Automation in Construction 20 (2011) 313–320

Contents lists available at ScienceDirect

Automation in Construction

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

Automated multi-objective optimization system for airport site layouts

Ahmed Khalafallah [a,*], Khaled El-Rayes [b]

[a] University of Central Florida, Department of Civil, Environmental, and Construction Engineering, Orlando, FL 32816-2450, USA
[b] University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering, Urbana, IL 61801, USA

A R T I C L E   I N F O

Article history:
Accepted 4 November 2010
Available online 30 November 2010

Keywords:
Optimization
Evolutionary computation
Security
Airport construction
Construction site
Site evaluation
Site preparation
Construction management

A B S T R A C T

Airport construction planners often face the problem of identifying optimal locations for temporary construction facilities on site, as the planned locations of these facilities usually influence important and conflicting planning objectives such as improving the efficiency of construction operations and maintaining safety on site. Careful evaluation of all feasible locations for temporary facilities and the selection of an optimal layout are needed in order to achieve these multiple important objectives. This paper presents the development of a practical automated system to optimize multiple conflicting planning objectives and provide all possible optimal tradeoff solutions among these objectives. The system is implemented and integrated in four main modules: (1) a comprehensive multi-objective optimization engine that integrates and optimizes construction work zone safety, construction-related aviation safety, construction-related airport security, and all relevant site layout costs; (2) a relational database that integrates planning data and stores all the generated optimal solutions; (3) an Input/Output module to facilitate specifying planning and optimization parameters and retrieving the generated optimal site layout solutions; and (4) a visualization module that communicates with external CAD software in order to support the visualization of the generated optimal site layout plans.

1. Introduction

In airport expansion projects, the planning of construction site layouts requires construction planners and decision makers to identify the best location of each temporary construction facility on site in order to achieve a number of important planning objectives. These objectives include (1) minimizing the cost of all the items influenced by the site layout; (2) maintaining the safety of airport operations during construction; (3) reducing construction-related security breaches; and (4) improving the safety of construction operations [1–4]. In order to assist construction planners in this important task, several methodologies have been adopted in the literature, aiming to develop site layout planning models. These methodologies included genetic algorithms [5–8], linear programming [9,10], knowledge-based systems [11–14], artificial neural networks [15], simulation [16,17], and ant colony optimization [31].

Over the past decades multi-objective genetic algorithms have evolved as powerful tools to solve problems that involve optimizing a number of objectives simultaneously. Some of these algorithms were also used in solving site layout planning problems [3,18,19,28]. For example, Soltani and Fernando presented a framework for supporting path planning analysis of construction sites based on multi-objective evaluation of transport cost, safety, and visibility [28]. Their work investigated the use of a fuzzy-based multi-objective optimization approach in making more informed strategic decisions regarding the movement path of workers and vehicles on construction sites, and detailed decisions regarding travel distance and operational paths on workplaces. The approach allows distance, safety, and visibility objectives to be combined and decision to be made on the preference given to a certain objective. El-Rayes and Said developed an approximate dynamic programming model that is capable of searching for and identifying global optimal dynamic site layout plans [30]. The model applies the concepts of approximate dynamic programming to estimate the future effects of layout decisions in early stages on future decisions in later stages. The model is designed to identify a global optimal location and orientation for each temporary construction facility on site, and is capable of considering and complying with practical site layout constraints such as operational and safety constraints.

Few research studies investigated the optimization of airport and other critical facilities construction sites. For example, El-Rayes and Khalafallah developed a model to maximize the safety of construction operations while minimizing the overall site layout cost [3]. Khalafallah and El-Rayes also developed a second model to minimize construction-related hazards and the overall site layout cost simultaneously [18]. The same researchers developed a third model to maximize construction-related airport security while minimizing the overall site layout cost [19].

* Corresponding author. Tel.: +1 407 823 4826; fax: +1 407 823 3315.
E-mail addresses: khalafal@mail.ucf.edu (A. Khalafallah), elrayes@uiuc.edu (K. El-Rayes).

0926-5805/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.autcon.2010.11.001

Said and El-Rayes presented the development of an automated multi-objective optimization framework for the planning of construction site layout and security systems of critical infrastructure projects [29]. The framework provides the capability of minimizing overall security risks and minimizing overall site costs. The framework included four main modules to facilitate risk identification and system modeling, security lighting optimization, security-cost optimization, and performance evaluation.

Despite the contributions of these models, they were limited to optimizing one or two objectives, including the minimization of travel cost of resources on site, at most. As such, there is a pressing need for practical and automated systems that can account for all the aforementioned important planning objectives and optimize them simultaneously. This paper presents the development of a multi-objective optimization system that addresses this need.

The primary objective of the present system is to provide practical automated support for construction planners and airport operators who need to optimize site layout plans. To this end, the present system is designed to provide a number of unique and practical capabilities, including: (1) utilizing multi-objective genetic algorithms in order to enable the simultaneous optimization of construction safety, construction-related aviation safety, construction-related airport security and the overall site layout costs; (2) automating the development of tradeoff charts among construction safety, aviation safety, airport security and the overall site layout costs; and (3) supporting the visualization of the generated optimal site layout plans through seamless integration with commercially available CAD software systems.

