety are conflicting objective functions. The final site layout plan should be determined based on the established compromise between cost reduction and the required level of safety. When designing the safety objective function, risks resulting from falling objects, site waste, and hazardous chemicals are not adequately quantified in the objective function or explored in the optimization problem. In addition, interaction flows are not fully considered in the safety objective function. Interaction flows have a close relationship with site safety, as a higher number of interaction flows between facilities causes more resource conflicts and collisions, resulting in construction site accidents (El-Rayes and Khalafallah, 2005). Site safety zones are locations available for facilities assignment within the site boundary (Isaac and Edrei, 2016) and can be recognized in light of the necessary regulations, e.g., there should be 10 ft of clearance with respect to each existing building, and drive-ways between and around an open yard storage area should be at least 15 ft wide (Elbeltagi et al., 2004). If the construction site space is limited, temporary facilities in many cases must be assigned to locations outside of the predefined safe zone to facilitate the construction operation. The regulations on safety zones are sometimes ignored and hardly satisfied. Thus, a construction site layout often extends beyond the safety zone boundary in practice, thus exposing the construction site to potential risk.

Based on the above analysis, this paper aims to develop a safety risk assessment model which can assist site managers making decisions when facing different site layout scenarios. First, the model identifies, classifies and analyzes the safety risk factors of construction site layout planning. Then, a quantitative safety risk assessment function is developed to compute the safety risk levels for different construction site layout scenarios via a holistic factor evaluation. Then, a case study is used to validate the proposed model and illustrate its applicability in practice. This study will help site managers make scientific decisions pertaining to site layout safety in the preconstruction stage, thus effectively improving site safety and reducing the number of accidents caused by improper site layout design in the construction stage.

To illustrate the proposed safety risk assessment model in a more detailed and clearer manner, Fig. 1 is provided. This figure presents the model structure and the research process of this paper. The remainder of this paper is organized as follows. Section 2 introduces the development of the safety risk level assessment model, which includes factor identification and classification (Section 2.1), factor analysis (Section 2.2), and assessment function development (Section 2.3). Section 3 presents a case study to verify the practicality of the proposed model. After a discussion of the results (Section 4), major conclusions and implications are drawn (Section 5).

2. Model development

First, the safety risk factors involved in a construction site layout plan are identified and classified in the model. There are two categories of risk factors: interaction flows and safety/environmental concerns. Interaction flows consist of material flow, equipment flow, personnel flow and information flow. Risks due to site waste, risks due to hazardous materials and equipment, and risks due to heavy equipment are included in the safety/environmental concerns. In the section on factor analysis, the risk factors are quantified in terms of their corresponding inherence, i.e. quantitative factor or qualitative factor. Via a holistic factor analysis, the safety risk assessment functions are developed based on the relationship between the risk factors and the safety risk level. For interaction flows and safety/environmental concerns, assessment functions are built based on the likelihood of the occurrence of accidents due to conflicts and the linear attenuation law, which considers that hazard decreases with increasing distance, respectively.

2.1. *Safety risk factors identification and classification*

The laying out of a construction site involves the coordinated use of limited site space to accommodate temporary facilities (e.g., fabrication shops, material laydown area, or labor hut) so that they can function efficiently on site (Zouein et al., 2002). The temporary facilities are organized at the construction site based on the management's requirements, with consideration of the interaction relationships and locations of the facilities. In a construction site layout, the safety level of the environment is strongly influenced by the interactions between temporary facilities. The safety risk factors can be identified after analyzing the interaction relationships between facilities. This paper classifies the safety risk factors into two categories: interaction flows and safety/environmental concerns.

2.1.1. *Interaction flows*

A reasonable assignment of facilities within a site is significantly influenced by the movement of, or interactions between, resources, which can be called the interaction flows between facilities (Abotaleb et al., 2016; Dweiri and Meier, 1996; Hegazy and Elbeltagi, 1999; Karray et al., 2000). Interaction flows are essential factors considered in the construction cost (Lien and Cheng, 2012; Matai, 2015; RazaviAlavi and AbouRizk, 2017). Among the interaction flows, material flow involves the basic product transportation for each construction activity during the entire construction process. To ensure that the construction materials become construction products, information flow, equipment flow and personnel flow between facilities are necessary to promote material transportation during the production process. Detailed explanations of material flow, information flow, personnel flow and equipment flow (Dweiri and Meier, 1996; Karray et al., 2000) are given in Fig. 2.

The material flow, personnel flow and equipment flow between facilities have a close relationship with site safety. The transportation of materials, personnel, and equipment at a construction site leads to travel routes overlapping or interacting, which can potentially trigger accidents. Correspondingly, frequent interactions between materials, personnel, and equipment flows create more intersection points along heavily traveled routes. Thus, the likelihood of accidents occurring at these interaction points is high (El-Rayes and Khalafallah, 2005). Information flow involves verbal communication or reports between facilities, which ensure that a construction operation continues smoothly in a safe manner (Karray et al., 2000). Construction site safety performance is notably improved because of regular and frequent verbal safety communications between laborers on site (Kines et al., 2010). Through the use of mobile devices, construction workers are able to receive instant reports, replacing the traditional face-to-face information communication that used to occur on site regarding the safety status. Thus, time-consuming errors can be reduced, and site safety performance is improved correspondingly (Li, 2015). Therefore, information flow is closely related to and has a positive impact on construction site safety.

2.1.2. *Safety/environmental concerns*

Safety/environmental concerns (Elbeltagi and Hegazy, 2010)

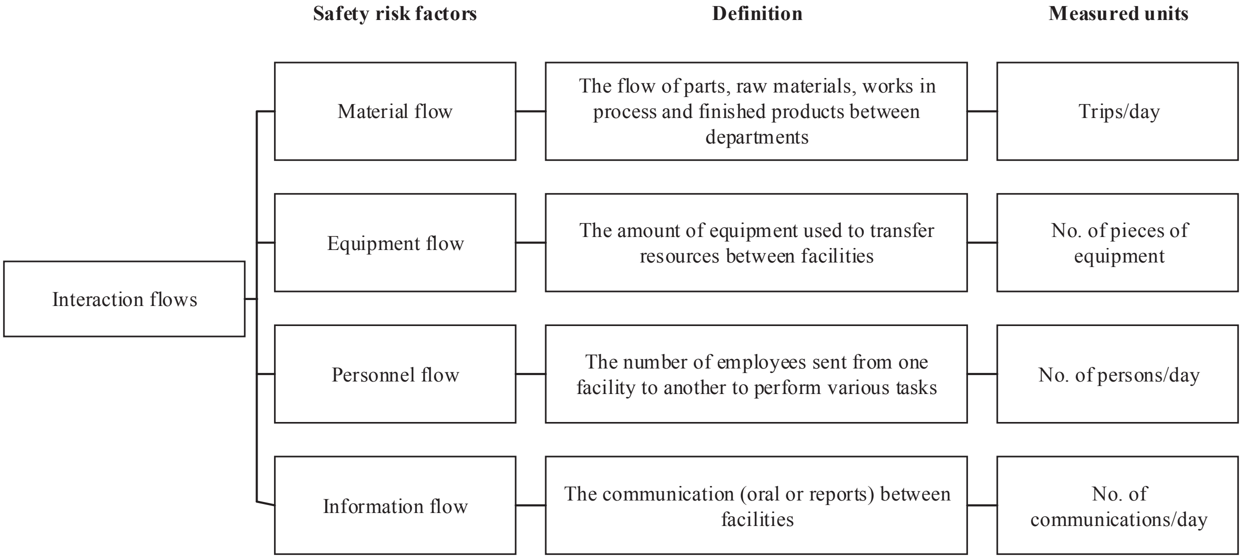

Fig. 2. Safety risk factors identified in interaction flows.

represent the level of safety and environmental hazards, which may arise when two facilities are close to each other, and may affect site workers by increasing the likelihood of accidents, noise, uncomfortable temperatures and pollution. This paper expands the definition of safety/environmental concerns and divides those concerns into different categories: risks due to site waste, risks due to hazardous materials and equipment, and risks due to heavy facilities.

