Minimizing Construction-Related Hazards in Airport Expansion Projects

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Abstract: Airport expansion projects often require the presence and movement of construction labor and equipment near critical airport traffic areas. This close proximity between construction activities and airport operations needs to be carefully considered during the planning of construction site layouts in order to minimize and eliminate all potential construction-related hazards to aviation safety. This paper presents the development of a multiobjective optimization model for planning airport construction site layouts that is capable of minimizing construction-related hazards and minimizing site layout costs, simultaneously. The model incorporates newly developed optimization functions and metrics that enable: (1) maximizing the control of hazardous construction debris near airport traffic areas; (2) minimizing site layout costs including the travel cost of construction resources and the cost of debris control measures on airport sites; and (3) satisfying all operational safety constraints required by the federal aviation administration as well as other practical site layout constraints. The model is implemented using a multiobjective genetic algorithm and an application example is analyzed to demonstrate the use of the model and its capabilities in optimizing construction site layouts in airport expansion projects.

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Introduction

The Federal Aviation Administration (FAA) estimates that the demand for airport and air carrier passenger services will increase approximately 50% in the next decade, and air cargo will increase approximately 80% over the same period (FAA 2001a). To meet this significant increase in air traffic demand, a large number of major airport expansion projects are either ongoing or being planned, including the construction of new terminals, new and extended runways, and improved taxiway systems (FAA 2001b). One of the main and unique challenges in managing construction sites in this type of projects is caused by the close proximity between construction equipment/materials and airport operational areas leading to an increased level of risk to aviation safety. To minimize these risks, the FAA sets forth guidelines for operational safety on airports during construction operations through a number of Advisory Circulars including: (1) "Operational safety on airports during construction" (FAA 2003); (2) "Debris hazards at civil airports" (FAA 1996); and (3) "A model zoning ordinance to limit height of objects around airports" (FAA 1987).

To ensure aviation safety, the aforementioned FAA guidelines need to be carefully considered and complied with during the planning of airport construction site layouts which typically involves identifying the locations of temporary construction facilities such as storage areas, stockpiles of excavation, site offices and fabrication shops (Yeh 1995; Hegazy and Elbeltagi 1999). For construction projects in general, site layout planning is essential to promote safe and efficient operations, minimize travel time of construction crews, and decrease material handling costs. For airport construction projects in particular, site layout planning is indispensable as it plays a vital role in maximizing aviation safety during construction through enhanced compliance with the aforementioned FAA guidelines and advisory circulars.

A number of models have been proposed in the literature to facilitate the planning of construction site layouts using a variety of approaches including artificial intelligence (Tommelein et al. 1992), annealed neural networks (Yeh 1995), dynamic layout planning (Tommelein and Zouein 1993; Zouein and Tommelein 1999), geographic information system (GIS) (Cheng and O'Connor 1996), and genetic algorithms (Li and Love 1998; Hegazy and Elbeltagi 1999). Despite the significant research efforts and contributions of the above models, they focused on minimizing the travel distance of construction resources on site in order to maximize the efficiency of general construction projects. As such, the application of existing models to plan airport construction site layouts is limited due to their inability to consider aviation safety and FAA guidelines in the optimization process. In order to circumvent this limitation, this paper presents the development of a multiobjective optimization model for planning airport construction site layouts that is capable of maximizing compliance with both FAA aviation safety requirements and practical site layout requirements, as shown in Fig. 1.

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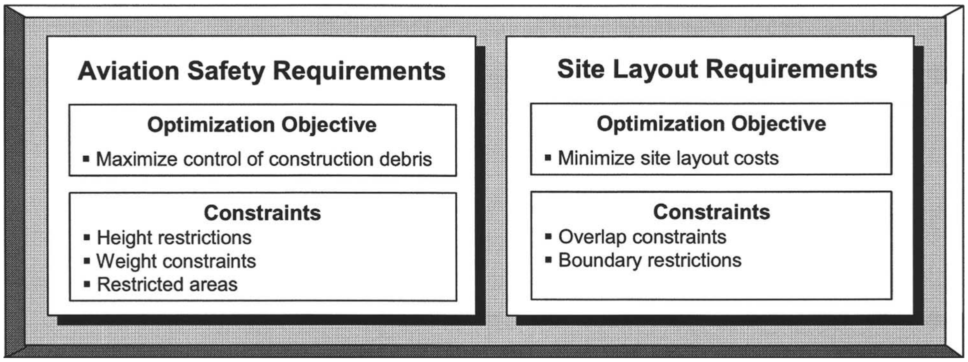

Fig. 1. Optimization objectives and constraints

Optimization Model for Airport Construction Site Layouts

The present optimization model is designed to assist airport operators and construction planners in their search for optimal construction site layout plans for airport expansion projects. As shown in Fig. 1, the present model is formulated to support two main optimization objectives: (1) maximizing the control of construction debris hazards near critical airport traffic areas in compliance with FAA guidelines (FAA 1996, 2003); and (2) minimizing overall site layout costs including the travel cost of construction resources on site and the cost of utilizing containment measures in debris-producing facilities whenever needed. Furthermore, the model is capable of fully complying with two sets of constraints, as shown in Fig. 1: (1) FAA aviation safety constraints, including limiting the heights of temporary facilities and equipment in airport construction zones, protecting underground utilities from excessive weight and maintaining airport restricted safety areas (FAA 2003); and (2) practical construction site layout constraints to ensure that the location of all temporary facilities are within the site boundaries and that their allocated spaces on site do not overlap. The present model is designed to optimize two main decision variables: (1) the location of each temporary facility on site which can be represented by the coordinates of its center of gravity (X_i, Y_i); and (2) the optional use of containment measures to control the spread of construction debris beyond the perimeter of all debris-producing facilities (c_b), as shown in Fig. 2.

For each temporary facility on site, the present model is designed to search for and identify an optimal solution for these two decision variables in order to maximize the control of construction debris hazards and minimize site layout costs simultaneously. These are two conflicting optimization objectives as maximizing the control of construction debris hazards often increases site layout costs as illustrated in Fig. 3. In this simplified example, a temporary facility (e.g., fabrication shop) needs to be located near the newly constructed building (see location 1 in Fig. 3) in order to minimize the travel distance and travel cost of resources on site. This location increases the level of debris hazards to the operational aircrafts in the nearby taxiway as this temporary facility is capable of producing hazardous construction debris. Maximizing the control of this hazard can be accomplished by: (1) increasing the separation distance between the facility and the taxiway by relocating it from location 1 to 2; and/or (2) utilizing debris containment measures to control the spread of construction debris. As shown in Fig. 3, these two hazard control measures lead to an increase in site layout costs as a result of the higher travel cost of resources and/or the additional cost of containment measures on site.