In order to provide the aforementioned capabilities, the system is implemented and integrated into four main components: (1) a comprehensive multi-objective optimization engine that integrates and optimizes the overall impact of site layout planning on construction safety, construction-related aviation safety, construction-related security, and all relevant site layout costs; (2) a relational database to support storing and retrieving construction site layout data and the generated optimal solutions; (3) an Input/Output module that facilitates the input of project data and the retrieval of the generated optimal site layout solutions; and (4) a visualization interface that communicates with external CAD software in order to provide construction planners with the capability of visualizing the generated optimal site layouts, as shown in Fig. 1. These four system components are described in more detail in the following sections.

2. Multi-objective optimization engine

The main function of the comprehensive multi-objective optimization engine is to facilitate the optimization of five site layout objectives (Eqs. (1)–(5)) that were designed to: (1) maximize construction safety, (2) maximize construction-related aviation safety (i.e. debris and wildlife control), and (3) maximize construction-related security level, while minimizing all relevant site layout costs [3,18,19,32]. This overall optimization system is designed to search for and identify optimal solutions for all the site layout decision variables, including: (1) the coordinates (x and y) of the center of gravity of each temporary facility; (2) the optimal utilization of debris containment measures; (3) the optimal use of wildlife management measures;

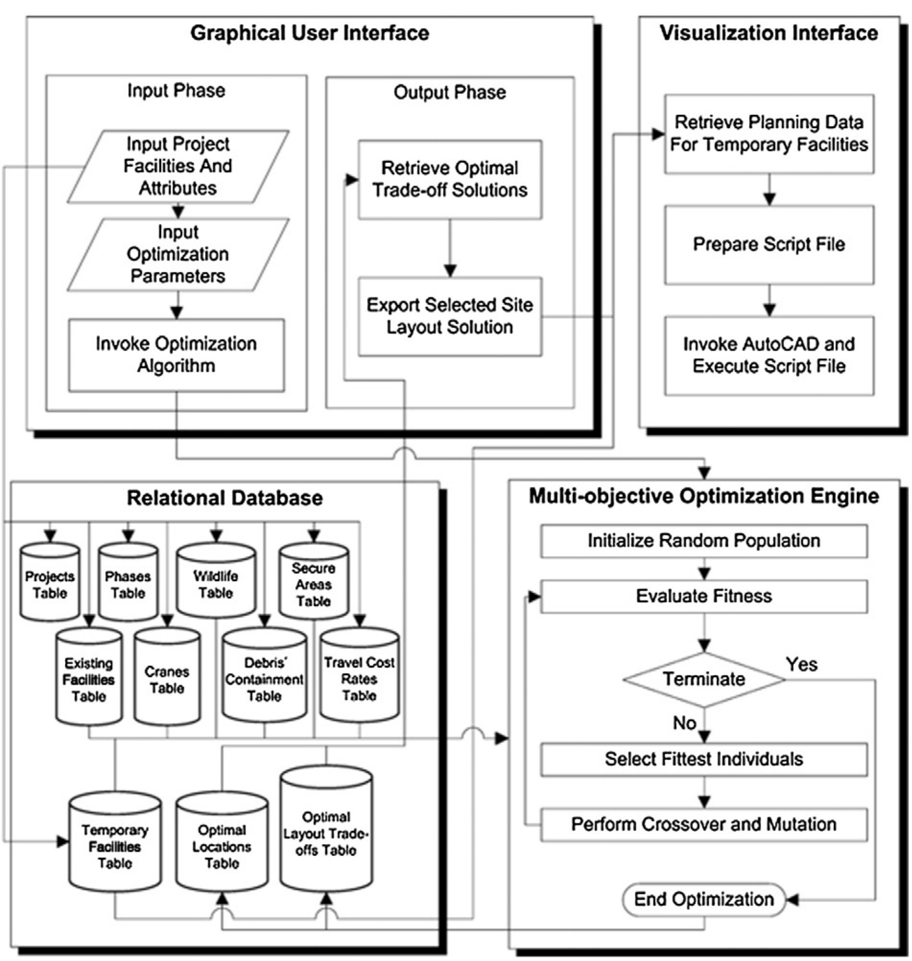

Fig. 1. Main modules of the multi-objective optimization system.

(4) the location of security fence with respect to secure areas/facilities; and (5) the security control systems utilized on site.

$$\text{Maximize Construction Safety} = Max\{w_i \times CSC + w_{ii} \times NHCC + w_{iii} \times IPC\} \quad (1)$$

$$\text{Maximize Debris Control Criterion(DCC)} = Max\left\{\frac{\sum_{o=1}^{O}\frac{\sum_{b=1}^{B}(DS_{bo})}{B}}{O}\right\} \quad (2)$$

$$\text{Maximize Wildlife Control Criterion(WCC)} = Max\{w_1 \times WHMC + w_2 \times WECC + w_3 \times WRHC\} \quad (3)$$

$$\text{Maximize Construction-Related Security Level} = Max\{w_{s1}\,SRDC + w_{s2}\,SSC\} \quad (4)$$

$$\text{Minimize Overall Site Layout Cost} = Min\{TT + DCT + WCT + CRSCT\} \quad (5)$$