2.1.2.1. Risks due to site waste. A good site layout can protect workers from risks. Hazardous waste site management will directly affect the health and safety of not only the personnel working at the site but also those in surrounding areas. The establishment of controlled work zones at hazardous waste sites is the basis of a good site layout (Martin and Levine, 1994). In the paper, site waste includes construction noise, dust, and vibration. Potential safety hazards increase as the distance between facilities decreases, and the rates of accidents, noise, discomfort, temperature and pollution increase accordingly.

A construction operation process involves the connection of different construction procedures, the alternate use of construction equipment and construction methods. A variety of irregular noise, known as construction noise, is present at construction sites (Kantová, 2017). The harm to operators exposed to noise at a construction site is equivalent to that of operators in a noisy workshop. Noise not only causes hearing loss but also leads to high blood pressure, heart disease and other diseases (Li et al., 2016). More seriously, the distraction of workers is the root cause of a variety of safety accidents (Kwon et al., 2016).

Vibrations are mainly induced by dynamic compaction during soft soil ground treatment. The process involves repeatedly dropping a heavy weight on ground composed of soft soil. The instantaneous stress energy produced during the compaction process is the same as that of a small earthquake and can damage the surrounding buildings in the same manner as an earthquake, thus undermining the safety of the buildings. Temporary facilities or temporary buildings can be damaged by compaction. Those facilities, such as steel processing plants and wood processing plants, will generate vibration when processing components and in turn cause damage to the surrounding facilities, leading to accidents (Meng et al., 2011).

Dust is the main site waste produced during the construction process. The dust between stacking facilities and other facilities is harmful to staff and results in potential hazards (Azuma et al., 2017).

2.1.2.2. Risks due to hazardous materials and equipment. Hazardous materials and equipment are often utilized and located at construction sites, exposing construction workers and engineers to safety risks. Hazardous materials must be controlled onsite by providing adequate separation between combinations of temporary facilities that can create hazardous conditions. Hazardous materials include explosives and blasting devices used during rock excavation; inflammable material or fuel used by construction equipment; sources of harmful radiation and high electric voltage; and the leakage and volatilization of various hazardous chemicals at a construction site. These hazardous chemicals can trigger fires or explosions, being potentially very dangerous with respect to the construction site. These hazardous materials and equipment must be properly stored and adequately separated to minimize the risk of accidents on site (Abune'Meh et al., 2016; El-Rayes and Khalafallah, 2005).

2.1.2.3. Risks due to heavy equipment. Falling objects are a primary cause of occupation fatalities and fatal injuries (Aneziris et al., 2014; Chen and Leu, 2014; Zhang et al., 2015). In a construction site layout, some temporary facilities, such as tower cranes and material hoists, remain at a specific location for material transportation. The locations of tower cranes in this project mainly depend on the steel structure hoisting magnitude, temporary material area, building structure geographical distribution, surrounding building height constraints, unloading area and vertical transportation of curtain walls. A material hoist is used for the transportation of materials to the superstructure, and its location is dependent on the structural elements to which it is tied; as such, site managers typically restrict this type of facility to a set location. The increasing industrialization of construction emphasizes the centrality of tower cranes as the main transportation equipment used on site. Although tower cranes largely determine the production rate of a site, they are arguably also the main generators of on-site safety hazards (Raviv et al., 2017a,b). The frequent material transportation conducted using tower cranes and material hoists induce risk to the facilities around them. Potential safety hazards increase as the distances between facilities decrease, and the rate of accidents increases accordingly.

2.2. Factor analysis

The safety risk factors involved in the proposed model are either quantitative or qualitative. Because of the different units of quantitative factors and qualitative factors, all factors must be normalized. In systematic layout planning (Hosseini et al., 2013; Muther, 1973),

Table 1
Intensity scale for quantitative factors.

Intensity scale	Symbol	Quantity for interaction flows (%)
Absolutely important	A	40–100
Especially important	E	30–40
Important	I	20–30
Ordinarily important	O	10–20
Unimportant	U	0–10

qualitative factors are measured using a closeness scale, and quantitative factors are measured using an intensity scale.

2.2.1. Determination of the intensity scale for quantitative factors

The interaction flows are evaluated by the intensity scale of five ranks, i.e. A (absolutely important), E (especially important), I (important), O (ordinary closeness acceptable), and U (unimportant), in terms of their quantity (Liu and Zhao, 2015; Muther, 1973), as shown in Table 1.

The imbalanced ranking rule in Table 1 is adopted from Muther's systematic layout planning (Muther, 1973), which is a traditional procedure layout design approach and proven to be an effective tool in providing layout design guidelines in practice in the past few decades (Yang et al., 2000). As construction site layout planning is a typical layout design problem, the ranking rule used in Muther's (1973) systematic layout planning is adopted. For Muther's (1973) research, the quantity for interaction flows between 40% and 100% is defined to A (Absolutely important), which means the amount of interaction flows played absolutely important roles in the construction process. For the intensity scale, U below 10% plays relatively unimportant roles in the construction process.

2.2.2. Determination of the closeness scale for qualitative factors

Risks due to site waste, risks due to hazardous materials and equipment, and risks due to heavy equipment are qualitative risk factors. The closeness scale of qualitative factors is determined by the site manager and also divided into five ranks, i.e. A, E, I, O, and U, according to the negative consequences of each factor if an accident does occur.

After the intensity scale and closeness scale are determined, the risk factors with different measurement units are all standardized to conform to the scales of A, E, I, O, and U. To quantify the safety risk level for a construction site layout based on the risk factors, the assumed values for the scales of A, E, I, O, and U are set to 243, 81, 27, 9 and 3, respectively (Grobelny, 1987; Karray et al., 2000; Lee and Moore, 1967; Ning et al., 2010; Yahya and Saka, 2014). Actually, the setting of proximity value is largely problem dependent, and is used as the basis for the placement of the facilities. The project manager can set other values based on his/her judgement or use a quantitative measure (Hegazy and Elbeltagi, 1999). The assumed value of 243, 81, 27, 9 and 3 are also proven to be effective in the previous site layout research (Karray et al., 2000; Ning et al., 2010). Therefore, this set of assumed values is adopted in the study. Moreover, the assumed values for the A-E-I-O-U scale mean the importance of this risk factor to the safety risk level of the whole site. With the assumed values, the safety level in the construction site can be assessed in a quantitative way.

2.3. Assessment functions development

A construction site consists of a series of unoccupied locations and locations occupied by temporary facilities and existing buildings. The safety risk level of a construction site is dependent on the site layout plan, with the safety environment changing based on the assignments of the different facilities. The safety risk level for a construction site should consider the unoccupied locations and locations occupied by the temporary facilities. The risk level of unoccupied locations is influenced by the existence of dangerous facilities, such as tower cranes (which have high risks related to the potential for falling objects) and workshops that generate noise pollution, in the surrounding area. These hazards are considered in the risk factors, i.e. risks due to site waste, risks due to hazardous materials and equipment, and risks due to heavy equipment. A location occupied by temporary facilities is influenced by not only the existence of dangerous facilities in the surrounding area but also the interaction flows between other facilities. Thus, the site safety risk level can be calculated in terms of the interaction flows (material flow, personnel flow, equipment flow and information flow) and safety/environmental concerns (risks due to site waste, risks due to hazardous materials and equipment, and risks due to heavy equipment). Assessment functions are developed based on the relationship between the risk factors and the safety risk level.

2.3.1. Safety risk level considering interaction flows

A high material flow, personnel flow and equipment flow between facilities along a road can result in an increased likelihood of accidents. This situation occurs because safety hazards develop at the intersection points or overlapping points along a road and because a high probability of conflicts and collisions exists at these points during resource transport (El-Rayes and Khalafallah, 2005). When the distances between facilities are greater, the resulting longer roads are more likely to create more intersection points or overlapping points, which is a root cause of accidents that occur during resource transport. Therefore, a safe construction site layout features proper shortening of the distances between facilities to reduce potential safety hazards and simplify construction operations for the efficient transport of materials, personnel and equipment. As discussed in Section 2.1.1, information is the communication transferred between facilities to guarantee the necessary transportation of materials, personnel and equipment among the facilities in a smooth and safe manner. Lower material flow, personnel flow, and equipment flow and greater information flow between facilities will lead to a higher safety level in the construction site layout.