In order to enable the simultaneous optimization of the two conflicting optimization objectives in this site layout planning problem, the present optimization model is developed using a multiobjective genetic algorithm named NSGA II (Deb 2001). NSGA II adopts the survival of the fittest approach in addition to the concept of Pareto optimality in order to converge to a set of nondominated optimal solutions that represent various tradeoffs among the conflicting optimization objectives (Zitzler and Thiele 1999; Deb et al. 2000). NSGA II has been successfully utilized in recent years to support multiobjective optimization in other construction decision making problems such as time-cost tradeoff analysis and optimizing the utilization of lighting equipment in nighttime highway construction (El-Rayes and Hyari 2005; El-

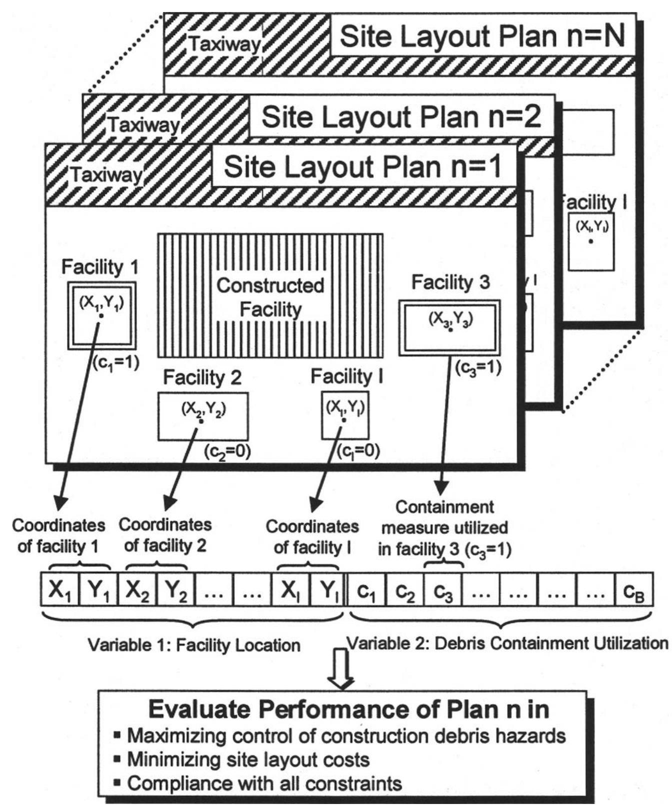

Fig. 2. Optimization variables

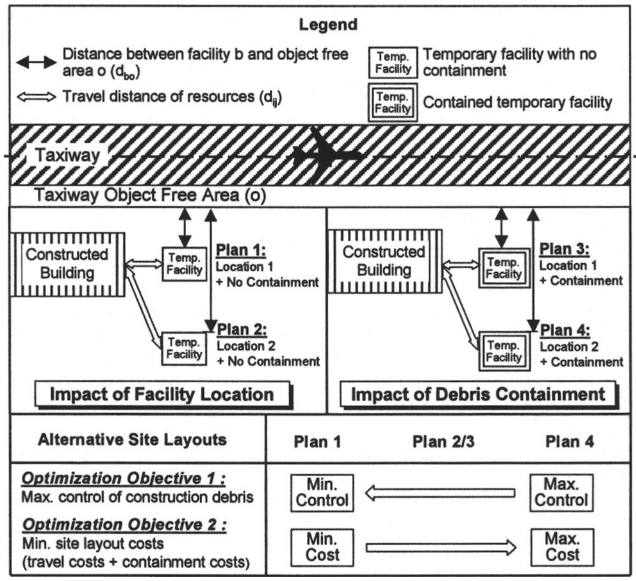

Fig. 3. Impact of optimization variables on optimization objectives

Rayes and Kandil 2005; Kandil and El-Rayes 2005; Hyari and El-Rayes 2006).

The present model starts the optimization process by randomly generating a number of initial construction site layout plans ($n=1-N$), as shown in Fig. 2. This initial set of site layout plans forms the first generation ($t=1$) that evolves over T successive generations in order to reach a set of optimal tradeoffs between the control of construction debris hazards and site layout costs. To accomplish this multiobjective optimization of airport construction site layouts, the present model incorporates newly developed optimization functions and performance metrics that are designed to: (1) maximize the control of construction debris hazards near airport operational areas (FAA 2003); (2) comply with all FAA aviation safety constraints such as the FAA imposed restrictions on the maximum permissible heights and weights of temporary facilities in various zones of the airport (FAA 2003); (3) minimize site layout costs; and (4) comply with all practical construction site layout constraints. The following sections provide a detailed discussion of these newly developed optimization functions and performance metrics.

Maximizing Control of Construction Debris Hazards

Construction debris in airport work zones include waste and loose materials such as sand, stones, pieces of wood, plastic, polyethylene materials, nails, nuts, and washers (FAA 1996). Construction debris is capable of causing damage to aircraft propellers, jet engines, and landing gears, as tests and experience have shown that such debris can be ingested by aircraft engines, leading to engine failure (FAA 2003). The direct economical losses resulting from damages in aircraft engines due to debris are reported to cost the aerospace industry an estimated $4 billion per year (Boeing 2004). Furthermore, such debris-related incidents are reported to cause significant additional indirect costs due to flight delays and cancellations; schedule disruptions; potential liability; and additional work for airline management and staff (Boeing 2004).

In order to minimize debris-related hazards, FAA guidelines recommend establishing active prevention programs and measures to eliminate the presence of debris on or near active aircraft movement areas. For example, FAA recommends: (1) locating construction activities that can produce debris in safe areas to minimize their hazardous impact on airport operations; and (2) identifying and eliminating debris entrapment areas (FAA 2003). In order to comply with these FAA regulations, construction planners need to identify construction tasks and temporary facilities that can produce debris and ensure that they are adequately separated from critical airport operations areas, and/or safely contained to prevent the spread of hazardous construction debris on site. To support construction planners in this vital task, the present model incorporates a newly developed optimization function [see Eq. (1)] that is designed to maximize the control of construction debris hazards (CCDH). As shown in Fig. 4, the developed model utilizes this function to allow planners to measure and calculate the different levels of reducing the hazards of construction debris for each debris-producing facility as a function of: (1) the planned distance (d_{bo}) that will be used to separate each debris-producing facility (b) from critical airport operation area (o) on site; (2) the recommended distance (d^*) that provides a far enough and safe