where,

B total number of facilities classified to produce hazardous construction debris [18];
CRSCT construction-related security control cost [19];
CSC cranes safety criterion to place high occupancy facilities far away from crane operation zones [3];
DCC overall debris control criterion score to locate all debris producing facilities far away from taxiways/runways [18];
DCT cost of utilizing debris control methods [18];
DS_{bo} debris safety score for locating facility b at a distance of d_{bo} from runway/taxiway object free area (o) [18];
IPC criterion of minimizing the number of travel path intersection points [3];
NHCC criterion of locating hazardous facilities far from high occupancy facilities [3];
O total number of runway/taxiway object free areas [18];
SRDC criterion of providing security response distance for critical facilities [19];
SSC criterion of accounting for the effectiveness of each physical security system utilized [19];
TT resource travel cost [3];
w_i relative weight or scaling constant of crane safety criterion [3];
w_{ii} relative weight or scaling constant of hazards control criterion [3];
w_{iii} relative weight or scaling constant of intersection point criterion [3];
w_1 planner-specified relative importance/weight of habitat modification criterion [32];
w_2 planner-specified relative importance/weight of exclusion control criterion [32];
w_3 planner-specified relative importance/weight of wildlife harassment criterion (WRHC) [32];
w_{s1} relative weight of security response distance criterion (SRDC) [19];
w_{s2} relative weight of security systems criterion (SSC) [19];
WCT cost of all wildlife control systems used [32];
WHMC criterion of excluding possible wildlife habitats [32];
WECC criterion of using wildlife exclusion control [32]; and
WRHC criterion of using wildlife repelling and harassment methods [32].

As shown in Fig. 1, the overall model is designed to start the optimization operations by generating a set of random site layout solutions. From this set of candidate solutions, new solutions are reproduced, through a number of genetic optimization operations such as crossover or random mutation, forming an offspring population. The population is then evaluated to select the best candidates to undergo crossover and mutation again in an iterative process that tends to eliminate the worst site layout solutions and keep the best ones. The selection of individuals here is based on the domination and ranking criterion [20]. In selecting the best candidates, each site layout solution is evaluated on a number of criteria, including: (1) the overall construction safety; (2) the level of construction-related aviation safety; (3) the level of construction-related airport security; and (4) the total site layout costs. The aforementioned set of genetic operations are repeated over a number of cycles, generating better and better solutions until the population evolves to a stable state.

3. Relational database

The main function of this system component is to store the necessary site layout input data (e.g. temporary facilities attributes, existing facilities attributes, and crane data) and the generated optimal site layout data (e.g. temporary facilities locations, optimal utilization of debris, and location of security fence). This relational database is composed of eleven main tables that are designed to store the following site layout planning data: (1) project information; (2) project phases information; (3) temporary facility attributes; (4) existing facility attributes; (5) crane data; (6) debris containment information; (7) wildlife data; (8) secure area attributes; (9) travel cost rates data; (10) optimal locations of temporary facilities; and (11) optimal tradeoff solutions. Fig. 2 illustrates an entity relationship diagram that describes the attributes of these tables and the relationships among them using a crow's foot model [21].

The “Projects” table is designed to store information about the project being planned such as its name and ID. This table is linked to the “Phases” table using a “one to many” relationship. The “Phases” table is also linked using a one to many relationship to four other tables: (a) “Temporary Facilities” table which stores the information of each temporary facility that needs to be assigned a location on site, including facility ID, phase ID, name, length, width, and the sensitivity of the facility to crane proximity according to the level of occupancy [3]; (b) “Existing Facilities” table that stores the locations, dimensions, and information about permanent facilities which already exist on site; (c) “Cranes” table which stores data on each crane utilized on site such as its base length, base width, jib length, reach and mast width; and (d) “Secure Areas” table which stores the coordinates of each secure area which is located in close proximity to the construction site.

The “Temporary Facilities” table is also linked using a many-to-many relationship to four other tables. These tables are: (a) “Optimal Locations” table which stores the generated optimal locations for each temporary facility; (b) “Travel Cost Rates” table which stores the resource travel cost rates between facilities; (c) “Debris Containment” table which specifies the methods utilized on site to contain construction debris (e.g. tarpaulin covers, polyethylene meshes, covered boxes,…etc.), their efficiency and their associated costs [18]; and (d) “Wildlife” table which includes the necessary data on wildlife management such as the utilization of exclusion techniques (fences, blankets,…etc.) and repelling techniques (e.g. chemical, audio, visual repellents, …etc.) [32], as shown in Fig. 2.

The “Optimal Tradeoff Solutions” table is designed to store the overall cost of site layout, the construction safety index, the overall level of aviation safety, the construction-related security level of each of the generated optimal site layout plans. This table is also connected to the “Optimal Locations” table using a “one to many” relationship. The data stored in these tables can be entered by the construction

