Trade-off between Safety and Cost in Planning Construction Site Layouts

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Abstract: Planning construction site layouts involves identifying the positions of temporary facilities on site, and accordingly it has a significant impact on the safety and efficiency of construction operations. Although available models are capable of minimizing the travel cost of resources on site, they do not consider safety as an important and separate objective in the optimization of site layouts. This paper presents the development of an expanded site layout planning model that is capable of maximizing construction safety and minimizing the travel cost of resources on site, simultaneously. The model incorporates newly developed concepts and performance criteria that enable the quantification of construction safety and travel cost of resources on site. The present model is developed in three main phases: (1) formulating decision variables and optimization objectives in this site layout planning problem; (2) identifying and satisfying all practical constraints in this optimization problem; and (3) implementing the model as a multiobjective genetic algorithm. An application example is analyzed to illustrate the use of the model and demonstrate its capabilities in optimizing construction site layouts and generating optimal trade-offs between safety and travel cost of resources on site.

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Introduction

Planning construction site layouts requires identifying the locations of temporary facilities including security fences, access roads, storage areas of material and equipment, stockpiles of excavation, site offices, fabrication shops, and batch plants (Yeh 1995; Hegazy and Elbeltagi 1999). A proper site layout can lead to (1) reducing the cost of materials handling; (2) minimizing travel times of labor, material, and equipment on site; (3) improving construction productivity; and (4) promoting construction safety and quality (Tommelein et al. 1992; Anumba and Bishop 1997). As such, developing and maintaining an effective site layout is a significant and critical task that should be properly performed and updated during the project planning and construction phases.

A number of studies were conducted in order to improve site layout planning in construction projects. These studies adopted a wide range of methodologies and development tools including neural networks, simulation, knowledge-based systems, and genetic algorithms. For example, Yeh (1995) used annealed neural networks to arrange a set of predetermined facilities on a set of predetermined locations on construction sites. Several expert systems and knowledge-based systems were also developed to integrate domain knowledge of experts and assist in facility layout planning tasks (Kumara et al. 1988; Hamiani 1989; Tommelein et al. 1991; Tommelein and Zouein 1993). Other studies proposed heuristic algorithms including the use of the early commitment criterion to design site layouts (Zouein and Tommelein 1999); and the utilization of relative significance and ranking of temporary facilities (Tam et al. 2002). Dawood and Marasini (2001) used simulation to develop a model that assists managers in designing and managing the layout of stockyards. Tawfik and Fernando (2001a) integrated simulation with genetic algorithms in an attempt to optimize site layouts. Genetic algorithms were also used in several studies to optimize the layouts of construction sites (Tam 1992; Islier 1998; Li and Love 1998; Hegazy and Elbeltagi 1999; Shayan and Al-hakim 1999; Harmanani et al. 2000; Tawfik and Fernando 2001b; Mawdesley et al. 2002). These genetic algorithms have shown improvements in the search process for near optimal solutions, especially in this type of problem that is characterized by a large search space.

Despite the contributions and practical features of the above site layout planning models, they all focused on providing a solution that seeks to optimize the single objective of reducing travel distances of resources. In many real-world projects, this is often considered inadequate as other objectives such as improving safety may prove to be equally if not more significant. Construction safety is one of the most important but least considered objectives in site layout planning and design (Anumba and Bishop 1997). This is particularly true in the construction industry which suffers from more accidents of greater severity than other industrial sectors (LU and UMIST 2003). The National Institute for Occupational Safety and Health (NIOSH) ranks the construction industry as the first in causing nonfatal injuries at a rate of 9.3 injuries per 100 full-time workers in 1997 (NIOSH 2000). Moreover, the Bureau of Labor Statistics (BLS) ranks the construction

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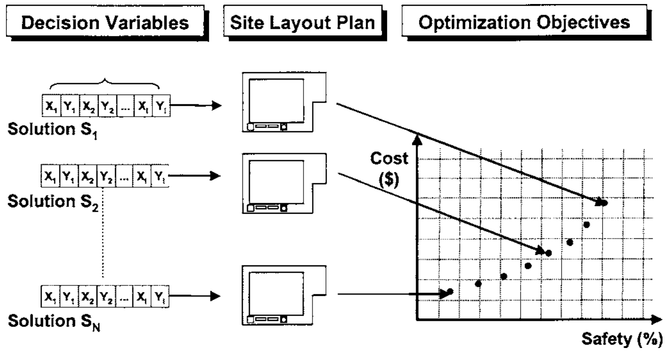

Fig. 1. Model formulation

industry among the top three industries causing fatal injuries in the United States in 2002 with a rate of 12.2 fatalities per 100,000 workers (BLS 2004). These statistics highlight the need for further research efforts to develop advanced and expanded site layout planning models that are capable of considering and improving safety while seeking to minimize the travel cost of resources on construction site.

Objective

The objective of this study is to develop a robust model that supports multiobjective optimization of site layout planning in order to enable the simultaneous maximization of safety and minimization of travel cost of resources on site. To accomplish this objective, the present site layout planning model is developed in three main phases: (1) formulating decision variables and optimization objectives; (2) identifying and satisfying all practical constraints in planning construction site layouts; and (3) implementing the model as a multiobjective genetic algorithm. The following sections provide a detailed description of these three development phases.

Decision Variables and Optimization Objectives

The present model is formulated to support construction planners in identifying near optimal locations for all temporary facilities on construction sites such as storage areas of material and equipment, stockpiles of excavation, site offices, fabrication shops, and batch plants. As such, the considered decision variables in the present model are the coordinates (X_i, Y_i) of the center of gravity of each temporary facility ($i=1$ to I). In the present model, these variables are represented by an artificial genetic chromosome that depicts the coordinates (X_i, Y_i) of each temporary facility (i) on site, as shown in Fig. 1. The designed chromosome enables the present model to evaluate the impact of various site layout solutions (S_1 to S_N) on safety and travel costs of resources (see Fig. 1).

The two main optimization objectives supported in the present model are (1) to maximize the safety of construction operations; and (2) to minimize the travel cost of resources on site. The following sections present newly developed concepts and performance criteria that enable the quantification and measurement of these two important site layout planning objectives.