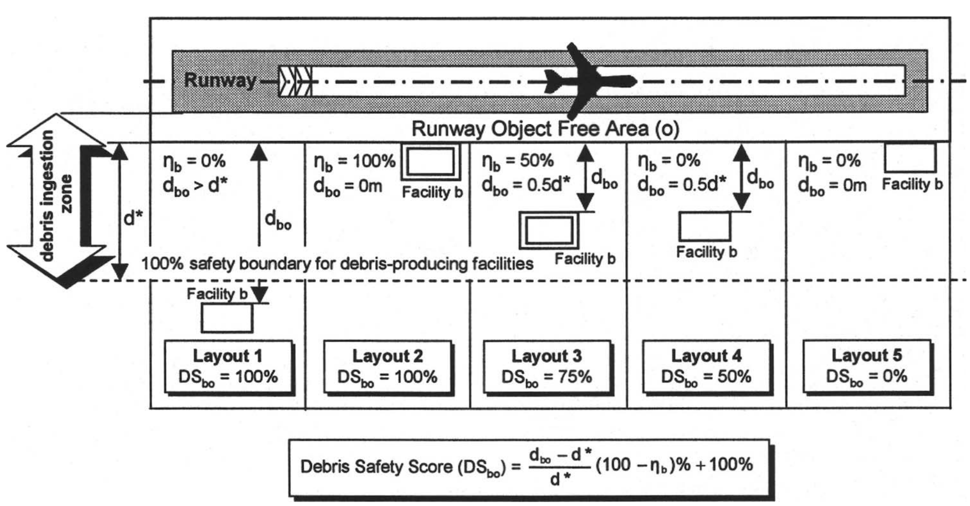

Fig. 4. Impact of facility location and effectiveness of containment on debris safety score

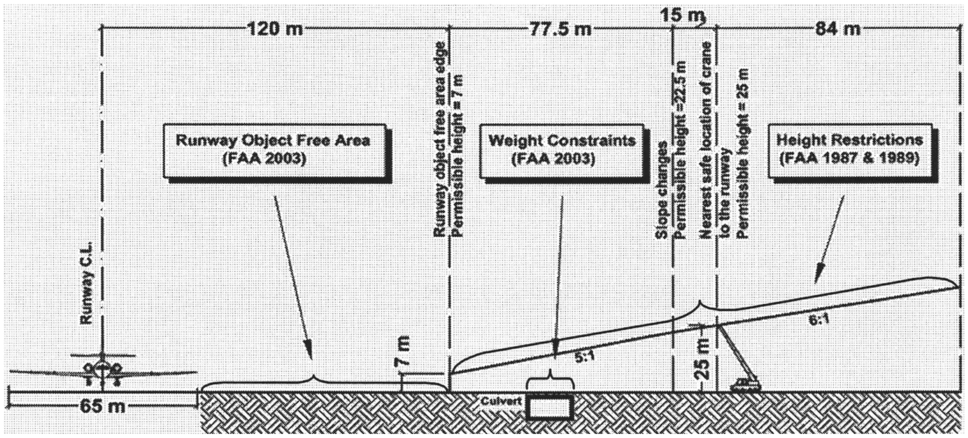

Fig. 5. Aviation safety constraints

separation distance between debris-producing facilities and airport operation areas in order to ensure full elimination of the potential hazard of such debris on airport traffic operation; and (3) the utilization of supplemental containment measures and barriers around the perimeter of debris-producing facilities to ensure that the construction debris is contained within the facility and cannot approach airport traffic areas (FAA 1996; FAA 2003).

In the present model, maximizing the CCDH requires planners to: (1) classify all facilities as either hazardous or nonhazardous debris facilities, where the former produces hazardous debris such as nails, nuts, washers, gravel stones, and polyethylene materials, and the latter either produces no debris or nonhazardous debris such as large concrete blocks that are too heavy to be blown away or ingested by the jet engines; (2) specify the location and dimensions of runway/taxiway object free area required by FAA safety regulations (FAA 1989); (3) recommend a safe separation distance (d^*) between debris-producing facilities and runway/taxiway object free areas that guarantees full elimination of debris-related hazards; and (4) specify available containment measures for each debris-producing facility, if any, and their estimated effectiveness (e.g., 80%) and cost. The present model utilizes this data to evaluate the impact of various locations (X_i, Y_i) for each facility and the optional utilization of debris containment measures (c_b) on the CCDH, as shown in Fig. 2. This is achieved by calculating a safety score (DS_{bo}) for each debris-producing facility (b) that represents the combined impact of: (1) the ratio between the planned separation distance (d_{bo}) and the recommended safe separation distance (d^*) between the facility and the runway/taxiway object free areas; and (2) the effectiveness of the utilized containment measure (η_b), if any, in preventing the spread of construction debris beyond the perimeter of the facility as shown in Fig. 4. For each debris-producing facility (b), this newly developed safety score (DS_{bo}) is designed to range from 0 to 100% [see Eqs. (1) and (2) and Fig. 4]. For example, a perfect debris safety score (i.e., $DS_{bo}=100\%$) can be achieved by either: (1) locating the debris-producing facility outside the debris ingestion zone at a distance greater than the recommended safe separation distance (i.e., $d_{bo} > d^*$) even without the use of containment measure; or (2) utilizing a perfect containment measure (i.e., $\eta_b=100\%$) even if the facility is located at the edge of the runway/taxiway object free area, as shown in layouts 1 and 2, respectively, in Fig. 4. The calculated safety scores for each facility (DS_{bo}) are then averaged for all debris-producing facilities to obtain the achieved performance level in controlling the construction debris hazards (CCDH) in the entire site layout, which is designed to range from 0 to 100%, as shown in the following equation:

$$\text{maximize CCDH} = \frac{\sum_{o=1}^{O} \frac{\sum_{b=1}^{B} (DS_{bo})}{B}}{O} \tag{1}$$

$$DS_{bo} = \begin{cases} \dfrac{d_{bo} - d^\star}{d^\star}(100 - \eta_b)\ \% + 100\% & (d_{bo} < d^\star) \\ 100\% & (d_{bo} \geqslant d^\star) \end{cases} \tag{2}$$

where CCDH=average performance level in controlling the construction debris hazards in the entire site layout (ranges from 0 to 100%); DS_{bo}=debris safety score for locating facility b at a distance of d_{bo} from runway/taxiway object free area o (ranges from 0 to 100%); B=total number of facilities classified to produce hazardous construction debris; O=total number of runway/taxiway object free areas; η_b=effectiveness of active containment measure/barrier used in facility b; d_{bo}=planned distance between facility b and runway/taxiway object free area o; and d^*=recommended distance between debris-producing facilities and runway/taxiway object free areas.

Compliance with Aviation Safety Constraints

The planning of construction work in and around airport operational areas need to comply with a number of aviation safety constraints such as: (1) height restrictions; (2) weight constraints; and (3) restricted areas (FAA 1987, 1989, 2003). These constraints and the newly developed algorithm to comply with them in the present model are discussed in the following sections.