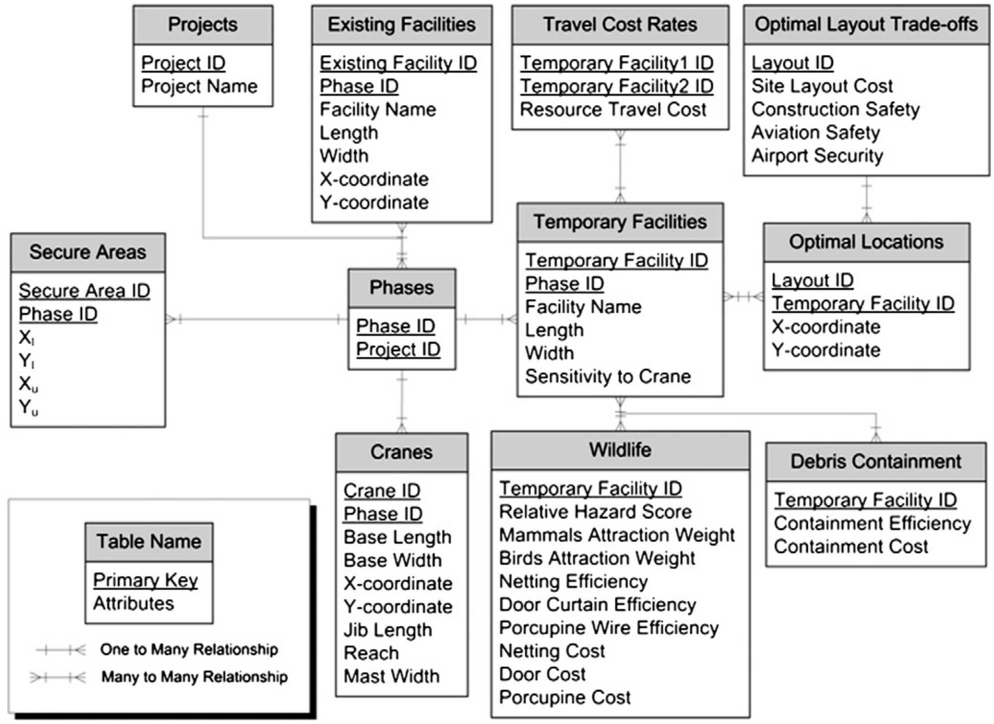

Fig. 2. Entity relationship diagram.

planner using a practical Input/Output module, which is described in more detail in the following section.

4. Input/Output module

The Input/Output module is developed to help construction planners and airport operators input all necessary site layout planning data and retrieve the generated optimal site layout designs. This module is designed to operate in two main phases: (1) an input phase, which allows construction planners to store all the necessary construction site data, and genetic optimization parameters; and (2) an output phase to facilitate the retrieval of the optimal site layout plans and their visualization on CAD software. The module is implemented using Microsoft Visual Basic in order to benefit from its advanced capabilities in facilitating the development of graphical user-friendly interfaces and the integration of all the developed system components. The relationships and interactions between the input and output phases and the other system components are illustrated in Fig. 1. The following two sections provide a detailed discussion on the flow of data during the input and output phases.

4.1. Input phase

This phase is designed to assist construction planners in entering and storing all the necessary planning and optimization data for optimizing the site layout plan. During this phase, the user is asked to enter site layout planning data on: (1) all the temporary facilities that will be used on the construction site; (2) existing permanent facilities on site; (3) cranes; (4) travel cost rates between facilities; (5) available debris containment measures; (6) feasible wildlife management techniques as shown in; and (7) possible security management techniques.

The input of the aforementioned site layout planning data is organized and managed by an optimization control form. This form allows the construction planners to select the required optimization objectives and accordingly input only the relevant data required for these objectives. The input phase also facilitates the input of the genetic optimization parameters which are needed to run the multi-objective optimization algorithm. These parameters include the population size; the number of generations; the type of crossover and its probability; the search ranges for decision variables; the probability of mutation; and the random seed used to initiate the first population of solutions randomly [20]. These parameters can be specified based on empirical rules-of-thumb that are reported in the literature [22]. For example, the initial population size can be specified to be twice the number of desired non-dominated solutions. This initial population size can then be doubled if the generated solution does not produce the desired conversion level. Similarly, the initial number of generations is empirically specified to be double the length of the binary chromosome representing the variables [22].

These optimization parameters are then utilized to run the optimization process which can be invoked by selecting the option “Optimize Site”. The optimization process runs until completing the specified number of generations, and after completion, the results can be retrieved and visualized in the output phase.

4.2. Output phase

The output phase is designed to enable the retrieval of the optimal tradeoffs among (1) construction operations safety; (2) construction-related aviation safety; (3) construction-related airport security; and (4) site layout costs. The output phase also can be used to invoke the visualization interface to help visualize optimal site layout plans using commercially available CAD software systems, as shown in Fig. 3. This phase is implemented to execute its functions in two steps: (1) retrieve the generated optimal tradeoff solutions and display the tradeoff curves, allowing the planner to navigate through these generated solutions, as shown in Fig. 3; and (2) export selected optimal site layout plans to the visualization interface.

5. Visualization interface

The main function of this component is to transform the generated optimal site layout solutions into a form that can be readily exported