The related safety risk is dependent on the intensity of interaction flows and the distance between facilities. This paper uses the risk interaction value r_{1kl} to represent the hazard of temporary facility k due to another temporary facility l because of the interaction flows between them. The risk interaction value r_{1kl} has a positive relationship with material flow, equipment flow, and personnel flow and a negative relationship with information flow. Extremely high flows between facilities yield a high likelihood of an accident occurring along the road between them. The likelihood of an incident will be reduced if some safety information exists. Except for the interaction flows, the distance between facilities also has a positive relationship with safety risk because a longer distance will increase the number of conflicts caused by the interaction flows. If the positive and negative impacts of the interaction flows and the effect of distance on the safety risk level are considered, the assessment function related to the interaction flows, denoted by the risk interaction value r_{1kl} can be expressed as Eq. (1).

$$r_{1kl} = \frac{(MF_{kl} + EF_{kl} + PF_{kl}) \times d_{ij}}{IF_{kl}} \tag{1}$$

When the facility k ($k = 1, 2, \ldots, m$) is assigned to location i ($i = 1, 2, \ldots, n$) and the facility l ($l = 1, 2, \ldots, m$) is assigned to location j ($j = 1, 2, \ldots, m$), $m \le n$, MF_{kl}, EF_{kl}, PF_{kl} and IF_{kl} are the assumed values for the material flow, equipment flow, personnel flow and information flow between facilities k and l, respectively. A high transportation frequency of material, equipment and personnel and a long distance between facilities will increase the construction site safety risk. If a higher information flow between facilities is available, the material, equipment, and personnel flows could occur smoothly to avoid conflicts along the roads between facilities. The construction site safety risk decreases as the information flow between facilities increases. The Euclidean distance d_{ij} between the locations i and j is shown in Eq. (2).

$$d_{ij} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} \tag{2}$$

The safety risk level R_{1IR} for all temporary facilities, considering interaction flows, is calculated as Eq. (3).

$$R_{1IR} = \sum_{l=1}^{m} \sum_{k=1}^{m} r_{1kl} \tag{3}$$

2.3.2. Safety risk level considering safety/environmental concerns

Risks due to site waste, hazardous materials and equipment mainly affect the personnel working around dangerous facilities and can produce noise, vibration, dust and dangerous chemicals. Thus, occupational health safety influences these personnel over the long term. For safety reasons, facilities should be located far away from these facilities. Objects falling from tower cranes and material hoists represent potentially fatal risks. The frequent transport of materials around these fixed facilities will increase the likelihood of an accident at the construction site. The unoccupied temporary facilities must be located far away from heavy facilities to reduce the conflicts due to material transport and decrease the fatal risk due to falling objects.

For unoccupied locations and locations occupied by temporary facilities, determination of the safety risk must include an evaluation of the different hazards originating from surrounding sources, i.e. risks due to hazardous materials and equipment, risks due to site waste and risks due to heavy equipment. The risk due to hazardous facilities depends on the distance between the location and facilities. A linear attenuation law, according to which hazard decreases with distance, i.e. a linear relationship exists between the risk values and the distance from the hazardous facilities, is assumed (Abune'Meh et al., 2016). The hazard due to dangerous facilities decreases as the distance between a facility and dangerous facilities increases. The decrease in hazard is represented by the linearly decreasing slope shown in Fig. 3.

In Fig. 3, the risk due to hazardous facilities, r_{2ik}, represents the hazard of location i due to a different dangerous facility k considering the three risk factors, i.e., RSW_{ik}, $RHME_{ik}$ and RHE_{ik}, the risks of location i due to the surrounding hazardous facility k originating from the site waste, hazardous materials and equipment, and heavy equipment, respectively, adhere to the linear attenuation law can be calculated by Eq. (4).

$$r_{2ik} = r_{2ik}^{0} + (1 - Z_{ik})\cdot r_D \cdot d_{ij} \tag{4}$$

where r_{2ik}^{0} is the assumed value for hazardous facility k considering site waste, hazardous materials and equipment, and heavy equipment. r_D is the decrease in risk (the slope of risk attenuation with distance). Z_{ik} is a binary variable with a value of 1 when facility k is assigned to location i and 0 otherwise.

The unoccupied location is surrounded by the different hazardous facilities with variable risk due to safety/environmental concerns, which have different impacts on the overall safety risk level. The impacts can be denoted as weights between the risks. In this study, the inverse distance weighting (IDW) method (Chen and Liu, 2012; Eum et al., 2010) is adopted to calculate the weights. IDW presents that the measured value closer to the prediction location have more influence on the predicted location than those farther away. It gives greater weights to points which are closer to the prediction location, and the weights diminish as a function of distance, i.e. $w = 1/d^e$, where e is exponent of d. The value for e is problem dependent. When this method is used to predict space risk in construction site, e is equal to 1. With the weights and risks derived from Eq. (4), the safety risk level of the unoccupied location can be calculated.

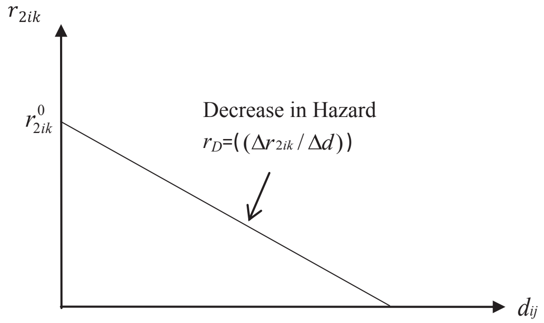

Fig. 3. Linear decrease in hazard at a construction site.

The safety risk level of unoccupied location i (i = 1, 2, …, n) from hazardous facility k when facility k (k = 1, 2, …, m) is assigned to location j (j = 1, 2, …, n) is expressed in Eq. (5).

$$R_{2IR} = \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{k=1}^{m} \frac{RSW_{ik} + RHME_{ik} + RHE_{ik}}{d_{ij}} \tag{5}$$

To compare and summarize the construction site risk levels, the safety risk associated with interaction flows and safety/environmental concerns should be normalized as shown in Eqs. (6) and (7).

$$r_{1kl}^{*} = \frac{r_{1kl}}{\max[r_{1kl}]} \tag{6}$$

$$r_{2ik}^{*} = \frac{r_{2ik}}{\max[r_{2ik}]} \tag{7}$$

where $\max[r_{1kl}]$ and $\max[r_{2ik}]$ are the maximum values for r_{1kl} and r_{2ik}, respectively. The safety risk corresponding to the interaction flows for all temporary facilities is expressed in Eq. (8).

$$R_{1IR}^{*} = \sum_{l=1}^{m} \sum_{k=1}^{m} r_{1kl}^{*} \tag{8}$$

For unoccupied locations and locations occupied by temporary facilities, the safety risk level corresponding to safety/environmental concerns is expressed as Eq. (9).

$$R_{2IR}^{*} = \sum_{i=1}^{n} \sum_{k=1}^{m} r_{2ik}^{*} \tag{9}$$

The safety risk level of a construction site layout is determined via the summation of Eqs. (8) and (9).

The safety risk level of facility k is calculated to offer an example. In Fig. 4, a construction site is divided into numerous grid units.