Height Restrictions

Construction activities can cause fatal and costly collisions between aircrafts and construction equipment/temporary facilities if their heights exceed the allowable limits in and around aircraft movement zones (FAA 2003). In order to control this construction-related hazard, the FAA sets regulations and guidelines of height restrictions in various airport areas (FAA 1987, 1989). For example, Fig. 5 shows a height restriction profile for a runway that is capable of accommodating a Boeing 747 airplane with a wingspan of 65 m. For this type and size of runway, the maximum allowable height for construction equipment and facilities varies using two different slopes of 5:1 and 6:1 depending on the distance between these facilities and the edge of the runway object free area, as shown in Fig. 5 (FAA 1989).

Construction planners and airport operators need to fully comply with these FAA height restrictions during their planning of construction site layouts in order to eliminate any risk of collisions between aircrafts and construction equipment, temporary facilities, and/or stockpiled materials (FAA 2003). The present model facilitates this vital and challenging planning task by enabling the designation of a maximum height restriction (H_{zh}) for various airport construction site layout zones ($zh=1-Zh$). The model then applies a newly developed algorithm to ensure that each generated and evaluated site layout solution ($n=1-N$) fully complies with the designated height restrictions in all site layout zones. For each site layout solution (n), the model identifies the zone in which each temporary facility ($i=1-I$) is to be located and applies a three-dimensional spatial analysis to compare its height (H_i) to the permissible height in the assigned zone (H_{zh}). If the height of the facility exceeds the permissible height in the zone ($H_i > H_{zh}$) then the model applies a high penalty on this site layout solution in order to designate it as infeasible and ultimately preclude it from further consideration, as shown in Fig. 6. For example, the location of a crane that is expected to reach a height of 25 m can be evaluated by the present model in order to identify its closest safe location from the runway object free area and preclude other site layout solutions that violates the FAA height restrictions (FAA 1989) shown in Fig. 5.

Weight Constraints

The Federal Aviation Administration requires that all heavy equipment and material be located in safe areas on airport construction sites to prevent damaging critical underground facilities (FAA 2003). Accordingly, this weight constraint needs to be fully complied with during the planning of construction site layouts. For example, the location of all heavy equipment and/or storage facilities on site should be carefully examined to avoid placing them over underground utilities that cannot support their weight, as shown in Fig. 5. In order to support construction planners in this important task, the present model can be used to classify the airport site layout to various weight zones ($zw=1-Zw$), each with its maximum allowable weight stress (σ_{zw}) that specifies the structural strength of underground facilities in that zone and/or the bearing capacity of its soil. The model then applies a newly developed algorithm to ensure that each generated and evaluated site layout solution ($n=1-N$) fully complies with all the specified weight constraints in various zones on site, as shown in Fig. 6. For each site layout solution (n), the model identifies the zone in which each temporary facility ($i=1-I$) is to be located and compares its generated weight stress on soil (σ_i) to the maximum allowable weight stress in the assigned zone (σ_{zw}). If the generated weight stress of the facility exceeds the allowable weight stress in the zone ($\sigma_i > \sigma_{zw}$), then this site layout solution violates the weight constraints and thus the model applies a high penalty on this solution to ultimately preclude it from further consideration, as shown in Fig. 6.

Restricted Areas

The Federal Aviation Administration guidelines and regulations prohibit the presence of construction equipment and/or material in a number of restricted areas around operational runways and taxiways in order to ensure aviation safety during construction operations (FAA 1987). These FAA restricted areas include: (1) runway safety area; (2) taxiway safety area; (3) obstacle-free zone; and (4) object-free area. First, the runway safety area is a defined surface surrounding the runway prepared or suitable for reducing the risk of damage to airplanes in the event of undershoot, overshoot, or excursion from the runway. Second, the taxiway safety area is a defined surface alongside the taxiway prepared or suitable for reducing the risk of damage to an airplane unintentionally departing the taxiway (FAA 2003). Third, the obstacle-free zone is the airspace below 45 m above the established airport elevation and along the runway and extended runway centerline that is required to be clear of all objects, except for visual navigational aids, in order to provide clearance protection for aircraft landing or taking off from the runway and for missed approaches. Fourth, the object-free area is an area on the ground centered on the runway, taxiway, or taxilane centerline provided to enhance safety

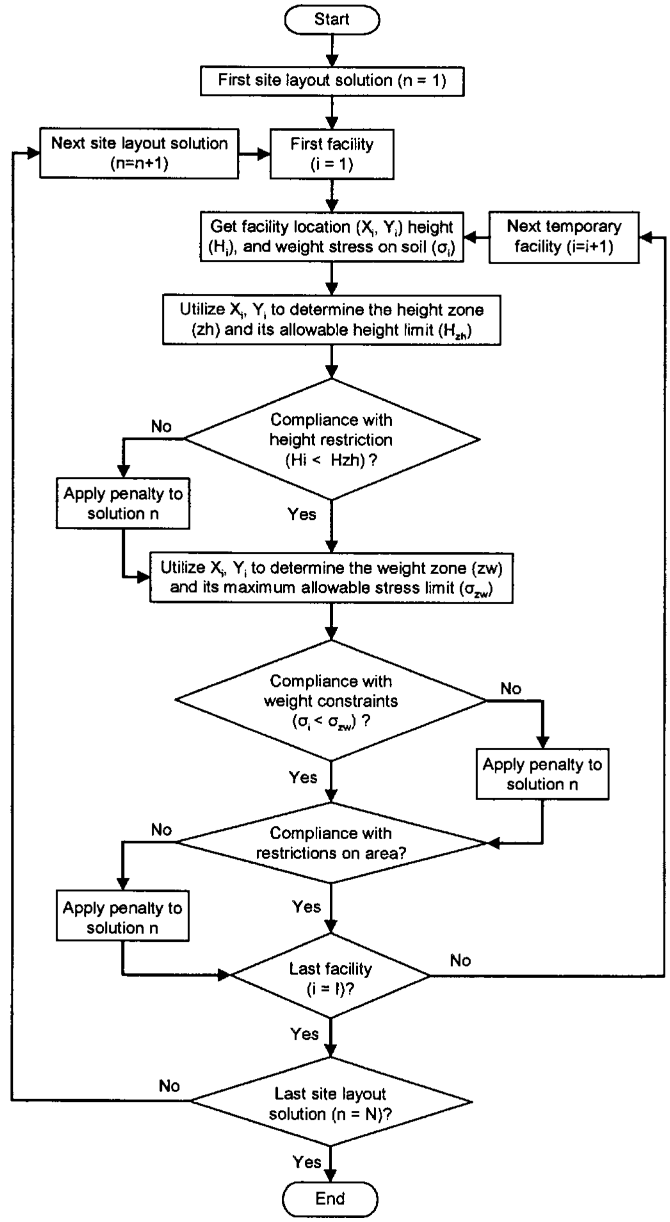

Fig. 6. Compliance with aviation safety constraints

of aircraft operations by having the area free of objects except for those objects needed for aircraft navigation or maneuvering purposes, as shown in Fig. 5 (FAA 2003).