Maximize Construction Safety

The first optimization objective in this model is to maximize the safety of construction operations. In order to achieve this, the impact of relevant site layout measures that can improve construction safety needs to be identified and quantified. To this end, a comprehensive literature review (Anumba and Bishop 1997; Tawfik and Fernando 2001b; UO 2003; OSHA 2003c) and several field studies were conducted in order to explore and identify practical measures that can be taken during the site layout planning process in order to maximize construction safety. This investigation led to the identification of three major measures: (1) proper positioning of temporary facilities to improve the safety to crane operations and minimize accidents caused by falling objects; (2) control of hazardous material and equipment on site; and (3) reducing intersections between heavily traveled routes of construction resources. The following sections provide a brief description of these three measures and the newly developed performance criteria to quantify their impact on construction safety in the present model.

Safety of Crane Operations

Although cranes play an indispensable role in handling heavy material and equipment on construction sites, available statistics indicate that cranes and falling objects are one of the leading causes of construction accidents (Anumba and Bishop 1997; NIOSH 2000; Hiller and Schneider 2001; OSHA 2004b). For example, the Occupational Safety and Health Administration (OSHA) reports that an average of 71 fatalities occur each year in the United States due to crane accidents (OSHA 2003b). OSHA also reported that 151 safety violations were caused by crane operations during the recovery efforts following the disastrous collapse of the World Trade Center on September 11, 2001 (OSHA 2003a).

In order to maximize the safety of crane operations, OSHA requires contractors to provide protection and safety measures against falling objects especially below steel erection operations (OSHA 2003c, 2004b). To this end, the present model is designed to search for safe locations of temporary facilities in an attempt to minimize the risk of crane accidents and falling objects, especially on areas where construction workers and engineers are concentrated. For example, one of the practical safety measures that can be adopted during site layout planning is to locate site offices and high occupancy facilities outside the range of crane operations whenever possible. In order to achieve this, the present model incorporates a newly developed performance metric named crane safety criterion (CSC). This new performance metric (CSC) enables planners to measure and quantify the degree of safety for all occupants of temporary facilities on site according to their planned positions and exposure to falling objects from operating cranes as a function of (1) the sensitivity (V_i) of each temporary facility i to potential falling objects from cranes, which can be used to represent the potential risk of injuries and/or fatalities if such an incident occurs; (2) the distance (d_{ik}) between facility i and crane k, as shown in Fig. 2 and Eqs. (1) and (2); and (3) the positioning of the facility either within the operating or nonoperating angles of the crane as shown in Fig. 2. First, the sensitivity of temporary facilities (V_i) can be specified by construction planners by selecting from three categories of low, medium, and high sensitivity. A low category represents facilities that pose little or no risk if they are subjected to falling objects due to their limited occupancy of workers. Conversely, a high category represents high risk facilities that expose a large number of workers to fall-

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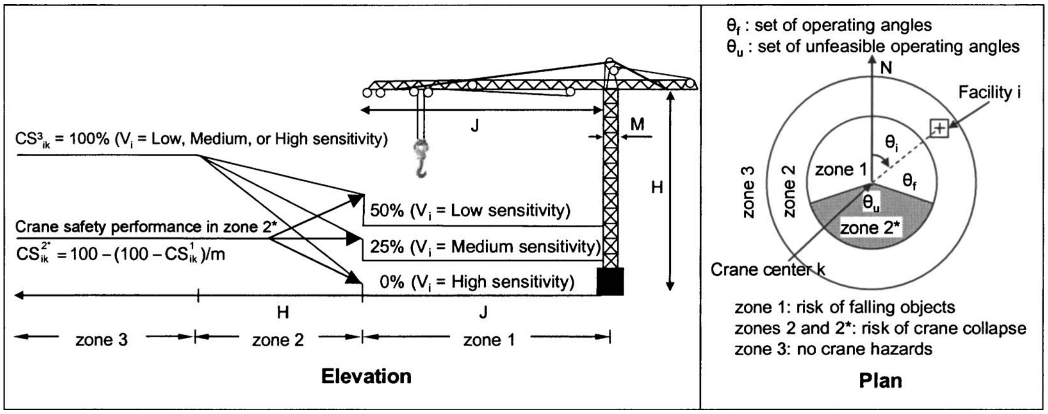

Fig. 2. Safety zones around cranes

ing objects. Second, the distances (d_{ik}) between temporary facilities and cranes on site are automatically calculated and considered by the model for each generated site layout plan. Third, the positioning of the facility is automatically generated by the model to examine whether it is located within the operating or nonoperating angles of the crane and accordingly whether it will be exposed to the risk of falling objects or the risk of crane collapse, respectively, as shown in Fig. 2.

In the proposed model, the sensitivity (V_i) of each facility and its proximity (d_{ik}) to cranes is considered using a crane safety indicator (CS_{ik}^z), as shown in Eq. (2). This indicator classifies the space around the crane into four zones, as shown in Fig. 2. Zone 1 is the area that covers the crane operating angles ($d_{ik} < J + M/2$ and $\theta_i \in \theta_f$), and it represents the highest risk zone due to its vulnerability to falling objects from the crane during its operations. Zone 2 is located between Zones 1 and 3 ($J + M/2 \leqslant d_{ik} < H + J + M/2$), and it represents an intermediate level of risk due to its minor vulnerability to low probability crane accidents such as the tilting and/or collapse of the crane. Zone 2^* is the area representing the range of unfeasible crane operating angles ($d_{ik} < J + M/2$ and $\theta_i \in \theta_u$) due to various site restrictions on crane motion such as the existence of power lines, and thus Zone 2^* can only be exposed to the risk of crane collapse rather than falling objects as shown in Fig. 2. Zone 3 lies outside the crane risk areas ($d_{ik} \geqslant H + J + M/2$), and therefore its safety is unaffected by crane operations (i.e., $CS_{ik}^3 = 100\%$). Based on the sensitivity of each facility (V_i), its location (d_{ik}) within these three zones, and its exposure to the risk of either falling objects or crane collapse, the present model calculates a crane safety indicator (CS_{ik}^z), as shown in Eq. (2). The model is designed to allow a relative increase in the crane safety indicator (CS_{ik}^z) if the facility is moved from the zone of falling objects (Zone 1) to the zone of crane collapse (Zones 2 and 2^*) as shown in Fig. 2. In the present model, this relative increase in safety is calculated as a function of the ratio (m) between the expected risk of falling objects to that of crane collapse (e.g., 1:10), which can be expressed by planners based on their previous experience [see Fig. 2 and Eq. (2)].