The temporary facilities around facility k are a rebar bending yard (Facility 1), tower crane (Facility 2), and fuel storage (Facility 3). The assumed intensity scales for information flow, material flow, personnel flow and equipment flow between facility k and the rebar bending yard, the tower crane, and the fuel storage are A, E, I, and I, respectively. The closeness scales for RSW, $RHME$ and RHE originating from the rebar

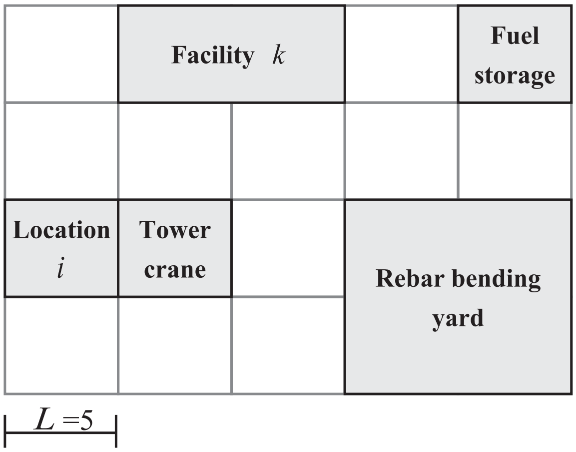

Fig. 4. Diagram of construction site with grid units.

bending yard are A, U, and U, respectively. *RSW*, *RHME* and *RHE* originating from the fuel storage are O, A, and U, respectively. *RSW*, *RHME* and *RHE* originating from the tower crane are I, U, and A, respectively. The assumed values for A, E, I, O, and U are 243, 81, 27, 9 and 3, respectively. The distances between facility k and the rebar bending yard, the tower crane and the fuel storage are 3.2L, 2.1L and 2.5L, respectively. Thus, the safety risk level of facility k for the interaction flow is as shown in Eqs. (10)–(12).

$$r_{1k1} = \frac{(81 + 27 + 27) \times 3.2L}{243} = 8.89 \tag{10}$$

$$r_{1k2} = \frac{(81 + 27 + 27) \times 2.1L}{243} = 5.83 \tag{11}$$

$$r_{1k3} = \frac{(81 + 27 + 27) \times 2.5L}{243} = 6.94 \tag{12}$$

The normalized safety risk for facility k is expressed as Eq. (13).

$$R^{*}_{2IR} = \frac{8.89}{8.89} + \frac{5.83}{8.89} + \frac{6.94}{8.89} = 2.44 \tag{13}$$

Assume that facility k is assigned to location 1; thus, the safety risk level for facility k considering the safety/environmental concerns caused by the rebar bending yard is expressed as in Eqs. (14)–(17).

$$RSW_{11} = 243\text{–}0.01 \times 3.2L = 242.84 \tag{14}$$

$$RHME_{11} = 3\text{–}0.01 \times 3.2L = 2.84 \tag{15}$$

$$RHE_{11} = 3\text{–}0.01 \times 3.2L = 2.84 \tag{16}$$

$$r_{211} = \frac{242.84 + 2.84 + 2.84}{3.2L} = 15.53 \tag{17}$$

In Eqs. (14)–(16), RSW_{11}, $RHME_{11}$ and RHE_{11} are calculated in terms of Eq. (4), the value for r_D is set to -0.01(Abune'Meh et al., 2016).

Similarly, $RSW_{12} = 26.90$, $RHME_{12} = 2.90$ and $RHE_{12} = 242.90$, and the safety risk is 25.97; $RSW_{13} = 8.88$, $RHME_{13} = 242.88$ and $RHE_{13} = 2.88$, and the safety risk is 20.37. The normalized safety risk is shown in Eq. (18).

$$R^{*}_{2IR} = \frac{15.53}{25.97} + \frac{25.97}{25.97} + \frac{20.37}{25.97} = 2.38 \tag{18}$$

For unoccupied location i, the calculation process used to determine its safety risk level is similar to that for facility k when considering the safety/environmental concerns.

3. Case study

3.1. Case description

A case study is used to demonstrate the application of the proposed method, which helps site managers make decisions regarding different site layout scenarios. The site layout with the minimum safety risk level is the optimal choice for site managers. Figs. 5–7 show three different site layout scenarios for the construction site layouts (Scenarios 1, 2, and 3) when a tower building of 18 to 50 floors is under construction. The facilities involved in the site layout are listed in Table 2.

As seen from the construction site layout, the construction site is divided into the living area and the construction area. The construction area includes adequate temporary facilities in terms of the construction requirements. In this study, only the locations of temporary facilities in the construction area are considered, as the temporary facilities in the construction area have a critical effect on the construction operation. The two tower cranes and three material hoists are fixed at a specific location.

3.2. Safety risk assessment for the three site layout scenarios

3.2.1. Safety risk factors analysis in the case study

The intensity scales for the material flow, personnel flow, equipment flow and information flow are shown in Figs. 8–11. Interaction flows exist between each pair of facilities. If no interaction between facilities is shown in Figs. 8–11, their interaction scale is U.

The qualitative risk factors that influence the safety risk level between facilities are risks due to hazardous materials and equipment, risks due to site waste and risks due to heavy equipment. The classification of the closeness scale for the qualitative factors is shown in Table 3.

3.2.2. Safety risk level for the three site layout scenarios

The three site layout scenarios are divided into a series of grids to calculate the safety risk levels; the dimensions of the grid are 5 m × 5 m (see Figs. 5–7). Table 4 shows the risk of each temporary facility based on the interaction flows and safety/environmental concerns. Table 5 shows the risk levels for unoccupied locations and the entire construction site layout.

In Table 5, the risk levels for Scenarios 1, 2 and 3 are 116.98, 80.99 and 102.76, respectively. Comparing the safety risk levels of the temporary facilities in the three scenarios, the safety risk level of Scenario 2 is lower than those of the other two scenarios. Regarding the risk level of the unoccupied locations, Scenario 2 also has the lowest risk (67.31) among the three scenarios. Thus, Scenario 2 is selected as the final construction site layout plan.

4. Discussion

In Section 3, using the proposed safety risk assessment model, the safety risk levels of temporary facilities are determined as shown in Table 4. Temporary facilities are influenced by the interaction flows and dangers originating from hazardous facilities, i.e. risks due to site waste, risks due to hazardous materials and equipment, and risks due to heavy equipment. For each temporary facility, the safety risk level is calculated via the summation of Eqs. (8) and (9). Section 4.1 presents a discussion of the results corresponding to temporary facilities.

With the exception of temporary facilities, unoccupied locations constitute the main part of a construction site layout. Because the safety risk level of unoccupied locations has a close relationship with the surrounding hazardous facilities and because interaction flows exist between them and other facilities, their safety risk level is calculated using only Eq. (9). A discussion on the safety risk level of unoccupied locations for the three scenarios is presented in Section 4.2.

4.1. Safety risk levels of temporary facilities for the three scenarios

The risk level of temporary facilities is mainly influenced by the interaction flows and relative positions of the different facilities. Figs. 12–14 show the distributions of the temporary facilities in the different three site layout scenarios for further discussion. The facility with the highest safety risk level has the darkest color.

In Table 4, the safety risk level of temporary facilities in the facility layout in Scenario 2 (see Fig. 13) has the lowest value (13.76). The safety risk level due to the interaction flows and safety/environmental concerns between facilities are 4.84 and 8.84, respectively. The facility layout in Scenario 2 is more compact, and the locations of F6 (steel raw material storage area), F7 (rebar bending workshop) and F8 (semi-finished steel products) are adjacent. F9 (installation material laydown area) and F11 (decoration material laydown area) are located around material hoists #1 and #3, respectively. The safety risk levels for F6, F7, F8, F9 and F11, considering interaction flows, are 0.18, 0.17, 0.13, 0.17 and 0.17, respectively. Much material flow occurs between those facilities, and the safety risk levels will be reduced as they become closer to each other because the shortened distance decreases conflicts