Construction planners and airport operators need to fully comply with these FAA guidelines during site layout planning in order to prevent locating any construction facility in one of the above restricted areas. In order to facilitate this planning task, the present model enables planners to specify the locations and dimensions of all restricted areas/zones (zr=1–Zr) in and around the construction site layout. The model then applies the algorithm shown in Fig. 6 to ensure that no temporary construction facility is located in one of the restricted areas on site. For example, the present model can be used to ensure that construction material, equipment, and/or excavations are kept outside the runway object free area shown in Fig. 5.

Minimizing Site Layout Costs

The present model is designed to enable the minimization of site layout costs that are affected by the earlier described planning decision variables, namely the location of temporary facilities and the utilization of debris containment measures, as shown in Fig. 2. Accordingly, the term “site layout costs” in this paper does not include costs that are not impacted by these two planning decisions such as the rental cost of site facilities that is independent of the location of the facility. Instead, site layout costs is used in the present model to cover only: (1) the travel cost of resources on site; and (2) debris containment costs, as shown in the following equation:

$$\text{minimize site layout costs (SLC)} = \text{minimize(travel cost of resources} + \text{debris containment cost)} \quad (3)$$

Travel Cost of Resources

The travel cost of resources on airport construction sites is directly affected by the planned locations of and distances between temporary construction facilities, as shown in Eq. (4). In order to minimize this cost, construction planners need to carefully select an optimal location for each facility so as to minimize the distance of heavily traveled routes on site. To facilitate this quantitative analysis, the present model incorporates a newly developed performance metric that can be used to represent the travel cost rate (C_{ij}) between any two facilities on site. As shown in Eq. (5), this travel cost rate is designed to consider: (1) the frequency of travel (f_r) between facilities on site; (2) the hourly cost rate (c_r) of traveling crews; and (3) the speed of each traveling crew (s_r). For example, the travel cost rate (C_{ij}) between a lumber storage facility and the planned constructed facility can be estimated based on: (1) the planned travel frequency of the utilized crew (e.g., crew B-67 from Means 2005) which is expected to transport a total of 300 t using its capacity of 3 t per trip (i.e., f_r=200 one-way trips); (2) the hourly cost rate (c_r) of crew B-67 which is estimated at \$81.84/h (Means 2005); and (3) the average speed of the travelling crew (s_r) which is identified to be 8 km/h (CAT 2005). Accordingly, the travel cost rate (C_{ij}) between the lumber storage facility and the constructed facility in this example can be estimated using Eq. (5) to be \$2.046/m

$$\text{travel cost of resources} = \sum_{i=1}^{I-1} \sum_{j=i+1}^{J} C_{ij} \times d_{ij} \quad (4)$$

$$C_{ij} = \sum_{r=1}^{R} \left(\frac{f_r \times c_r}{s_r} \right) \quad (5)$$

$$d_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2} \quad (6)$$

where C_{ij}=travel cost rate (\$/meter) of distance traveled between facilities i and j; d_{ij}=distance (meters) between facilities i and j; I=total number of temporary facilities on site; J=total number of temporary and fixed-location 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 rate of traveling crew r (\$/hour); s_r=speed of traveling crew r (m/h); X_i, Y_i=coordinates of center of gravity of facility i; and X_j, Y_j=coordinates of center of gravity of facility j.

Debris Containment Cost

The containment cost of all debris-producing facilities on site can be calculated based on: (1) the cost of installing, operating and maintaining active debris containment measures (Cc_b); and (2) the total number of facilities on site (B) that are planned to utilize these active containment measures, as shown in the following equation. For example, the unit cost of installing a containment measure that consists of a tarpaulin cover hung over scaffolding can be estimated at \$4.95/m^2 (Means 2005), and accordingly the total cost of utilizing this measure to contain an area of 90 m^2 can be estimated at \$450

$$\text{debris containment cost} = \sum_{b=1}^{B} c_b \times Cc_b \quad (7)$$

where c_b=binary variable to represent the utilization of active containment measure to control the construction debris produced by facility b; and Cc_b=cost of installing, operating, and maintaining the selected containment measure in facility b.

Compliance with Site Layout Constraints

The present model imposes two types of constraints on the generated site layout 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 all temporary facilities are located within the site boundaries, while overlap constraints are required to avoid the overlap of facilities on site. The present model utilizes the algorithm shown in Fig. 7 to ensure full compliance of each possible solution (n=1–N) with these two site layout constraints.

Application Example

An application example is analyzed to illustrate the use of the developed model and demonstrate its capabilities in optimizing airport construction site layouts (see Fig. 8) and providing optimal tradeoffs between maximizing the control of construction debris hazards and minimizing the site layout costs (see Fig. 9). In this example, the airport layout is selected to closely resemble that of an existing airport to enable examining the performance of

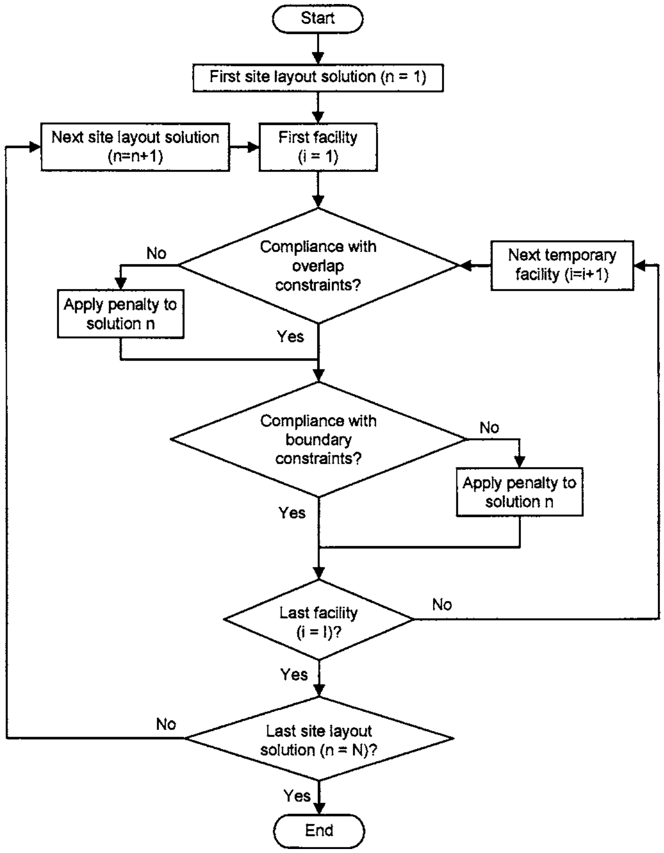

Fig. 7. Compliance with construction site layout constraints

the model in a real-life setting (AirNav 2004). The example involves the construction of a new building that requires the utilization of 17 temporary construction facilities such as field offices, workshops, and lay down areas, as shown in Table 1. The construction site is also located in close proximity to an operational runway and one of its parallel taxiways (see Fig. 8), which can create hazardous conditions to ongoing airport traffic operations if the temporary facilities do not fully comply with all the aforementioned FAA safety regulations.