The calculated indicators (CS_{ik}^z) for each combination of facility i and crane k are then averaged to identify a crane safety criterion (CSC) for the overall site layout plan, as shown in Eq. (1). It should be noted that the overall crane safety criterion (CSC) in the present model is formulated in a practical way that enables its measurement on a performance scale that ranges from 0 to 100%.

$$\text{Crane safety criterion (CSC)} = \frac{\sum_{k=1}^{K} \frac{\sum_{i=1}^{I} (CS_{ik}^z)}{I}}{K} \tag{1}$$

$$CS_{ik}^z = \begin{cases} CS_{ik}^1 = \begin{cases} 0\% \ (V_i = \text{high}) \\ 25\% \ (V_i = \text{medium}) \\ 50\% \ (V_i = \text{low}) \end{cases} & \text{(Zone 1)} \\ CS_{ik}^{2^*} = 100 - \dfrac{100 - CS_{ik}^1}{m} & \text{(Zone 2}^*\text{)} \\ CS_{ik}^2 = (100 - CS_{ik}^{2^*})\left(\dfrac{d_{ik} - J - M/2}{H}\right) + CS_{ik}^{2^*} & \text{(Zone 2)} \\ CS_{ik}^3 = 100\% \ (V_i = \text{high, medium, or low}) & \text{(Zone 3)} \end{cases} \tag{2}$$

where CS_{ik}^z = crane safety performance for temporary facility i due to its proximity to crane k in Zone z; V_i = sensitivity of facility i to falling objects; d_{ik} = distance between facility i and crane k; I = total number of facilities on site; K = total number of cranes on site; J = length of the crane jib; M = width of the crane mast; m = ratio between the risk of falling objects from crane and the risk of crane collapse; H = reach of the crane; θ_i = angle representing the location of temporary facility i measured clockwise from the north direction; θ_f = set of crane operating angles; and θ_u = set of unfeasible crane operating angles.

Control of Hazardous Material

Hazardous material and equipment are often utilized and located on construction sites, exposing construction workers and engineers to safety risks (OSHA 2004a). Hazardous materials include (1) explosives and blasting devices used in rock excavation; (2) flammable material such as fuel used by construction equipment; (3) toxic substances such as asbestos, coal tar pitch volatiles, cadmium, benzene, formaldehyde, methyl chloride among other materials including 13 carcinogens identified by OSHA (OSHA 2003c); and (4) sources of harmful radiation and high electric voltage. These hazardous materials and equipment need to be properly stored and adequately separated to minimize the risk of accidents on site. For example, OSHA standard 1926.407 recommends storage facilities of electrical equipment and possible sources of sparks be located far away from flammable material (OSHA 2003c).

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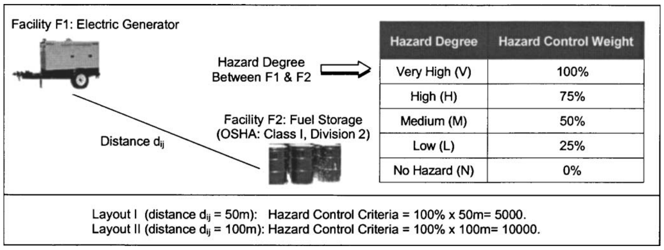

Fig. 3. Measuring the performance of hazard control on site

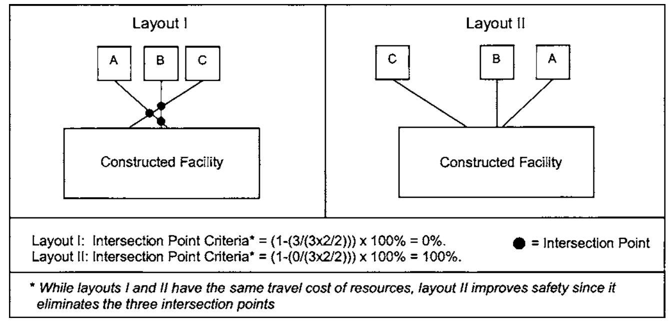

Fig. 4. Intersections among heavily traveled routes of resources

In order to improve safety on construction sites, planners need to comply with OSHA standards and identify proper storage locations for all hazardous material on site. These locations should be selected to ensure that there is adequate separation between (1) specific combinations of material and/or equipment that can create hazardous conditions on site (e.g., explosives and blasting devices); and (2) hazardous material and workers. In order to support planners in this vital site layout planning task, the present model incorporates a newly developed performance metric named hazards control criterion (HCC). As shown in Eq. (3), HCC enables planners to measure and quantify the degree of hazard control on site as a function of (1) the hazard control weight (HCW_{ij}) of facilities i and j which represents the degree of hazard that can be encountered on site if the two facilities are not adequately separated; and (2) the separation distance (d_{ij}) between facilities i and j. In the present model, the value of hazard control weight between facilities i and j ranges from 0 to 100% for combinations of facilities that create no hazards to those that pose the highest level of hazard if they are not separated on site. Construction planners can specify this level of hazard for each combination of facilities using one of five categories ranging from none to very high level of hazard, as shown in Fig. 3. The separation distance (d_{ij}) on the other hand is calculated by the present model for each generated site layout plan.

$$\text{Hazards control criterion (HCC)} = \sum_{i=1}^{I-1} \sum_{j=i+1}^{I} (\text{HCW}_{ij} \times d_{ij}) \tag{3}$$

$$d_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2} \tag{4}$$

where HCW_{ij}=hazard control weight that represents the risk of accidents that can be encountered on site if facilities i and j are not adequately separated as shown in Fig. 3; d_{ij}=separation distance between facilities i and j; X_i, Y_i=coordinates of center of gravity of facility i; X_j, Y_j=coordinates of center of gravity of facility j; and I=total number of facilities on site.