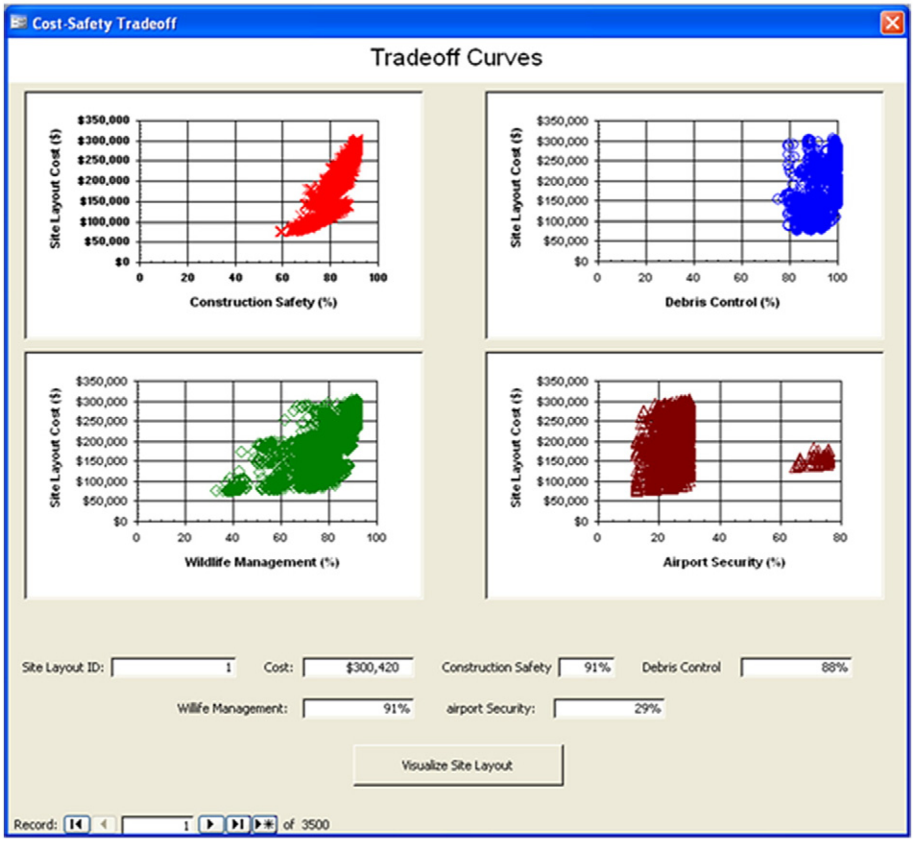

Fig. 3. System output.

to and visualized in CAD software systems such as AutoCAD. To accomplish this, the visualization interface is designed to execute three sequential tasks: (1) retrieve the dimensions of temporary facility from the temporary facilities database table, as shown in Fig. 1; (2) call a function to prepare a script file with all the necessary AutoCAD commands needed to draw the temporary facilities; and (3) start AutoCAD and execute the script file commands to draw the temporary facilities, as shown in Fig. 4. The user can then visualize the

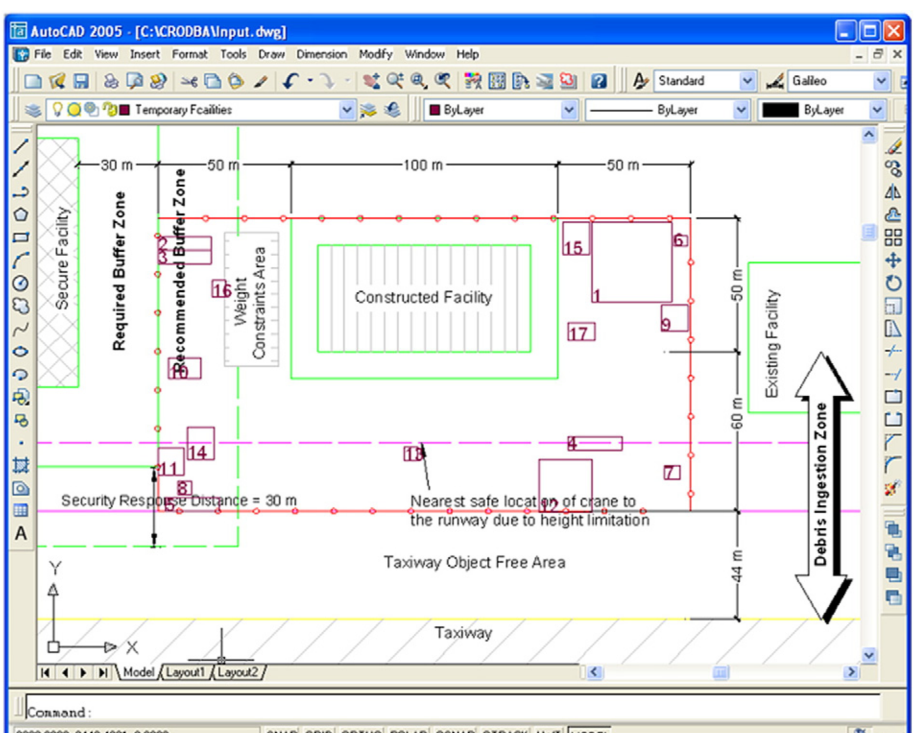

Fig. 4. Site layout generated by the system.

Table 1
Temporary facilities.

Symbol	Facility name	Length in m	Width in m	Height in m	Pressure in kgf/m^2	Debris producing (Yes/No)	Debris containment measure	
							Effectiveness in %	Cost in $
F1	Parking lot (a)	30	30	3.5	65,000	No	NA	NA
F2	Field office (a)	20	5	2.7	845	No	NA	NA
F3	Field office (b)	20	5	2.7	845	No	NA	NA
F4	Field office (c)	20	5	2.7	845	No	NA	NA
F5	Field office (d)	20	5	2.7	845	No	NA	NA
F6	Workshop(a)	5	4	3	1100	Yes	95	375
F7	Workshop(b)	6	5	3	1100	Yes	95	450
F8	Welding shop	5	5	3	1100	Yes	95	400
F9	Storage facility (a)	10	10	4	2460	Yes	85	800
F10	Storage facility (b)	12	8	4	2460	Yes	85	800
F11	Storage facility (c)	10	10	4	2460	Yes	85	800
F12	Equipment storage (a)	20	20	6	65,000	No	NA	NA
F13	Equipment storage (b)	5	5	3	65,000	No	NA	NA
F14	Lay down area (a)	10	12	3	2460	Yes	80	400
F15	Lay down area (b)	10	12	3	2460	Yes	80	450
F16	Toilets	5	6	3	465	No	NA	NA
F17	Crane	10	6.5	25	102,000	Yes	NA	NA

site layout plan and perform further analysis to ensure that the site layout plan satisfies all project requirements.

6. Limitations

Despite the aforementioned capabilities, the current limitations of the developed system include (1) modeling temporary and existing facilities using two-dimensional rectangles, (2) representing site boundaries by straight lines that could be oriented, (3) approximating resource travel paths as the center-to-center distance between site facilities, and (4) assuming that site space requirements are predetermined and static. To address these limitations, future research will be directed towards expanding the system to support 3D modeling of site layouts, planning of resource travel paths, and incorporating the dynamic impact of changes in schedule and construction requirements on site layout planning.