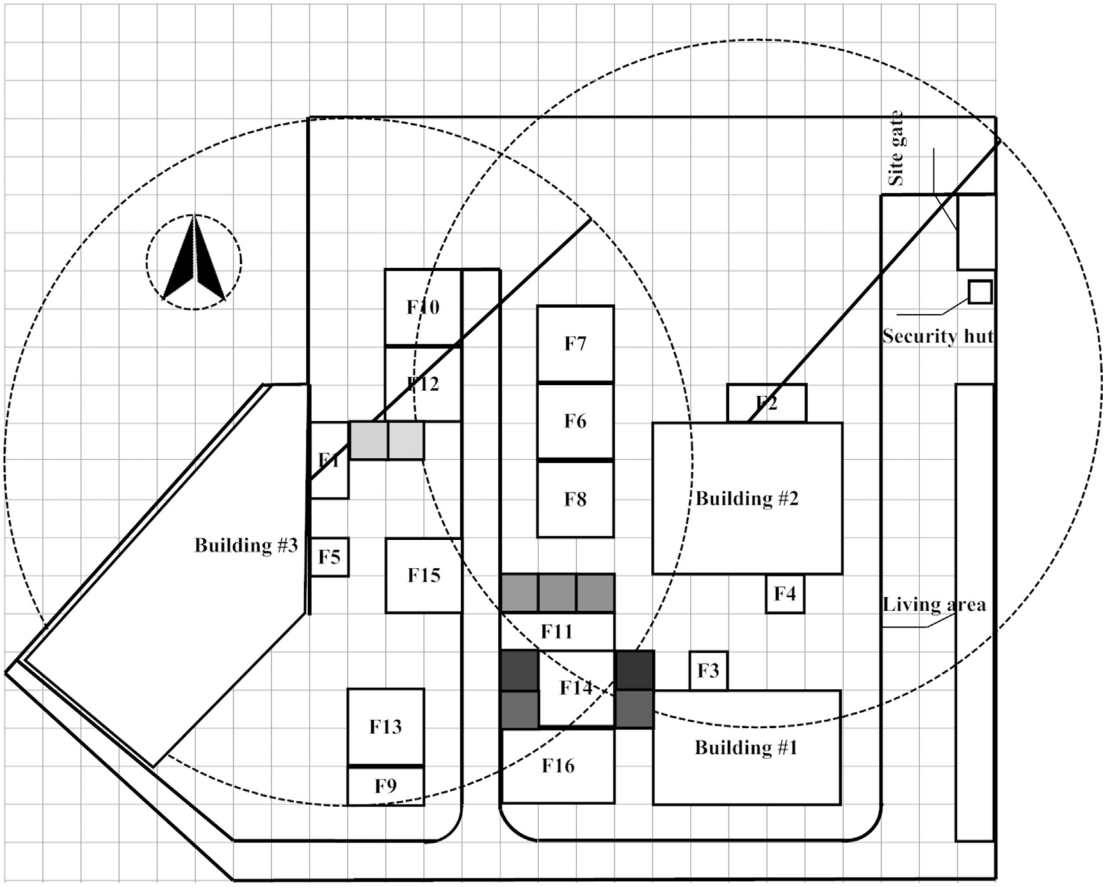

Fig. 5. Construction site layout of Scenario 1.

resulting from material transport. Such a layout will facilitate the transport of resources for service building construction. The safety risk levels between F6, F7 and F8 due to safety/environmental concerns are 0.89, 0.52 and 1, respectively. A high risk level occurs because there is a smaller distance between hazardous facilities. F11 is far away from the tower crane, steel bending workshop and fire equipment storage area; thus, the safety risk level, considering safety/environmental concerns, is small (0.43). There is a larger amount of information flow for F12 (inflammable material area) due to the potential risk, and F12 is located in the top left area of the construction site, where few personnel move around. Thus, the safety risk level due to the interaction flows of F12 is decreased to 0.19. Both F10 (carpentry workshop) and F14 (fire equipment area) are adjacent to F1 (tower crane #1); thus, the safety risk levels due to site waste and a heavy facility (i.e. the tower crane) are high, i.e. the safety risk levels for F10 and F14 are 0.69 and 0.62, respectively. F8 is completely surrounded by dangerous temporary facilities and has a significantly high safety risk level equal to a value of 1.00, considering safety/environmental concerns.

In site layout Scenario 1 (see Fig. 12), F10 (carpentry workshop) and F12 (inflammable material area) are farther away from tower crane #1 and material hoist #3 than in Scenario 2. The long transportation path increases the rate of accidents during the material-handling process. Therefore, the safety risk levels increase from 0.13 to 0.28 and from 0.19 to 0.47, respectively. There is a long distance between F13 (gravel yard) and the fixed facilities (F1 and F5) in Scenario 2; thus, the safety risk level, considering the interaction flow for F13, is 1.00.The safety risk level considering the safety/environmental concerns increases from 0.33 to 1.00 because F13 is arranged around other temporary facilities, such as F9, F14, F15 and F16, in Scenario 1. F14 (fire equipment storage area) is located between F11 and F16, and the distance is shorter than that in Scenario 2, which leads to a safety risk of 0.95. In Scenario 2, F16 (steel large formwork laydown area) is situated to the left of building #1, where temporary facilities are densely distributed; thus, the safety risk considering the safety/environmental concerns increases from 0.40 to 0.91. Accordingly, the safety risk level of temporary facilities in Scenario 2 is 18.31.

In Table 4, F12 has the highest safety risk level, with a value of 1.78, followed by F13 and F6 in the facility layout of Scenario 3 (see Fig. 14). Comparing the facility layouts of Scenario 3 and Scenario 2, F12 is located below building #3, which increases the distance from other facilities and ultimately increases the safety risk level. F13 and F15 are close to tower crane#1 and some other facilities in Scenario 3; thus, the safety risk level considering the safety/environmental concerns increases because of the shorter distances, compared to those in Scenario 2, with values of 0.87 and 1, respectively. Moreover, the locations of F6 (steel raw material storage area) and F7 (rebar bending workshop) in Scenario 3 are different from those in Scenarios 1 and 2. In this assignment, F6 is far away from the other facilities. Thus, the potential safety risk due to the interaction flows of F6 is larger than that in Scenario 2 (1.00 versus 0.18). However, the safety risk corresponding to safety/environmental concerns is decreased from 0.89 to 0.47, indicating that the increase in safety risk because of the interaction flow is greater than the reduction in safety risk corresponding to safety/environmental concerns. In addition, F11 is located in a crowded area between buildings #1 and #3. The safety risks generated from other facilities are extremely high. Such an arrangement increases the distance between F11 and other facilities, and the safety risk generated from the interaction flow is high. Under such an assignment of temporary facilities, the total safety risk level for the temporary facilities increases to 17.22.