It should be noted that unlike the earlier described crane safety criterion (CSC), the present hazards control criterion (HCC) values do not necessarily fall within a performance range of 0–100%. In order to ensure consistency in performance measurement among all the safety criteria in the present model, each calculated HCC value in Eq. (3) is then normalized to generate a normalized performance metric (NHCC) that ranges from 0 to 100%, as shown in Eq. (5). NHCC is dynamically calculated for each HCC value, using the maximum (HCC_{max}) and minimum (HCC_{min}) values obtained from all generated site layouts.

$$\text{Normalized hazards control criterion (NHCC)} = \frac{\text{HCC} - \text{HCC}_{\min}}{\text{HCC}_{\max} - \text{HCC}_{\min}} \tag{5}$$

where HCC=calculated hazards control criterion, using Eq. (3); HCC_{min}=minimum HCC value obtained from all generated site layouts; and HCC_{max}=maximum HCC value obtained from all generated site layouts.

Travel Routes Intersections

Frequent movements of resources (e.g., labor, material, and equipment) on site often create safety hazards and accidents when the travel routes of these resources intersect. The intersection points between heavily traveled routes create safety hazards due to the high potential of accidents and collisions that can occur in these points by traveling resources. Safety on construction sites can therefore be improved by generating site layout plans that minimize the total number of intersection points between heavily traveled routes. For example, in Fig. 4, Layout II provides an improved level of safety than that associated with Layout I as it eliminates the potential of accidents in intersection points on site, while providing the same travel distance and cost of resources on site.

In order to improve safety and minimize the risk of accidents, construction planners need to search for and identify site layout plans that minimize the total number of intersection points on site. The present model is designed to support planners in this important task by incorporating a newly developed performance metric named intersection point criterion (IPC). As shown in Eqs. (6) and (7), IPC enables planners to measure and quantify the impact of intersections between heavily traveled routes on construction safety using a ratio between the total number of intersection points (IP) and the maximum possible number of intersection points (IP_{max}). As such, the intersection point criterion (IPC) in the present model is formulated in a practical way that enables its measurement on a performance scale that ranges from 0 to 100%, for sites that have the maximum possible number of intersection points (IP_{max}) to those that are properly planned with no intersection points, respectively. In calculating IPC, the model allows the user to specify whether a route has (1) a high level of traffic, leading to critical intersection points when it intersects with other highly traveled routes; or (2) has a low level of traffic and therefore does not create a significant risk when it intersects with other routes. In generating these intersection points, the model considers only frequently traveled routes that can lead to an increased risk of accidents when they intersect with other highly traveled routes.

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$$\text{Intersection point criterion (IPC)} = \left(1 - \frac{\text{IP}}{\text{IP}_{\max}}\right) \times 100\% \quad (6)$$

$$\text{IP}_{\max} = NR(NR-1)/2 \quad (7)$$

where IP=total number of intersection points on the generated site layout between all heavily traveled routes; $\text{IP}_{\max}$=maximum possible number of intersection points between all heavily traveled routes; and NR=total number of heavily traveled routes on site.

Overall Construction Site Safety

The above three sections described the development of three major performance criteria that can be used to measure and quantify the impact of site layout planning on construction safety. These three criteria, however, need to be aggregated into a single objective function to facilitate the evaluation of the overall safety performance for each possible site layout plan. To this end, the present model incorporates a weighted average formula that depicts the overall safety performance on site, as shown in Eq. (8). In this formula, the relative weight/significance (w_1 to w_3) of the three safety criteria can best be obtained from historical safety records of previous company projects that classify fatalities and/or injuries into these three major categories. In the absence of such company data, the planner can provide his/her best judgment on their relative significance/weight considering national figures such as the accidents data collected and published by the Bureau of Labor Statistics (BLS 2005).

$$\text{Maximize construction safety} = \text{Maximize}\left[w_1 \times \text{CSC} + w_2 \times \text{NHCC} + w_3 \times \text{IPC}\right] \quad (8)$$

where w_1=relative weight or scaling constant of crane safety criterion; w_2=relative weight or scaling constant of hazards control criterion; and w_3=relative weight or scaling constant of intersection point criterion.

Minimize Travel Cost of Resources

The second major optimization objective in the present model is to minimize the travel costs of resources on construction sites. This can be achieved by efficiently planning the location of facilities on site such that travel distances of these resources are minimized. In order to enable estimating the total travel cost of resources on site, a newly developed metric and travel cost rate are incorporated in the present model as shown in Eqs. (9)–(11). The total travel cost of resources can be calculated and minimized using the objective function shown in Eq. (9).

$$\text{Minimize travel cost of resources} = \text{Minimize}\left[\sum_{i=1}^{I-1}\sum_{j=i+1}^{I}(C_{ij} \times d_{ij})\right] \quad (9)$$

$$d_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2} \quad (10)$$

$$C_{ij} = \sum_{r=1}^{R}\left(\frac{f_r \times c_r}{s_r}\right) \quad (11)$$

where C_{ij}=travel cost rate in \$/m of distance traveled between facilities i and j; d_{ij}=distance in meters between facilities i and j; X_i,Y_i=coordinates of center of gravity of facility i; X_j,Y_j=coordinates of center of gravity of facility j; I=total number of facilities on site; f_r=frequency of one-way traveling for construction crew r between facilities i and j during the lifecycle of the site layout plan; c_r=hourly cost of traveling crew r in \$/h; and s_r=speed of traveling crew r in m/h.