In this example, the present model is used to support construction planners in their search for optimal site layout plans that specify an optimal location for each temporary facility on site and

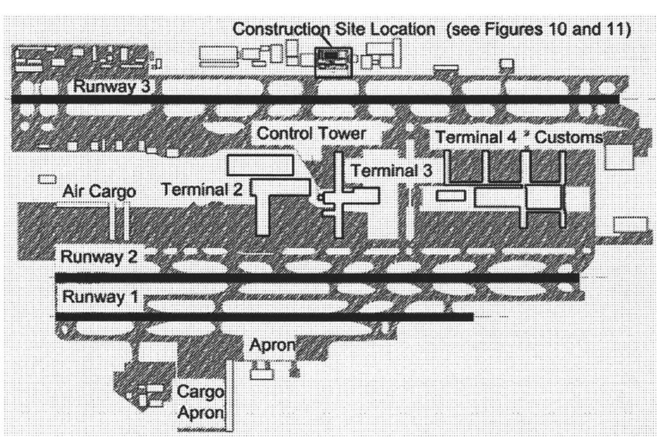

Fig. 8. Airport and construction site layouts

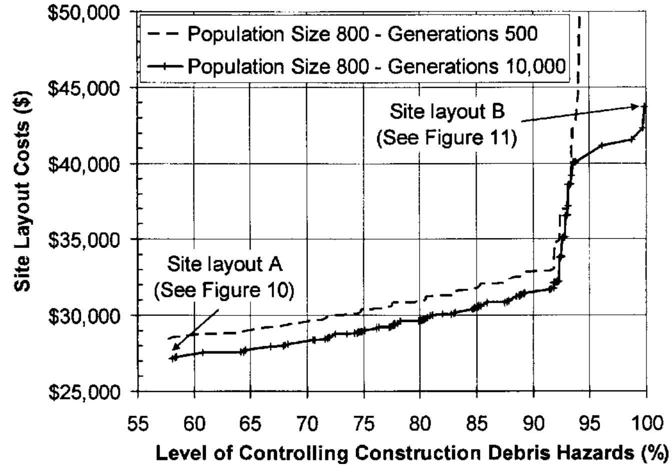

Fig. 9. Tradeoff between debris hazard control and site layout costs

an optimal use of containment measure for each debris-producing facility. The two main optimization objectives in this site layout problem are: (1) maximizing the control of construction debris hazards; and (2) minimizing the site layout costs. Similarly, the two sets of constraints that are fully complied with in this example are: (1) aviation safety constraints including height restrictions, weight constraints, and restricted areas; and (2) practical construction site layout constraints including boundary and overlap constraints.

In order to optimize site layout planning in this example, the present model requires construction planners to specify and input the following parameters: (1) the dimensions and weight stress $(L_x, W_y, H_i, \sigma_i)$ of each facility as shown in Table 1; (2) the identified facilities that are capable of producing hazardous construction debris (see Table 1); (3) the recommended safe separation distance between the facility and the taxiway object free area ($d^*=60$ m) to ensure full elimination of construction debris risk as shown in Fig. 10; (4) the estimated effectiveness and cost of utilizing available containment measures for each debris-producing facility as shown in Table 1; (5) the estimated travel cost rate of traveling crews between facilities (C_{ij}) as shown in Table 2; (6) the applicable height restrictions near the operating taxiway as recommended by FAA guidelines for this type of airport as shown in Fig. 5; (7) the maximum allowable stress (i.e., 3,000 kgf/m^2) in the restricted weight area shown in Fig. 10 to prevent damaging an existing underground facility; (8) the FAA recommended taxiway object free area that has a width of 118 m and is centered on the 30 m wide taxiway in this example as shown in Fig. 10; and (9) the boundaries of the construction site layout, as shown in Figs. 8 and 10.

The model was used to analyze the above input data using varying genetic algorithm setups (e.g., population size, number of generations) as shown in Fig. 9. These runs were able to generate a set of optimal site layout plans, where each provides an optimal and nondominated tradeoff between maximizing the control of construction debris hazards and minimizing site layout costs (see Fig. 9). This tradeoff exists because maximizing the control of construction debris hazards often requires: (1) an increased separation distance between the location of debris-producing facilities and operating airport traffic areas leading to an increase in the travel cost of construction resources; and/or (2) additional costs to utilize debris containment measures. For example, site layout *A* (see Figs. 9 and 10) provides a debris control level of 58% at a site layout cost of $27,198. This debris control level of solution *A*

Table 1. Temporary Construction Facilities

Symbol	Facility name	Length L_x (m)	Width W_y (m)	Height H_i (m)	Weight stress σ_i (kgf/m^2)	Debris producing (Yes/No)	Debris containment measure: Effectiveness η (%)	Cost Cc_b($)
$F1$	Parking lot (a)	30	30	3.5	65,000	No	NA[a]	NA[a]
$F2$	Field office (a)	20	5	2.7	845	No	NA[a]	NA[a]
$F3$	Field office (b)	20	5	2.7	845	No	NA[a]	NA[a]
$F4$	Field office (c)	20	5	2.7	845	No	NA[a]	NA[a]
$F5$	Field office (d)	20	5	2.7	845	No	NA[a]	NA[a]
$F6$	Workshop (a)	5	4	3	1,100	Yes	95	375
$F7$	Workshop (b)	6	5	3	1,100	Yes	95	450
$F8$	Welding shop	5	5	3	1,100	Yes	95	400
$F9$	Storage facility (a)	10	10	4	2,460	Yes	85	800
$F10$	Storage facility (b)	12	8	4	2,460	Yes	85	800
$F11$	Storage facility (c)	10	10	4	2,460	Yes	85	800
$F12$	Equipment storage (a)	20	20	6	65,000	No	NA[a]	NA[a]
$F13$	Equipment storage (b)	5	5	3	65,000	No	NA[a]	NA[a]
$F14$	Lay down area (a)	10	12	3	2,460	Yes	80	400
$F15$	Lay down area (b)	10	12	3	2,460	Yes	80	450
$F16$	Toilets	5	6	3	465	No	NA[a]	NA[a]
$F17$	Crane	10	6.5	25	102,000	Yes	NA[a]	NA[a]

[a]NA=not available.

can be improved to 99.9% at a higher cost of $43,727 as shown in solution *B* in Fig. 11.