7. Application example

A comprehensive real-life application example is analyzed to illustrate the capabilities of the developed system in integrating the optimization of (1) construction safety, (2) construction-related aviation safety, (3) construction-related security level, and (4) overall site layout cost. To ensure the applicability and practicality of the analyzed example, real-life construction site and layout planning data were obtained from the engineering team working on the O'Hare Airport Modernization project and utilized in this example. In this application example, a new facility is constructed near an operational taxiway and in the vicinity of airport secure facilities. The input data for this application example is summarized in Tables 1–6. Table 1 presents the attributes of temporary facilities that need to be located on site. These attributes include the dimensions of each temporary facility, the expected load (pressure) exerted by the temporary facility on soil, whether it is a debris producing facility, and the effectiveness and cost of each debris containment measure used for debris producing facilities. The effectiveness of debris containment is a user-specified quantitative value that should be specified to reflect the historic percentage of time the debris containment measure failed to contain debris. The identification of these parameters is discussed in the authors' previous work in more detail [3,18,19,32]. Table 2 summarizes the resource travel cost between facilities on site. These costs represent the summation of all travel unit costs for all crews traveling between pairs of facilities [3,4]. Table 3 introduces the effectiveness and cost of the analyzed wildlife repellent techniques. These techniques are utilized to minimize the dangerous attraction of wildlife species to operational airport areas during construction

Table 2
Travel cost rates among facilities.

Facility (j)	Facility (i)																
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17
F1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
F2	2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
F3	2	30	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
F4	2	30	30	0	–	–	–	–	–	–	–	–	–	–	–	–	–
F5	2	30	30	30	0	–	–	–	–	–	–	–	–	–	–	–	–
F6	0	2	2	2	2	0	–	–	–	–	–	–	–	–	–	–	–
F7	0	2	2	2	2	20	0	–	–	–	–	–	–	–	–	–	–
F8	0	2	2	2	2	20	14	0	–	–	–	–	–	–	–	–	–
F9	0	2	4	4	4	18	6	20	0	–	–	–	–	–	–	–	–
F10	0	2	16	16	16	14	16	14	2	0	–	–	–	–	–	–	–
F11	0	2	16	16	16	6	6	6	6	2	0	–	–	–	–	–	–
F12	0	0	0	0	0	0	10	0	16	16	16	0	–	–	–	–	–
F13	0	2	2	2	2	8	8	8	0	0	0	8	0	–	–	–	–
F14	0	5	5	6	6	16	16	18	6	6	6	0	0	0	–	–	–
F15	0	5	5	6	6	16	16	18	6	6	6	0	0	0	0	–	–
F16	0	30	16	16	16	10	10	10	0	0	0	0	0	0	0	0	–
F17	0	0	0	0	0	10	10	10	70	70	70	40	0	200	200	0	0
C1*	0	30	30	30	30	72	72	72	20	20	20	0	20	20	20	0	200

* Constructed Facility (80 x 40 m^2).

Table 3
Effectiveness and costs of available repellent techniques.

Wildlife	Repellent technique	Effectiveness in %	Total cost in $
Mammals	1	100	700
Birds	1	70	1150
	2	10	3267
	3	10	320
	4	10	450

activities. If ingested by airplane engines, these wildlife species could result in fatal accidents and/or expensive repairs [19]. Similarly, Table 4 summarizes the data for wildlife exclusion techniques such as the use of fences, netting, plastic sheeting and porcupine wire and spikes [19]. Table 5 summarizes the input data on the security control systems that can be used to eliminate or reduce security breaches on site, including their effectiveness and associated costs [23–27]. Table 6 illustrates the options available to construct the security fence around site.

The aforementioned data was input to the developed system using the previously described user input interface that requires construction planners to select the required optimization objectives. According to the selected objectives, the planner can input all relevant site layout planning data. These input data are then stored in a number of tables in the relational database, as shown in Fig. 1. After inputting all site layout-related data, the construction planner can then proceed to input the optimization parameters as, shown in Fig. 1.

Despite specifying the optimization parameters (population size, number of generations, type and probability of crossover, and mutation probability) according to the recommendations presented through the literature [22], the initially generated solutions were not near their expected optimal values. As such several runs were performed in order to study the effect of varying the optimization parameters on the quality of obtained solutions. It was observed that increasing the population size is more effective than increasing the number of generations. However, increasing the population size also entailed a significant increase in computational requirements. In addition, it was also observed that using a uniform crossover operator was much more effective than using a single point crossover. In this example, the best tradeoff solutions were obtained by running the system for 1500 generations using a population size of 3500 individuals, uniform crossover with a distribution index of 0.5 and a mutation probability of 0.003. The planner can then proceed with the optimization process by selecting the “Optimize Site” option. The optimization process then starts and runs through the specified number of cycles in order to optimize the selected objectives simultaneously.

After the completion of the optimization process, the planner can view the tradeoff between the selected objectives by selecting the “View Tradeoff Curves” option which displays these curves as shown in Fig. 3. The planner can then navigate through the various tradeoff solutions using the navigation buttons and invoke the visualization interface to prepare a script file and use it to plot the selected site layout solution as shown in Figs. 3 and 4. The planner can further analyze these generated site layout plans to ensure that they satisfy all project requirements. It could be argued that the use of extensive input data, as illustrated in the analysis of this example, is a hindrance for the utilization of the developed system. However, it should be noted that the majority of this input data are readily stored in various

Table 4
Temporary construction facilities and available exclusion techniques.