In the present model, the travel cost rate (C_{ij}) is designed to consider (1) the frequency of travel (f_r) between the two facilities; (2) the hourly cost (c_r) of all traveling crews between the two facilities; and (3) the speed of the traveling crew (s_r) on site, as shown in Eq. (11). For example, the travel cost rate (C_{ij}) between a brick storage facility and the constructed facility can be identified based on these three parameters. First, the frequency of travel in this example depends on (1) the type of traveling crew which is planned to be crew B-67 that includes one forklift and one equipment operator (Means 2005) and is capable of lifting and transporting a load of 3 tons per trip; and (2) the total amount of bricks that need to be transported during the lifecycle of the site layout plan which is estimated to be 680 tons. Accordingly, it is estimated that crew B-67 needs 227 round trips (i.e., f_r=454 one-way trips) to transport the entire brick load to the constructed facility. Second, the hourly cost (c_r) of crew B-67 is estimated at \$81.84/h (Means 2005). Third, the average speed of the operating crew (s_r) is identified to be 8 km/h (CAT 2005). Accordingly, the travel cost rate (C_{ij}) for crew B-67 in this example can be estimated using Eq. (11) to be \$4.644/m of distance traveled between the brick storage facility and the constructed facility. The same analysis can be performed to estimate the travel cost rate C_{ij} for all other combinations of planned facilities on the construction site.

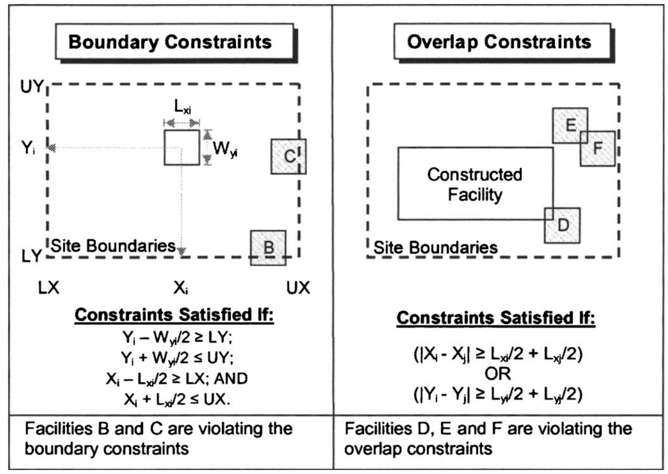

Fig. 5. Optimization constraints

Optimization Constraints

In the present model, two types of constraints are imposed on the generated solutions to ensure the development of practical site layout plans: (1) boundary constraints; and (2) overlap constraints. The purpose of boundary constraints is to ensure that temporary facilities are located within the site boundaries, while overlap constraints are required to avoid the overlap of facilities on site.

Boundary Constraints

Boundary constraints are examined in this model for each solution using the following four-step algorithm in order to ensure that each facility is located within the boundaries of the site.

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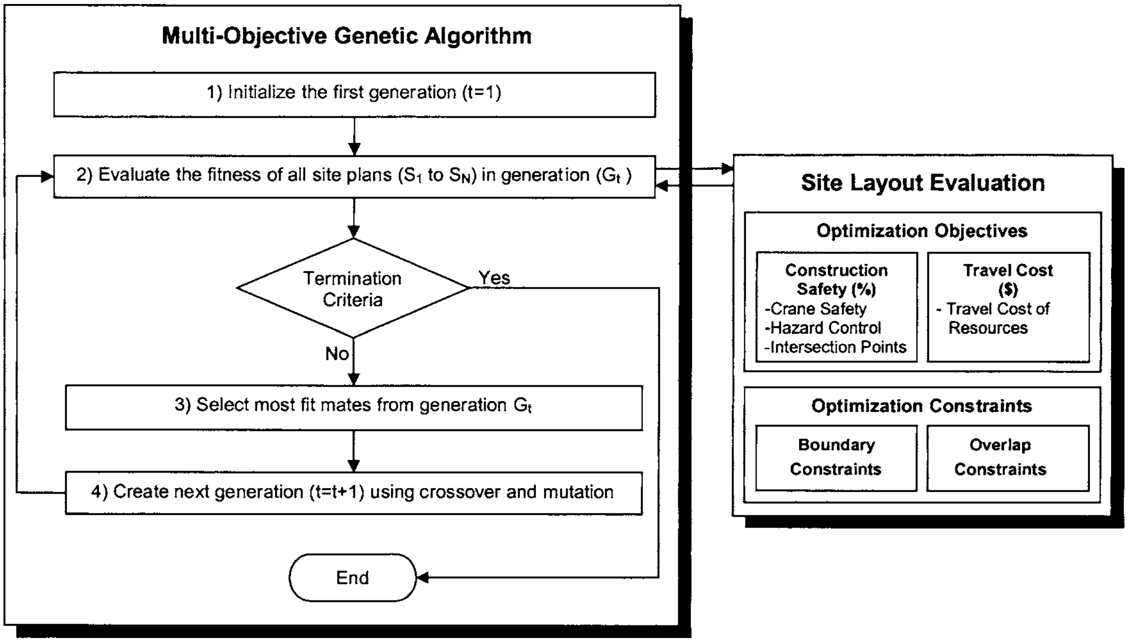

Fig. 6. Model implementation

1. For each temporary facility i, find the coordinates of its center of gravity (X_i, Y_i), and its length in the X direction (L_{xi}) and width in the Y direction (W_{yi});
2. In the Y direction, examine the following two conditions: (1) the upper boundary of each facility $(Y_i+W_{yi}/2)$ is less than the upper boundary of the site space (UY); and (2) the lower boundary of the facility $(Y_i-W_{yi}/2)$ is greater than the lower boundary of the site space (LY), as shown in Fig. 5;
3. If both conditions in Step 2 are satisfied, perform a similar examination in the X direction; and
4. If all the conditions in Steps 2 and 3 are satisfied, then facility i complies with boundary constraints. Otherwise, the solution is in violation of this type of constraint and therefore it should be precluded.

Overlap Constraints

In order to ensure that no overlap occurs between facilities on site, overlap constraints are examined using the following four-step algorithm.

1. For each temporary facility i, find the coordinates of its center of gravity (X_i, Y_i), and its length in the X direction (L_{xi}) and width in the Y direction (W_{yi});
2. To ensure that there are no overlaps between facilities i and j in the X direction, calculate the absolute difference between the X coordinates $(|X_i-X_j|)$ of facilities i and j, and compare it to the average length of the two facilities in the X direction $(L_{xi}/2+L_{xj}/2)$. If $[|X_i-X_j| \geqslant (L_{xi}/2+L_{xj}/2)]$, then there is no overlap in the X direction;
3. Repeat Step 2 for the Y direction; and
4. If overlaps are encountered in both Steps 2 and 3, then there is an overlap between the two facilities as shown in Fig. 5, and therefore this solution should be precluded. Otherwise, overlap constraints are satisfied.