In this application example, site layout *A* (see Fig. 10) was capable of minimizing the travel cost of resources on site by: (1) reducing the travel distances among all temporary facilities on site especially those associated with high travel cost rates; and (2) limiting the utilization of costly debris containment measures on site. This site layout plan, however, led to an increase in the level of construction debris hazards as a result of locating all of the nine debris-producing facilities (b=6, 7, 8, 9, 10, 11, 14, 15, and 17) within the debris ingestion zone of the taxiway and without the use of containment measures, as shown in Fig. 10. On the other end of the spectrum, site layout *B* (see Fig. 11) maximizes the control of construction debris hazards on site to 99.9% by: (1) locating eight of the nine debris-producing facilities (b=7, 8, 9, 10, 11, 14, 15, and 17) outside the debris ingestion zone at a safe distance from the taxiway object free area; (2) utilizing optimal containment measures for the single debris-producing facility (b=6) that remained within the specified debris ingestion zone; (3) locating all tall facilities (i=17) that violate the FAA height constraints outside the limited height transitional zone; (4) complying with all weight constraints especially for heavy facilities (i=1, 12, and 17); and (5) locating all temporary facilities outside the specified runway and taxiway object free areas.

In each of the generated optimal site layouts shown in Fig. 9, the model was used to calculate both the level of controlling construction debris hazards and site layout costs using the earlier described Eqs. (1) and (3), respectively. For example, the level of debris control for site layout *B* (see Fig. 9) was calculated to be 99.9% using Eq. (1). This control level for site layout *B* was computed in two main steps: (1) calculating the debris safety score (DS_{bo}) of each debris producing facility using Eq. (2); and (2) averaging out all these calculated debris safety scores using Eq. (1). In this site layout, eight of the nine debris-producing facilities (b=7, 8, 9, 10, 11, 14, 15, and 17) were located outside the debris ingestion zone (see Fig. 11) and accordingly the model applied Eq. (2) to calculate the debris safety score of each to be 100% ($DS_{bo}=100\%$). Similarly, the debris safety score of the remaining debris producing facility (b=6) was calculated using Eq. (2) to be 99.17% based on its identified location and the distance between its center of gravity and the taxiway object free area ($d_{bo}=50$) and the effectiveness of the utilized containment measure ($\eta_b=95\%$). The debris safety score of these nine debris producing facilities was then averaged out [see Eq. (1)] to calculate the overall performance level of controlling construction debris hazards in site layout *B* to be 99.9% ($\text{CCDH}=[99.17+8^*100]/9/1=99.9\%$).

It should be noted that the present multiobjective optimization model recommends the utilization of containment measures only when needed in order to keep site layout costs to a minimum. For example in site layout *B* that provides the highest level of debris control, the model located eight of the nine debris-producing fa-

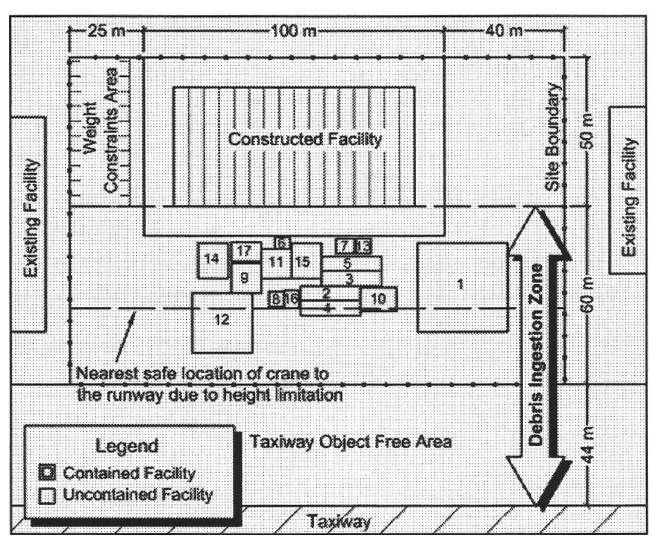

Fig. 10. Site layout with least costs

Table 2. Travel Cost Rates (C_{ij}) among Facilities

	Facility (i)																
Facility (j)	$F1$	$F2$	$F3$	$F4$	$F5$	$F6$	$F7$	$F8$	$F9$	$F10$	$F11$	$F12$	$F13$	$F14$	$F15$	$F16$	$F17$
$F1$	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
$F2$	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
$F3$	1	15	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—
$F4$	1	15	15	0	—	—	—	—	—	—	—	—	—	—	—	—	—
$F5$	1	15	15	15	0	—	—	—	—	—	—	—	—	—	—	—	—
$F6$	0	1	1	1	1	0	—	—	—	—	—	—	—	—	—	—	—
$F7$	0	1	1	1	1	10	0	—	—	—	—	—	—	—	—	—	—
$F8$	0	1	1	1	1	10	7	0	—	—	—	—	—	—	—	—	—
$F9$	0	1	2	2	2	9	3	10	0	—	—	—	—	—	—	—	—
$F10$	0	1	8	8	8	7	8	7	1	0	—	—	—	—	—	—	—
$F11$	0	1	8	8	8	3	3	3	3	1	0	—	—	—	—	—	—
$F12$	0	0	0	0	0	0	5	0	8	8	8	0	—	—	—	—	—
$F13$	0	1	1	1	1	4	4	4	0	0	0	4	0	—	—	—	—
$F14$	0	2.5	2.5	3	3	8	8	9	3	3	3	0	0	0	—	—	—
$F15$	0	2.5	2.5	3	3	8	8	9	3	3	3	0	0	0	0	—	—
$F16$	0	15	8	8	8	5	5	5	0	0	0	0	0	0	0	0	—
$F17$	0	0	0	0	0	5	5	5	35	35	35	20	0	100	100	0	0
$C1$[a]	0	15	15	15	15	36	36	36	10	10	10	0	10	10	10	0	100

[a]Constructed Facility (80×40 m^2).