Symbol	Facility name	TAM(a)	TAB(b)	Birds(c) exclusion		
				Technique	Effectiveness in %	Cost in $
F1	Parking lot	(d)	(d)	–	–	–
F2	Field office (a)	–	Blackbirds	2	35	200
				3	30	15
				4	35	950
F3	Field office (b)	–	Blackbirds	2	35	200
				3	30	15
				4	35	950
F4	Field office (c)	–	Blackbirds	2	35	200
				3	30	15
				4	35	950
F5	Field office (d)	(d)	(d)	–	–	–
F6	Workshop (a)	Coyotes	Vultures	2	35	40
				3	30	15
				4	35	340
F7	Workshop (b)	(d)	(d)	–	–	–
F8	Welding shop	Coyotes	Vultures	2	35	50
				3	30	15
				4	35	380
F9	Storage facility (a)	Coyotes	Vultures	2	35	200
				3	30	80
				4	35	760
F10	Storage facility (b)	Coyotes	Vultures	2	35	800
				3	30	80
				4	35	1520
F11	Storage facility (c)	(d)	(d)	–	–	–
F12	Equipment storage (a)	(d)	(d)	–	–	–
F13	Equipment storage (b)	(d)	(d)	–	–	–
F14	Lay down area (a)	–	Geese	2	100	240
F15	Lay down area (b)	–	Geese	2	100	240
F16	Toilets	Deer	Turkey	3	50	5
				4	50	418
F17	Crane	–	Vultures	2	100	280

(a)Typical attracted mammal.
(b)Typical attracted bird.
(c)Mammals exclusion: chain-link fence with barbed-wire outriggers (70% effective with expected cost of $6.2/m) or electric-fence (100% effective with expected cost of $8.7/m).
(d)Temporary facility does not attract wildlife.

Table 5
Effectiveness and cost of security systems.

Category (u)	Security control technology	User-specified quantitative effectiveness (%)	Average cost[a]
1— Physical barriers	Fence Type I[b]	50	e
	Fence Type II[c]	75	e
	Fence Type III[d]	100	e
2— Anti-intrusion	Closed circuit TV	75	480
	Motion detectors	100	1080
3— Detection technologies	X-ray scan	60	14,000
	Explosive detectors	100	18,000
4— Security light	Security lighting	100	1500
5— Access control	Magnetic swipe cards	60	150
	Keypad entry	60	200
	Fingerprint scan	80	1500
	Retina scan	100	2000

[a]Data from [23–27].
[b]Fence meeting the FAA minimum requirements, including: no. 10 gauge, galvanized steel, chain link fabric, installed to a height of 2.5 m, and topped with a three-strand (12 gauge) barbed-wire overhang.
[c]Specifications are the same as Fence Type I with the addition of ground penetration prevention.
[d]Specifications are the same as Fence Type II with the addition of vibration detection.
[e]Average costs of fence types are: $8.7/m for Type I, $9.7/m for Type II, and $11.7/m for Type III.

Table 6
Options to construct security fence.

	Option 1	Option 2	Option 3
Fence vertex coordinates	(2265, 2496)	(2290, 2496)	(2315, 2496)
	(2465, 2496)	(2465, 2496)	(2465, 2496)
	(2465, 2606)	(2465, 2606)	(2465, 2606)
	(2265, 2606)	(2290, 2606)	(2315, 2606)

maintained databases and automatically invoked whenever needed. As such, entering data to the system is facilitated and the input data could easily be reused in future site layout planning problems.

8. Summary and conclusion

This paper presented the development of a multi-objective site layout optimization system which facilitates the simultaneous optimization of a number of site layout planning objectives; namely, construction operations safety, construction-related aviation safety, construction-related airport security and overall site layout costs. The system is developed in four main components: (1) a multi-objective optimization engine to evaluate and optimize the impact of site layout planning on the aforementioned planning objectives; (2) a relational database to support the storage and retrieval of construction site layout data and the generated optimal solutions; (3) an Input/Output module to facilitate the input of project data and the analysis of the generated optimal site layout plans; and (4) a visualization interface that communicates with external CAD software systems in order to support the visualization of the generated optimal site layout plans. An application example is analyzed to illustrate the utilization of the model and demonstrate its capabilities in: (1) generating optimal tradeoff solutions among construction safety, construction-related aviation safety, construction-related security level and overall site layout costs; (2) visualizing the tradeoff among these important planning objectives; and (3) providing seamless integration with commercially available CAD software systems in order to enable the construction planner visualize the generated optimal site layout plans. These capabilities should prove useful to construction site layout planners and contribute to advance the optimization of site layout planning in airport expansion projects.

Acknowledgement

The authors gratefully acknowledge the financial support provided for this research project by the National Science Foundation under the NSF Award no. CMS 0626066.