Model Implementation

The present model is implemented as a multiobjective genetic algorithm (Deb et al. 2000) in order to enable the generation of near optimal site layout plans that maximize construction safety and minimize travel cost of resources simultaneously, while satisfying all the practical layout constraints described earlier. In order to achieve this, the model is implemented to perform the necessary computations (see Fig. 6) in four major steps.

1. **Initialization of first generation**
   The genetic algorithm initializes the search and optimization process by randomly generating a set of N possible site layout solutions $(S_1, S_2, \ldots, S_N)$, where each layout solution represents one possible arrangement for all facilities on site, as shown in Fig. 1. This initial set of site layout solutions represents the parent population in the first generation (G_1) that evolves over T generations $(G_1, G_2, \ldots, G_T)$ in an artificial process that simulates the evolution and natural selection theory (Goldberg 1989).
2. **Evaluation of fitness function**
   The algorithm evaluates the safety and cost performance of each possible site layout solution (S_n) in each generation (G_t) using the earlier described performance criteria [Eqs. (1)–(9)], as shown in Fig. 6. Based on the performance in these two optimization objectives, the algorithm calculates and assigns nondomination ranks for each solution (S_n) in generation (G_t). A solution is identified as "nondominated" if no other generated solution can provide better values for both construction safety and travel cost functions. Such nondominated site layout solutions are given rank 1, and the remaining solutions are given lower ranks based on their domination/nondomination by other solutions. These nondomination ranks are then used to represent the fitness of each solution for mating and reproduction in subsequent generations, as described in more detail in the next steps.
3. **Mating selection**
   The nondomination rank given by the algorithm to an individual solution of the population in the previous step is used to represent its fitness for survival and reproduction. In this process, site layout solutions with higher fitness are favored to be selected for reproduction in subsequent generations. Using a mating probability, the algorithm selects the most fit solutions from generation (G_t) to undergo reproduction ac-

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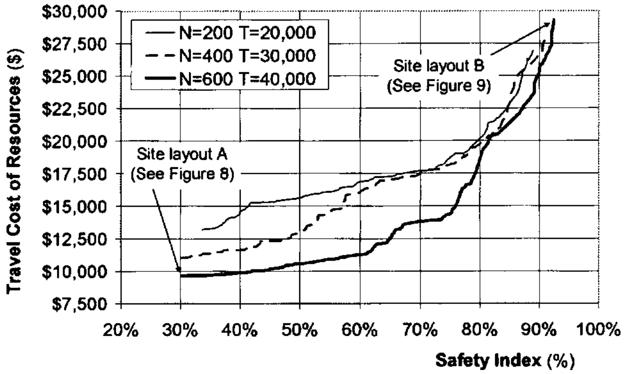

Fig. 7. Trade-off between construction safety and cost

cording to their ranks, crowding distances, and constraints satisfaction (Deb et al. 2000).

4. **Crossover and mutation**
The most fit solutions selected in the previous step from generation (G_t) are then used to mate and reproduce a new set of N children site layout solutions using the genetic algorithm operators of crossover and mutation. First, a crossover operator is used to reproduce a new child site layout solution by swapping and exchanging chunks of the genetic data from two of the parent solutions. Second, a mutation operator is used to change the genetic materials in the strings randomly to maintain diversity in the population and to prevent immature convergence to inferior solutions (Goldberg 1989). The fitness of the newly generated N children solutions is then evaluated using the earlier described procedure in the previous steps. The newly generated children solutions are then combined with their parents to form an expanded population of $2N$ individual solutions. From this expanded population, the most fit 50% of the solutions are chosen to survive and form the next generation (G_{t+1}) that will be used to reproduce new solutions in subsequent generations.

Steps 2, 3, and 4 are repeated over T generations (G_1 to G_T) in order to generate a set of optimal site layout solutions. Each of these solutions describes the locations of all temporary facilities on site, and provides a unique trade-off between construction safety and the travel cost of resources on site, as shown in Figs. 1 and 7. As such, the present model enables construction planners to generate and evaluate optimal trade-offs between construction safety and cost. This new and unique capability of the model can provide significant help to planners in selecting a site layout plan that provides the desired trade-off between safety and cost for the specific project being considered (see Fig. 7).

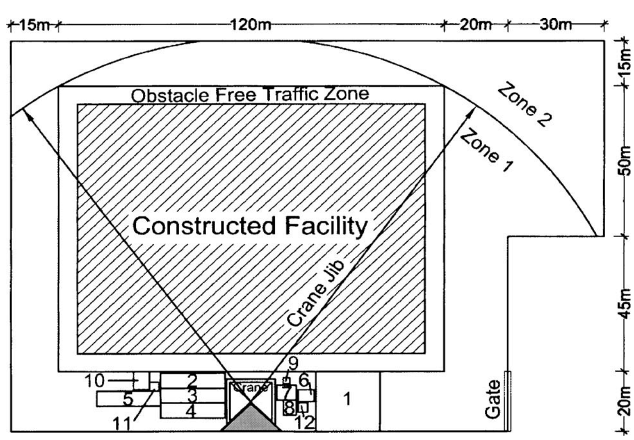

Fig. 8. Site Layout A: least travel cost of resources on site

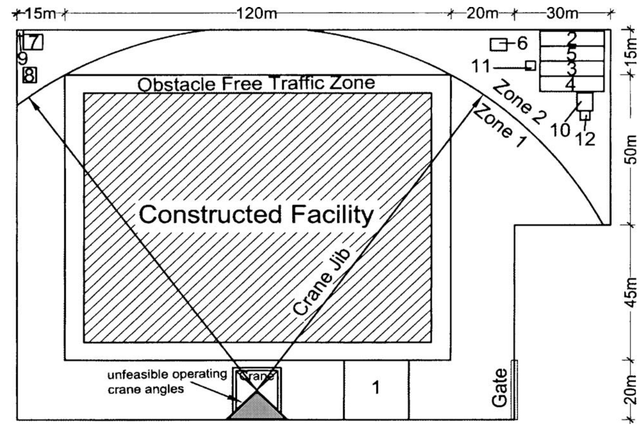

Fig. 9. Site Layout B: maximum construction safety

Application Example

An application example is analyzed to illustrate the use of the present model and demonstrate its capabilities in optimizing construction site layouts and generating optimal trade-offs between safety and travel cost of resources on site. The example involves the planning of a construction site layout for a real-life multistory garage building. The dimensions of the new building and its surrounding obstacle-free traffic zone (see Figs. 8 and 9) as well as those of all temporary facilities were directly acquired from the actual construction site, as shown in Table 1. Furthermore, the locations of the new building, the tower crane, and the gate on