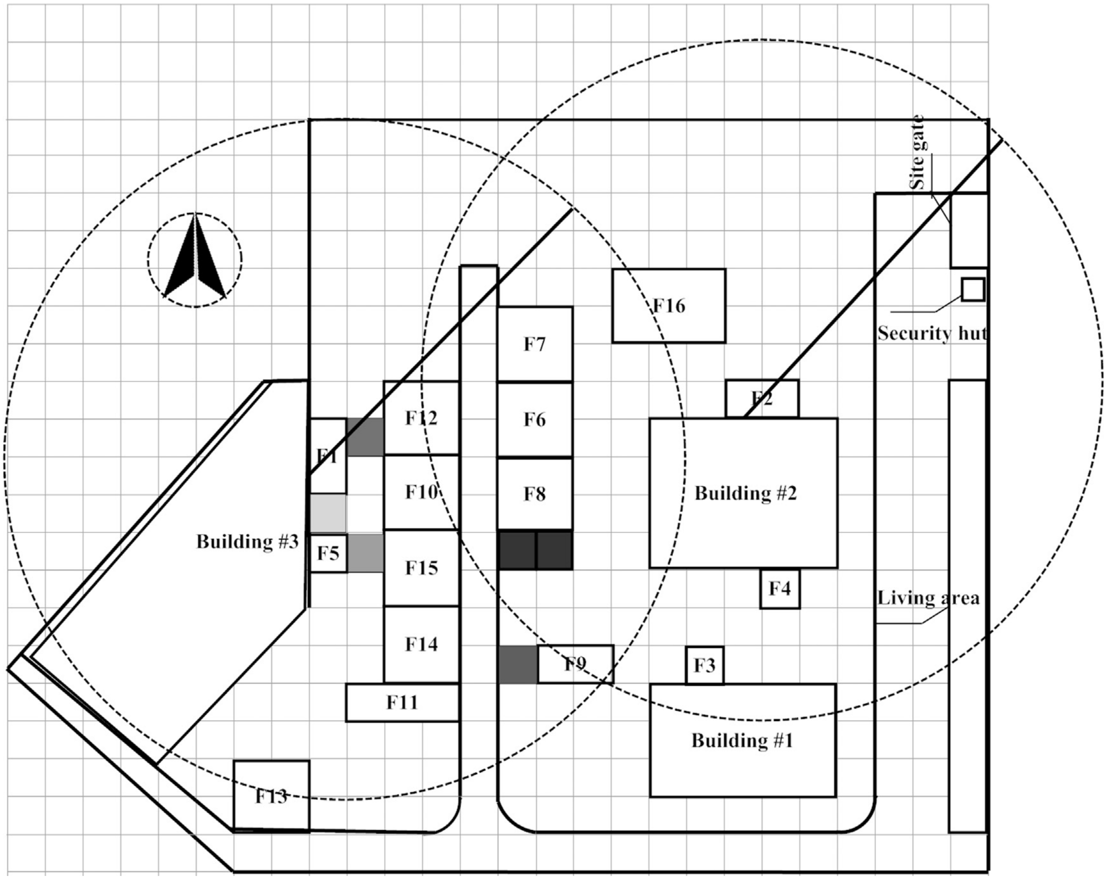

Fig. 6. Construction site layout of Scenario 2.

4.2. Safety risk level of unoccupied locations in the three scenarios

One hundred ninety-nine unoccupied locations exist in the construction site layout scenarios, and the total safety risk levels for Scenarios 1, 2, and 3 are 98.67, 67.31 and 85.84, respectively. The safety risk level of the unoccupied locations is lowest in Scenario 2. The shaded gray grids in Figs. 5–7 represent the highest safety risk among those unoccupied locations. The unoccupied locations around temporary facilities always have higher safety risk levels. A linear attenuation law exists between the decrease in hazard level and the distance. Therefore, the safety risk level of the unoccupied locations will be higher when the distance between the unoccupied locations and the surrounding temporary facilities is shorter. The unoccupied locations located far away from dangerous temporary facilities have a low safety risk level.

In Scenario 1, four unoccupied locations are surrounded by densely distributed temporary facilities, and the unoccupied locations around F14 have high safety risk levels of 1.00, 0.86, 0.93 and 0.83. Moreover, the three unoccupied locations above F11 are completely surrounded by temporary facilities, with high safety risk levels of 0.84, 0.98 and 0.86. In addition, the two unoccupied locations to the right of building #3 have relatively high safety risk levels (0.83 and 0.84, respectively) because of their proximity to F1 (tower crane #1) and F12 (inflammable material area). In Scenario 3, the unoccupied location to the left of tower crane #2 has the highest safety risk level of 1.00, followed by the two unoccupied locations next to F7 and F13, whose safety risk levels are 0.95 and 0.93. These unoccupied locations are near the tower crane and not far away from other facilities; thus, the safety risk levels are high. The unoccupied location near building #2 is located in the middle of the site and has a high safety risk level of 0.91. The safety risk levels for the unoccupied locations of the other shaded grids in Scenario 3 are relatively low, as they are far away from heavy equipment and not in a centralized location with respect to the temporary facilities. In Scenario 2, the two unoccupied locations below F8 have the highest potential safety risk levels (1.00 and 0.96), followed by the unoccupied location near F9 (0.91). These unoccupied locations are placed among temporary facilities. In addition, the unoccupied locations to the left of the construction site have higher safety risk levels than other locations because they are close to heavy equipment and other facilities, such as F10, F12, and F15. The layout of all temporary facilities is more compact in Scenario 2, which decreases the safety risk level of the entire site layout.

In summary, the safety risk level of Scenario 2 is lower than that of the other two scenarios, i.e. Scenario 2 has the maximum safety level. Therefore, Scenario 2 is the best choice for decision-makers.

4.3. Limitations and directions for future research

The construction site layout evolves as construction progresses and is a dynamic problem. However, this paper treats the site layout as a static problem without taking time into consideration. The selected construction site layout is suitable for a specific construction stage, but may be not applicable through the entire construction process. Based on the proposed safety risk assessment model, future research should further enhance construction site safety assessment and management for different construction stages.

The safety risk assessment model proposed in this paper is applicable in the preconstruction stage but may be not the case in the construction stage. As the construction environment is dynamic and transient, the risk factors in the construction stage tend to be different from those estimated in the preconstruction stage. Following the application of information technology (IT) in the construction industry, the risk factors can be captured in real-time manners; thus, an IT-based safety risk alerting and mitigating system based on the proposed model can be

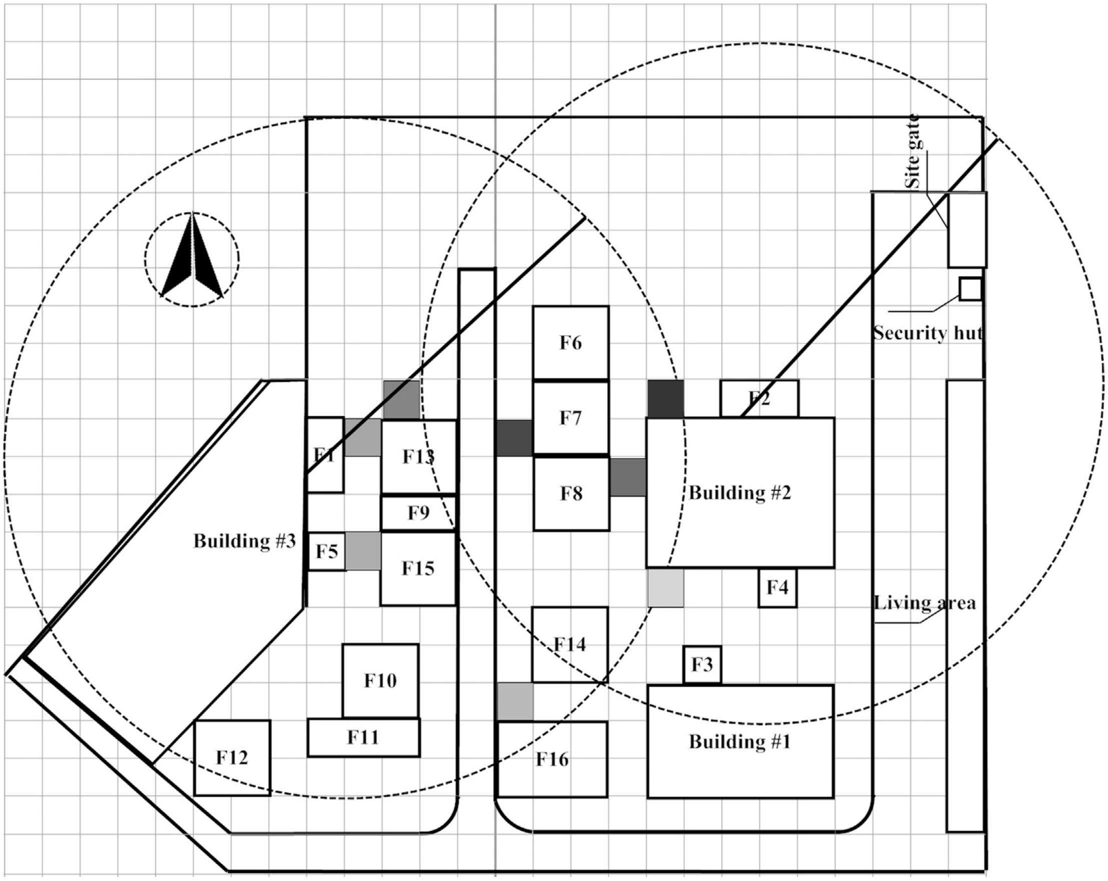

Fig. 7. Construction site layout of Scenario 3.

developed in the future research.

5. Conclusions and implications

This paper proposes a new safety risk assessment model to help site managers make scientific decisions when facing different site layout scenarios. The model consists of three parts, i.e. factor identification and classification, factor analysis, and assessment function development. The model classifies risk factors into two categories, i.e. interaction flows and safety/environmental concerns. The interaction flows include material flows, equipment flows, personnel flows and information flows. Risks due to site waste, risks due to hazardous materials and equipment, and risks due to heavy equipment constitute the safety/environmental concerns. In factor analysis, the risk factors are quantified using a five ranks, the assessment function pertaining to the interaction flow is established according to the likelihood of accident

Table 2
List of temporary facilities.