References

[1] I.D. Tommelein, R.E. Levitt, B. Hayes-Roth, SightPlan model for site layout, Journal of Construction Engineering and Management, ASCE 118 (4) (1992) 749–766.
[2] C. Anumba, G. Bishop, Importance of safety considerations in site layout and organization, Canadian Journal of Civil Engineering 24 (2) (1997) 229–236.
[3] K. El-Rayes, A. Khalafallah, Trade-off between safety and cost in planning construction site layouts, Journal of Construction Engineering and Management, ASCE 131 (11) (2005) 1186–1195.
[4] A. Khalafallah, Optimal Construction Site Layout Planning for Airport Expansion Projects, Ph.D. Thesis, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 2006.
[5] K.Y. Tam, Genetic algorithms, function optimisation, and facility layout design, European Journal of Operational Research 63 (1992) 322–346.
[6] H. Li, P.E.D. Love, Site-level facilities layout using genetic algorithms, Journal of Computing in Civil Engineering, ASCE 12 (4) (1998) 227–231.
[7] T. Hegazy, E. Elbeltagi, EvoSite: an evolution-based model for site layout planning, Journal of Computing in Civil Engineering, ASCE 13 (3) (1999) 198–206.
[8] M.J. Mawdesley, S.H. Al-jibouri, H. Yang, Genetic algorithms for construction site layout in project planning, Journal of Construction Engineering and Management, ASCE 128 (5) (2002) 418–426.
[9] G.C. Armour, E.S. Buffa, A heuristic algorithm and computer simulation approach to relative location of facilities, Management Science 9 (1) (1963) 294–309.
[10] N. Dawood, R. Marasini, Optimisation of stockyard layout for the precast building products industry, Proceedings of Association of Researchers in Construction Management (ARCOM'99, Sept 15–17), 2, 1999, pp. 445–454.
[11] S.R.T. Kumara, R.L. Kashyap, C.L. Moodie, Application of expert systems and pattern recognition methodologies to facilities layout planning, International Journal of Production Resources 26 (5) (1988) 905–930.
[12] A. Hamiani, Knowledge representation for the site layout problem, Sixth Conference on Computing in Civil Engineering, New York, 1989, pp. 283–289.
[13] I.D. Tommelein, R.E. Levitt, B. Hayes-Roth, T. Confrey, SightPlan experiments: alternate strategies for site layout design, Journal of Computing in Civil Engineering, ASCE 5 (1) (1991) 42–63.
[14] I.D. Tommelein, P.P. Zouein, Interactive dynamic layout planning, Journal of Construction Engineering and Management, ASCE 119 (2) (1993) 266–287.
[15] I. Yeh, Construction site layout using annealed neural networks, Journal of Computing in Civil Engineering, ASCE 9 (3) (1995) 201–208.
[16] N. Dawood, R. Marasini, Stockyard layout management for precast concrete products using simulation, Proceedings of the CIB-W78 International Conference, IT in Construction in Africa, Mpumalanga, South Africa, 26, 2001, pp. 1–13.
[17] H.M. Tawfik, T. Fernando, A simulation environment for construction site planning, 5th Int. Conf. Information Visualisation, London, UK, 2001.
[18] A. Khalafallah, K. El-Rayes, Minimizing construction-related hazards in airport expansion projects, Journal of Construction Engineering and Management, ASCE 132 (6) (2006) 562–572.
[19] A. Khalafallah, K. El-Rayes, Maximizing security of operating airports during expansion projects, Journal of Construction Engineering and Management, ASCE 134 (1) (2008) 40–48.
[20] K. Deb, S. Agrawal, A. Pratab, T. Meyarivan, A Fast Elitist Non-Dominated Sorting Genetic Algorithm for Multi-Objective Optimization: NSGA-II, KanGAL Report 200001, Indian Institute of Technology, Kanpur, India, 2000.
[21] P. Rob, C. Coronel, Database Systems: Design, Implementation, and Management, Thomson Learning, Boston, MA, USA, 2002.
[22] P. Reed, B.S. Minsker, D.E. Goldberg, Simplifying multiobjective optimization: an automated design methodology for the non-dominated sorted genetic algorithm-II, Water Resources Research, American Geophysical Union 39 (7) (2003).
[23] General Accounting Office (GAO), National Preparedness, Technologies to Secure Federal Buildings, Testimony before the Subcommittee on Technology and Procurement Policy, Committee on Government Reform, House of Representatives. Washington, D.C, 2002.
[24] A.F. Mazzara, D.C. Swanson, N.C. Nicholas, Sensor fence: a new approach to large-perimeter security, Corrections Today 65 (1) (2003) 94–95.
[25] Environmental Protection Agency (EPA), Fences, http://www.epa.gov/safewater/watersecurity/guide/fences.html 2005, June 2, 2005.
[26] Security Camera Surveillance Equipment (SCSE), Complete 4 Camera TV System, http://www.123cctv.com/cctv/cctv-systems-4.html 2006, (April 19, 2006).
[27] Security Pro USA (SPU), Explosives Detector EVD 2500, http://www.securityprousa.com/exdeevd25.html 2006, (April 19, 2006).
[28] A.R. Soltani, T. Fernando, A fuzzy based multi-objective path planning of construction sites, Automation in Construction, vol. 13,(6), Elsevier, 2004, pp. 717–734.
[29] H. Said, K. El-Rayes, Optimizing the planning of construction site security for critical infrastructure systems, Automation in Construction, 19(2), Elsevier, 2009, pp. 221–234.
[30] K. El-Rayes, H. Said, Dynamic site layout planning using approximate dynamic programming, Journal of Computing in Civil Engineering, ASCE 23 (2) (2009) 119–127.
[31] X. Ning, K.-C. Lam, M.C.-K. Lam, Dynamic construction site layout planning using max–min ant system, Automation in Construction 19 (1) (2010) 55–65.
[32] A. Khalafallah, K. El-Rayes, Optimizing airport construction site layouts to minimize wildlife hazards, Journal of Management in Engineering, ASCE 22 (4) (2006) 176–185.