Table 1. Dimensions of Site Facilities

Symbol (i)	Facility name	Length in m (L_{xi})	Width in m (W_{yi})
Temporary facilities			
F1	Parking lot	20	20
F2	Field office (a)	20	5
F3	Field office (b)	20	5
F4	Field office (c)	20	5
F5	Field office (d)	20	5
F6	Workshop	5	4
F7	Storage facility (a)	6	5
F8	Storage facility (b)	4	5
F9	Electric generator	2	2
F10	Toilets	5	6
F11	Fire equipment storage	3	3
F12	Inflammable materials storage	3	3
Facilities to be constructed			
C1[a]	Multistory garage building	120	95
Facilities with fixed locations			
K1[b]	Crane	15	15
G1[c]	Gate	N/A	N/A

[a]The coordinates of the center of the garage building are (75, 67.5).
[b]The coordinates of the center of the crane are (75, 10).
[c]The coordinates of the center of the gate are (155, 10).

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Table 2. Sensitivity of Facilities to Falling Objects

Facility (i)	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12
Sensitivity (V_i)	M	H	H	H	H	H	L	L	L	M	L	L

Note: H=high sensitivity; M=medium sensitivity; and L=low sensitivity.

site were predetermined by the planner as indicated by their center of gravity coordinates in Table 1. The locations of temporary facilities, however, need to be properly determined in an attempt to maximize construction safety and minimize the travel costs of resources on site. In order to support planners in this important and challenging task, the present model is applied to search for and identify optimal locations for all the temporary facilities listed in Table 1.

In order to maximize construction safety and minimize the travel costs of resources on site, the present model requires the planner to specify and input the following parameters: (1) the sensitivity (V_i) of each facility to falling objects from cranes which can be classified as low, medium, or high as shown in Table 2; (2) the ratio between the risk of falling objects to that of crane collapse which is considered to be 1:10 in this example (i.e., $m=10$); (3) the set of unfeasible operating crane angles which are specified to be $135° < \theta_u < 225°$ due to the existence of adjacent tall structures within that range, as shown in Fig. 9; (4) the hazard degree (HCW_{ij}) that can be encountered on site if facilities i and j are not adequately separated which can be classified as no hazard, low, medium, high, or very high degree of hazard as shown in Table 3; (5) the heavily traveled routes among facilities as shown in Table 4; (6) the relative weight/significance of the three main safety criteria which are specified in this example as $w_1:w_2:w_3=0.6:0.2:0.2$; and (7) the travel cost rate (C_{ij}) in \$/m of distance traveled between facilities (i) and (j) as shown in Table 4. The input data in this example (Tables 1–4) is used by the present model to search for and identify optimal locations for all temporary facilities, which can be located anywhere on site excluding the predetermined areas occupied by the new building and the tower crane shown in Fig. 8.

The present model was utilized to optimize the site layout for this example in an attempt to maximize construction safety and minimize the travel cost of resources on site, while satisfying the earlier described boundary and overlap constraints. Several runs were performed to generate optimal trade-offs between construction safety and cost and to study the impact of varying population sizes (N) and number of generations (T) on the quality of the obtained solutions. The results of this analysis confirm that increasing the population size leads to improved quality of the solution and higher computational requirements (see Fig. 7). Furthermore, the results highlight the impact of various site layout configurations on the possible trade-offs between construction safety and travel cost of resources, as shown in Fig. 7.

The generated optimal site layout solutions for this project provide optimal trade-offs between construction safety and travel cost of resources. For example, site Layout A (see Figs. 7 and 8) provides a safety performance level of 30% at a travel cost of resources of \$9,651. This safety level of Solution A can be improved to 92% at a higher cost of \$29,298, as shown in Solution B in Figs. 7 and 9. It should be noted that site Layout A minimizes the travel cost of resources on site (\$9,651) by (1) locating temporary facilities close to one other; and (2) reducing the travel distances between the facilities and both the crane and the new building, as shown in Fig. 8. Site Layout B, on the other end of the spectrum, maximizes overall construction safety on site (92%) by (1) locating highly sensitive facilities (e.g., facilities 2–6) far from crane operation zones, leading to a performance level of 92.7% in the crane safety criterion; (2) separating facilities that create hazardous conditions on site (e.g., facilities 9 and 12), achieving a performance level of 93.5% in the normalized hazards control criterion; and (3) minimizing intersection points among heavily traveled routes on site, leading to a performance level of 90.5% in the intersection point criterion (see Fig. 9). Construction planners can evaluate these optimal trade-offs between construction safety and travel cost of resources, and select a site layout that satisfies the specific requirements of the project being considered.

Table 3. Hazard Degrees among Facilities

	Facility (j)												
Facility (i)	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	C1
F1	N	—	—	—	—	—	—	—	—	—	—	—	—
F2	L	N	—	—	—	—	—	—	—	—	—	—	—
F3	L	N	N	—	—	—	—	—	—	—	—	—	—
F4	L	N	N	N	—	—	—	—	—	—	—	—	—
F5	L	N	N	N	N	—	—	—	—	—	—	—	—
F6	M	M	M	M	M	N	—	—	—	—	—	—	—
F7	M	M	M	M	M	L	N	—	—	—	—	—	—
F8	M	M	M	M	M	L	N	N	—	—	—	—	—
F9	M	H	H	H	H	H	L	L	N	—	—	—	—
F10	N	N	N	N	N	N	L	L	L	N	—	—	—
F11	N	N	N	N	N	N	N	N	N	N	N	—	—
F12	H	M	M	M	M	L	N	N	V	N	N	N	—
C1	H	V	V	V	V	M	M	M	H	M	N	M	N

Note: V=very high; H=high; M=medium; L=low; and N=no hazard; and —=equivalent values in this symmetric matrix.