Temporary facility	Code	Temporary facility	Code
Tower crane #1	F1	Installation material laydown area	F9
Tower crane #2	F2	Carpentry workshop	F10
Material hoist #1	F3	Decoration material laydown area	F11
Material hoist #2	F4	Inflammable material storage area	F12
Material hoist #3	F5	Fire equipment area	F13
Steel raw material storage area	F6	Gravel yard	F14
Rebar bending workshop	F7	Block yard	F15
Semi-finished steel products	F8	Steel large formwork laydown area	F16

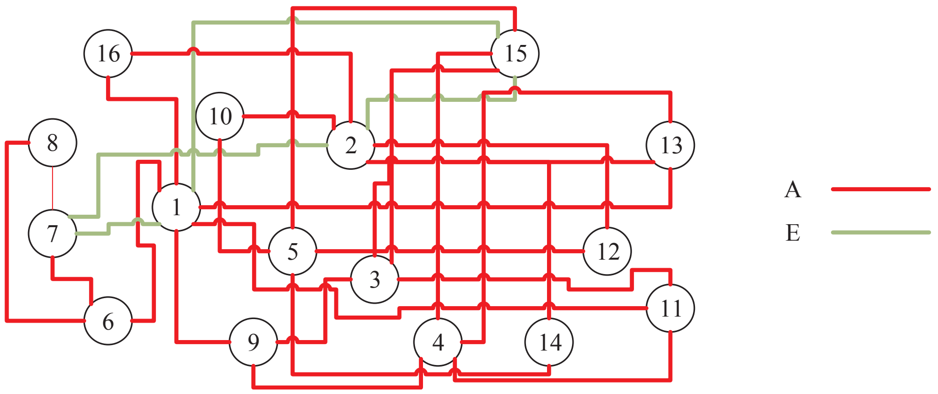

Fig. 8. Intensity scale for material flow.

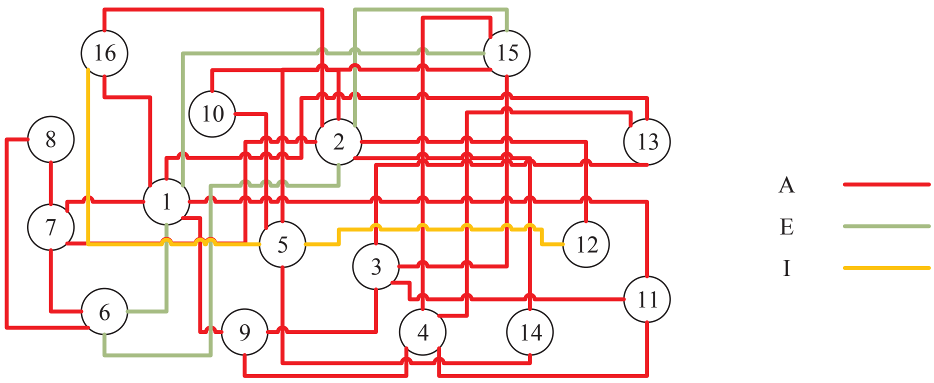

Fig. 9. Intensity scale for personnel flow.

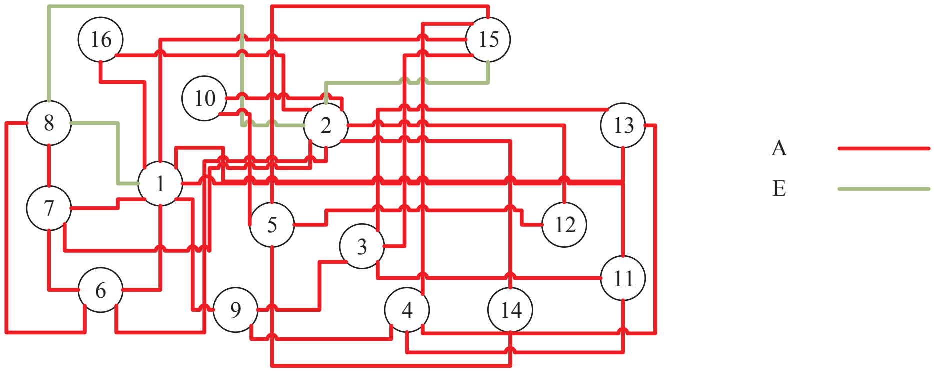

Fig. 10. Intensity scale for equipment flow.

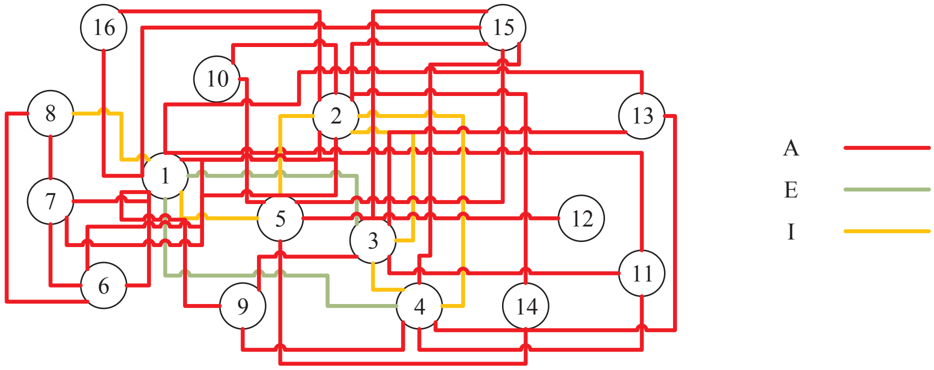

Fig. 11. Intensity scale for information flow.

Table 3
Risk closeness scale for the facilities.

Facility code	F1	F2	F3	F4	F5	F6	F7	F8
Risk due to site waste	*E*	*E*	*I*	*I*	*I*	*O*	*A*	*U*
Risk due to hazardous materials and equipment	*U*	*U*	*U*	*U*	*U*	*U*	*O*	*U*
Risk due to heavy equipment	*A*	*A*	*E*	*E*	*E*	*U*	*U*	*U*
Facility code	F9	F10	F11	F12	F13	F14	F15	F16
Risk due to site waste	*A*	*A*	*A*	*A*	*A*	*O*	*I*	*E*
Risk due to hazardous materials and equipment	*A*	*A*	*A*	*A*	*A*	*U*	*U*	*E*
Risk due to heavy equipment	*U*	*U*	*U*	*U*	*U*	*U*	*U*	*U*

occurrence. For safety/environmental concerns, the assessment function is developed based on the linear attenuation law. A case study of three construction site layout scenarios is used to verify the proposed model. The main findings of the paper support the following arguments.

- The facility layout for a construction site has a crucial impact on the safety risk level. The site environment varies for different facility distributions and assignments, as the existence of hazardous facilities in the surrounding area is the main driver of potential accidents.
- The safety risk level of a site layout should consider the safety status of unoccupied locations and facilities located at the construction site. The safety risk level of temporary facilities is related to the interaction flows and surrounding hazardous facilities. However, for unoccupied locations, the safety/environmental concern related to those hazardous facilities located in the surrounding area is the only risk factor considered when assessing the safety risk level.
- To improve site safety, facilities with high interaction flows between them should be placed near each other because along transportation path, the collisions and conflicts caused by the frequent transport of resources increase the likelihood of accidents. If dangerous and heavy equipment exist nearby, the facilities should be assigned to locations far away from them, as hazard decreases with distance.

Theoretical implications of this paper include the following three aspects.

Table 4
Safety risk levels of temporary facilities for the three site layout scenarios.