cilities (b=7, 8, 9, 10, 11, 14, 15, and 17) at a safe distance outside the specified debris ingestion zone, as shown in Fig. 11. Accordingly, there is no need to utilize containment measures for these facilities as they do not pose any hazard to aviation safety in these locations. The only debris-producing facility that is located within the debris ingestion zone is facility 6, and accordingly the model recommends it to utilize containment measures to control the spread of debris beyond its perimeter. To further illustrate the capability of the present model in recommending an optimal level of utilizing containment measures, the same example was reanalyzed under more restrictive conditions that relocated the eastern fence/boundary of the site further west, as shown in Fig. 12. This restricted site layout prohibits locating temporary facilities in the eastern zone of the site, forcing eight of the nine debris producing facilities (b=7, 8, 9, 10, 11, 14, 15, and 17) to be relocated to the debris ingestion zone (see Fig. 12). In order to maximize the control of construction debris hazards in that restricted site layout, the model recommends: (1) utilizing containment measures in all debris producing facilities that are located within the debris ingestion zone except for the crane (b=17) that cannot be practically contained as indicated by the planner in Table 1; and (2) locating the crane at the greatest and safest possible distance from the taxiway without violating the specified weight constraint, as shown in Fig. 12.

The above analysis of this application example highlights the unique and practical capabilities of the present model. It illustrates how the model can be effectively used to search for and identify a wide range of optimal site layout plans, where each provides a unique and optimal tradeoff between the control of construction debris hazards and site layout costs as shown in Fig.

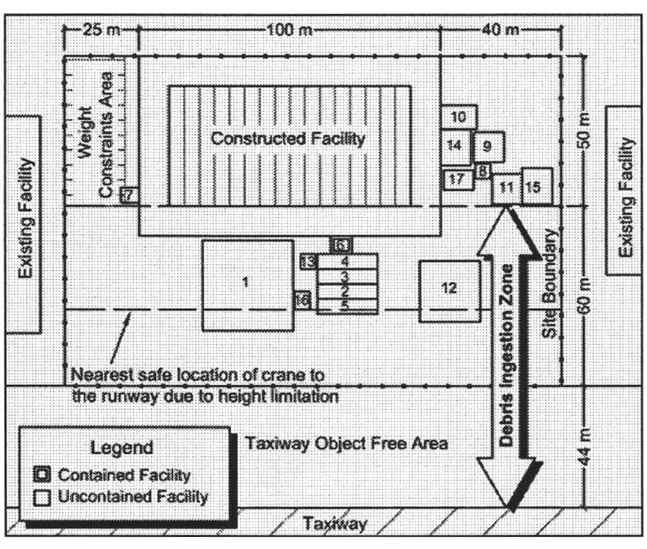

Fig. 11. Site layout with maximum debris control

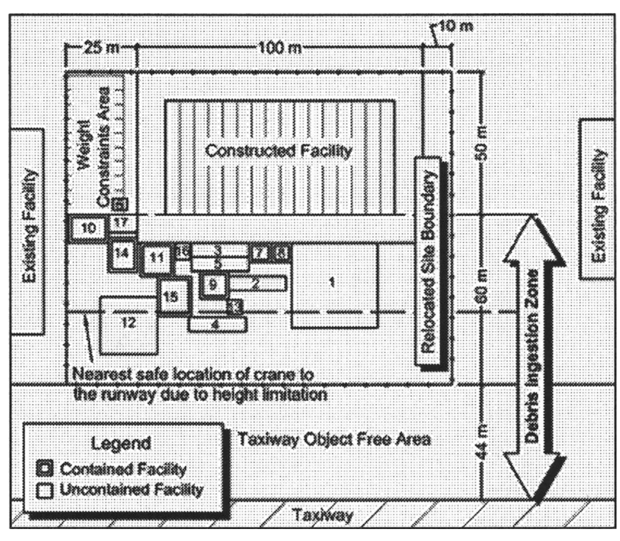

Fig. 12. Maximum debris control for restricted site layout

9. Construction planners can then evaluate these generated optimal tradeoffs and select an optimal site layout that satisfies the specific requirements of the project being planned.

Summary and Conclusion

A multiobjective optimization model was developed to support site layout planning in airport expansion projects. The model is capable of maximizing the control of construction debris hazards and minimizing site layout costs simultaneously, while complying with all FAA aviation safety guidelines including limiting the heights of temporary facilities in airport construction zones, protecting underground utilities from excessive weight and maintaining restricted airport safety areas. The model is implemented using a multiobjective genetic algorithm and is capable of generating optimal site layout plans that specify an optimal location for each temporary facility on site and an optimal use of containment measure whenever needed to prevent the spread of construction debris in critical airport traffic areas. An application example is analyzed to illustrate the use of the model and demonstrate its unique capabilities in generating optimal tradeoffs between aviation safety and site layout costs. This should prove useful to construction planners and airport operators alike and can lead to significant improvements in the optimization of site layout plans in airport expansion projects.

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Notation

The following symbols are used in this paper:

B = total number of facilities classified to produce hazardous construction debris;
Cc_b = cost of installing, operating, and maintaining selected containment measure in facility b;
CCDH = average performance level in controlling construction debris hazards in entire site layout (ranges from 0 to 100%);
c_b = binary variable to represent utilization of active containment measure to control construction debris produced by facility b;
C_{ij} = travel cost rate ($/meter) of distance traveled between facilities i and j;
c_r = hourly cost of traveling crew r ($/hour);
DS_{bo} = debris safety score for locating facility b at distance of d_{bo} from runway/taxiway object free area o (ranges from 0 to 100%);
d^* = recommended distance between debris-producing facilities and runway/taxiway object free areas;
d_{bo} = planned distance between facility b and runway/taxiway object free area o;
d_{ij} = distance (meters) between facilities i and j;
f_r = frequency of one-way traveling for construction crew r between facilities i and j during life cycle of site layout plan;
H_i = height of temporary facility i;
H_{zh} = maximum height restriction for construction zone zh;
I = total number of temporary facilities on site;
J = total number of temporary and fixed-location facilities on site;
O = total number of runway/taxiway object free areas;
s_r = speed of traveling crew r (meter/hour);
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;
η_b = effectiveness of active containment measure/barrier used in facility b;
σ_i = weight stress generated by temporary facility i on soil; and
σ_{zw} = maximum allowable weight stress for construction zone zw.

Subscripts and Superscripts

b = facilities classified to produce hazardous construction debris (from $b=1$ to B);
i = temporary facility counter (from $i=1$ to I);
n = site layout plan (from $n=1$ to N);
o = runway/taxiway object free areas (from $o=1$ to O);
r = traveling crew (from $r=1$ to R);
t = generation (from $t=1$ to T);
zh = height-restricted construction zone (from zh=1 to ZH);
zr = restricted operational area (from zr=1 to ZR); and
zw = weight-constrained construction zone (from zw=1 to ZW).

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