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Table 4. Travel Cost Rates (C_{ij}) and Heavily Traveled Routes among Facilities

	Facility (j)														
Facility (i)	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	C1	K1	G1
F1	0.0	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F2	4.0	0.0	—	—	—	—	—	—	—	—	—	—	—	—	—
F3	4.0	7.5[a]	0.0	—	—	—	—	—	—	—	—	—	—	—	—
F4	4.0	7.5[a]	7.5[a]	0.0	—	—	—	—	—	—	—	—	—	—	—
F5	4.0	5.5	5.5	2.5	0.0	—	—	—	—	—	—	—	—	—	—
F6	1.5	1.0	1.0	1.0	1.0	0.0	—	—	—	—	—	—	—	—	—
F7	1.5	1.0	1.0	1.0	1.0	9.5[a]	0.0	—	—	—	—	—	—	—	—
F8	1.5	1.0	1.0	1.0	1.0	9.5[a]	6.5	0.0	—	—	—	—	—	—	—
F9	1.5	2.0	1.0	3.0	3.0	3.0	3.0	3.0	0.0	—	—	—	—	—	—
F10	1.5	7.5[a]	7.5[a]	7.5[a]	7.5[a]	6.5	6.5	6.5	1.0	0.0	—	—	—	—	—
F11	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	—	—	—	—
F12	1.5	1.0	1.0	1.0	1.0	3.5	1.0	1.0	3.5	1.0	1.0	0.0	—	—	—
C1	1.5	3.5	3.5	3.5	3.5	6.5	4.5	4.5	5.5	3.0	1.0	4.5	0.0	—	—
K1	0.0	7.5[a]	5.5	7.5[a]	7.5[a]	9.5[a]	9.5[a]	9.5[a]	0.0	0.0	1.0	4.5	5	0.0	—
G1	1.5	0	0	0	0	3.0	7.0[a]	7.0[a]	0.0	0.0	0.0	1.0	0.0	0.0	0.0

Note: —=equivalent values in this symmetric matrix.

[a]Heavily traveled route.

Summary and Concluding Remarks

A robust site layout planning model was developed to enable the simultaneous optimization of construction safety and travel cost of resources on site. The model is designed to search for and generate optimal site layout plans that provide optimal trade-offs between these two important objectives, while satisfying all practical constraints in this construction problem. The model was developed in three main phases: (1) formulating decision variables and optimization objectives; (2) identifying and formulating all practical constraints; and (3) implementing the model as a multi-objective genetic algorithm. The model incorporates three newly developed performance criteria to enable the quantification and maximization of construction safety. These new safety criteria are designed to (1) improve the safety of crane operations by selecting safe locations for temporary facilities around cranes; (2) control hazardous material on site by providing adequate separation between combinations of temporary facilities that can create hazardous conditions; and (3) reduce intersections between heavily traveled routes of resources to minimize the potential of accidents and collisions that can occur in these points. An application example is analyzed to illustrate the use of the model and demonstrate its capabilities. The analysis results highlight the new and unique capabilities of the site layout planning model in generating optimal trade-offs between construction safety and travel cost of resources on site. This should prove useful to construction planners and can lead to significant improvements in the safety and cost performance of constructed facilities.

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Notation

The following symbols are used in this paper:

C_{ij} = travel cost rate in \$/m of distance traveled between facilities i and j;
CS^z_{ik} = crane safety performance for temporary facility i due to its proximity to crane k in Zone z;
c_r = hourly cost of traveling crew r in \$/h;
d_{ij} = separation distance between facilities i and j;
d_{ik} = distance between facility i and crane k;
f_r = frequency of one-way traveling for construction crew r between facilities i and j during the lifecycle of the site layout plan;
G_t = generation t;
H = reach of the crane;
HCC = calculated hazards control criterion;
$\mathrm{HCC}_{\min}$ = minimum HCC value generated and stored in all previous runs;
$\mathrm{HCC}_{\max}$ = maximum HCC value generated and stored in all previous runs;
HCW_{ij} = hazard control weight that represents the risk of accidents that can be encountered on site if facilities i and j are not adequately separated;
IP = total number of intersection points on the generated site layout between all heavily traveled routes;
$\mathrm{IP}_{\max}$ = maximum possible number of intersection points between all heavily traveled routes;
J = length of the crane jib;
L_{xi} = length of facility i in X-axis direction;
L_{xj} = length of facility j in X-axis direction;
M = width of the crane mast;
m = ratio between the risk of falling objects from crane and the risk of crane collapse;
NR = total number of heavily traveled routes on site;
S_n = site layout solution n;
s_r = speed of traveling crew r in m/h;
V_i = sensitivity of facility i to falling objects;

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W_{yi} = width of facility i in Y-axis direction;
w_1 = relative weight or scaling constant of crane safety criterion;
w_2 = relative weight or scaling constant of hazard control criterion;
w_3 = relative weight or scaling constant of intersection point criterion;
X_i = x-coordinate of center of gravity of facility i;
X_j = x-coordinate of center of gravity of facility j;
Y_i = y-coordinate of center of gravity of facility i;
Y_j = y-coordinate of center of gravity of facility j;
θ_i = angle representing the location of temporary facility i measured clockwise from the north direction;
θ_f = set of crane operating angles; and
θ_u = set of unfeasible crane operating angles.

Subscripts and Superscripts

i = temporary facility counter (from $i=1$ to I);
j = temporary facility counter;
k = crane counter (from $k=1$ to K);
n = solution (from $n=1$ to N);
r = traveling crew (from $r=1$ to R);
t = generation (from $t=1$ to T); and
z = Zone (1, 2, or 3).

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