Facility code	Scenario 1			Scenario 2			Scenario 3		
	IF	SEC	Σ	IF	SEC	Σ	IF	SEC	Σ
F1	0.16	0.70	0.86	0.10	0.54	0.64	0.18	0.57	0.75
F2	0.96	0.42	1.38	0.92	0.30	1.22	0.88	0.32	1.20
F3	0.41	0.76	1.17	0.53	0.40	0.93	0.49	0.53	1.02
F4	0.23	0.61	0.84	0.19	0.33	0.52	0.29	0.45	0.74
F5	0.19	0.78	0.97	0.13	0.65	0.78	0.21	0.79	1.00
F6	0.44	0.82	1.26	0.18	0.89	1.07	1.00	0.47	1.47
F7	0.24	0.76	1.00	0.17	0.52	0.69	0.25	0.54	0.79
F8	0.19	0.87	1.06	0.13	1.00	1.13	0.23	0.66	0.89
F9	0.28	0.52	0.80	0.17	0.38	0.55	0.21	0.60	0.81
F10	0.28	0.72	1.00	0.13	0.69	0.82	0.38	0.47	0.85
F11	0.19	0.93	1.12	0.17	0.43	0.60	0.29	0.80	1.09
F12	0.47	0.80	1.27	0.19	0.57	0.76	0.96	0.82	1.78
F13	1.00	1.00	2.00	1.00	0.33	1.33	0.84	0.87	1.71
F14	0.40	0.95	1.35	0.48	0.62	1.10	0.46	0.54	1.00
F15	0.19	0.92	1.11	0.15	0.80	0.95	0.21	1.00	1.21
F16	0.24	0.91	1.15	0.20	0.40	0.60	0.28	0.63	0.91
Σ	5.85	12.46	18.31	4.84	8.84	13.76	7.16	10.06	17.22

Note: IF denotes interaction flows, and SEC denotes safety/environmental concerns.

Table 5
Safety risk levels for the three construction site layout scenarios.

Site layout scenario	Safety risk level of temporary facilities	Safety risk level of unoccupied locations	Safety risk level of site layout plan
Scenario 1	18.31	98.67	116.98
Scenario 2	**13.76**	**67.31**	**80.99**
Scenario 3	17.22	85.54	102.76

Note: Bold values are the risk levels for the finally selected site layout plan.

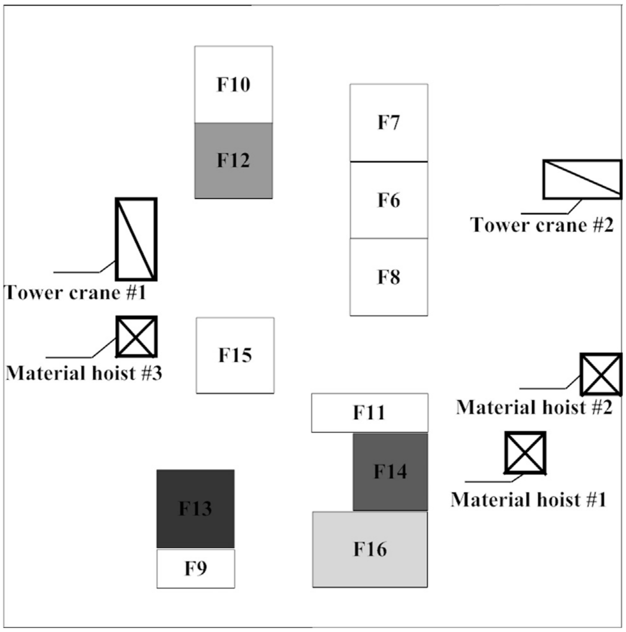

Fig. 12. Facilities layout in Scenario 1.

- The proposed model offers a systematic evaluation framework for risk factors that occurs in the preconstruction stage, including risk factor identification, classification and analysis. The interaction flows, which are highly related to construction costs, are initially considered as one major risk factor category. The remaining risk factors, such as noise, vibration, and dangers from hazardous materials and equipment, which have either been neglected or given insufficient emphasis to in previous studies, are all included in the safety/environmental concerns as risk factors.
- The intensity scale and closeness scale are adopted in this paper to yield normalized risk factors, respectively. This normalization method can serve as a reference for related research.
- Interaction flows were regarded as key factors influencing construction costs in previous studies. In this paper, interaction flows are initially recognized as risk factors, and a new assessment function related to material flows, equipment flows, personnel flows and information flows is developed.

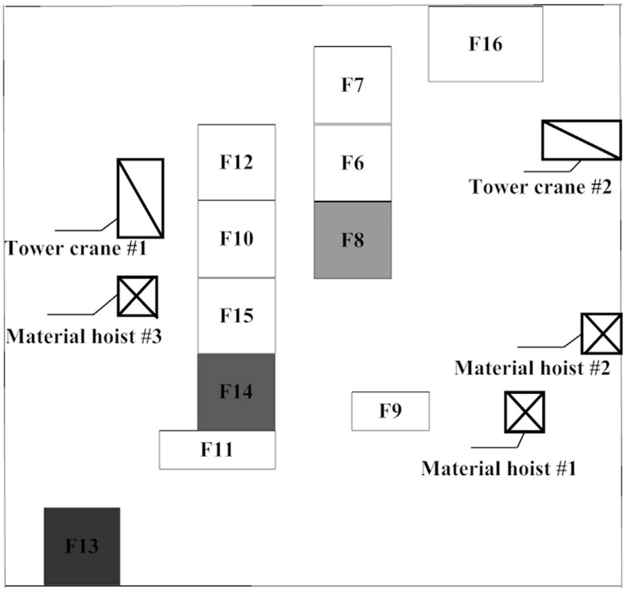

Fig. 13. Facilities layout in Scenario 2.

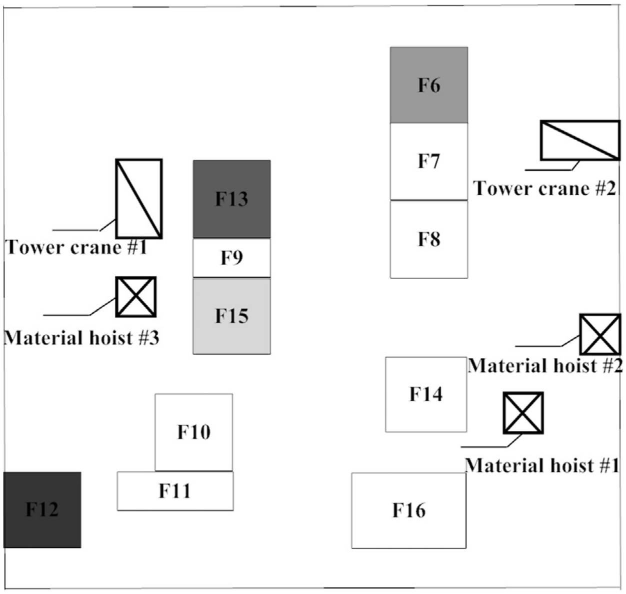

Fig. 14. Facilities layout in Scenario 3.

Practical implications of this paper include, but not limited to, the following three aspects.

- To improve the construction site safety level, site managers should decrease the transportation frequency of materials, personnel and equipment and shorten the travel distance. Meanwhile, regular and frequent verbal safety communications during construction operations would help improve site safety performance.

- A construction site surrounded by several dangerous facilities has a potentially high level of safety risks. Dangerous and heavy equipment and machinery should be assigned to locations far away from each other and far from the congested working areas.
- Site manager are encouraged to use mobile device to provide real-time safety information to on-site workers instead of face-to-face communication, which can improve safety performance without increasing resource conflicts caused by greater personnel flow on the construction site.

On the whole, this paper reveals the importance of site safety management during the preconstruction stage. The safety risk assessment model establishes a connection between the layout of facilities and site safety management, or more specifically, interprets how to implement site safety management in the perspective of site facility layout improvement. According to the above main findings and implications, it offers constructive recommendations encouraging site managers to conduct site safety management during the preconstruction stage. It contributes to and enriches occupational safety research by providing a uniform model for assessing construction site layout plans in a quantitative and more valid manner. Based on this study, future research can emphasize on developing a more dynamic risk assessment model considering changes in time and construction environments, so as to control site safety risks through the entire construction process.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ssci.2018.01.016.

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