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Multi-objective Construction Site Layout Planning Using Genetic Algorithms

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Abstract

Efficient layout planning of a construction site is fundamental for successful project undertaking as it enhances both productivity and safety in construction sites. This task usually consists of identifying the temporary facilities needed to support construction operations, determining their size and shape, and optimally positioning them in the unoccupied areas within the site boundaries. The site layout planning problem is a complex combinatorial optimization problem involving multiple objectives and it grows significantly in size as the number of facilities and constraints increases. The existing literature includes a variety of analytical, heuristic, and meta-heuristic techniques for solving the problem but existing studies usually examine a small number of facilities and focus on travel distance minimization, ignoring generally cost related or other decision parameters. The objective of this study is to develop feasible and efficient site layout solutions in a realistic representation scheme taking into consideration not only the total distance traveled but also cost and safety parameters as well. A multi-objective optimization model is developed aiming at minimizing a generalized cost function which results from the construction cost of a facility placed at alternative locations, the transportation cost among locations, and any safety concern in the form of preferred proximity or remoteness of particular facilities to other facilities or work areas. The development integrates the required robust search objective with the optimization capabilities of the genetic algorithms (GAs). The model has been tested on several test cases and the results of a comparative study with existing methods from the literature are presented. The evaluation indicates that the proposed model provides effective and rational solutions, in response to decision parameters and problem constraints, and that it results in more robust layout planning than previous methods both qualitatively and quantitatively.

Keywords: construction site, genetic algorithms, layout planning, optimization, safety

1. Introduction

The formulation of the construction site layout planning (CSLP) problem concerns the placement of a set of facilities in certain locations within the site boundaries, while optimizing layout objectives and satisfying layout constraints. An optimal construction site layout is crucial for project management as it reduces the transportation time and thus the cost of a project and also enhances the productivity and safety of working conditions. The CSLP problem can be defined as a number of predetermined facilities n, optimally being assigned to a number of predetermined unoccupied locations m, where $m \geq n$. The CSLP problem can generally be modeled either as *facility to location assignment* or *facility to site assignment*. The first assigns a set of predefined facilities to a set of predefined locations on site. The method of *facility to site assignment*, on the other hand, assigns a set of predefined facilities to any unoccupied space available on site and results in a more complicated formulation since several spatial constraints must be simultaneously satisfied. Both problem forms can be modeled as *equal-area CSLP* or *unequal-area CSLP* ones depending on whether all facilities can fit to every possible location or not. The CSLP problem can also be distinguished as a *static* or a *dynamic* one depending on whether non-changing or changing site facilities and site spaces are considered in different project phases.

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A variety of methods have been adopted to perform the optimization process, ranging from mathematical models to knowledge-based systems. Algorithms applied to CSLP can be broadly classified into artificial intelligence (AI), evolutionary algorithm (EA) and swarm intelligence (SI) methods. The decision to choose one of these algorithms depends on the solution quality, computational time, interaction of parameters, complexity, and behavior of the algorithm, especially in the analysis of larger problems [1].

Within artificial intelligence techniques, Yeh [2] proposed the use of annealed neural networks, merging the features of simulated annealing (SA) and the Hopfield neural networks (NN). Tam et al. [3] proposed a nonstructural fuzzy decision support system which integrates expert judgment into computer decision modeling.

Evolutionary algorithms are mainly represented by genetic algorithms (GA). Li and Love [4] used GA to solve the site-level facility layout problem while satisfying layout constraints and requirements. The same authors extended the previous model to the unequal–area layout problem ([5]). Mawdesley and Al-Jibouri [6] presented a sequence-based genetic formulation of the CSLP problem and evaluated its performance by comparing results to that of Yeh ([2]). El-Rayes and Khalafallah [7] presented the development of an extended site layout planning model that incorporates a trade-off between safety and cost on site using GAs. Lam et al. [8] introduced a joined max-min ant system (MMAS) and GA model in which the former is used to develop the initial population for the GA application. Cheung et al. [9] described the use of the GA software Evolver to handle a site pre-cast yard layout problem. Liang and Chao [10] proposed a multi-searching tabu search procedure based on efficient diversification and intensification strategies to effectively improve the various arrangements in the facility layout problem. To arrange the pre-cast facilities in the construction site, Wong et al. [11] developed a GA and a mixed integer programming (MIP) model to generate optimal layout solutions. Finally, Gholizadeh et al. [12] implemented a harmony search algorithm as an alternative tool for the solution of the CSLP problem.

The swarm intelligence algorithms mainly include ant colony optimization (ACO) and particle swarm optimization (PSO) algorithms. Lam et al. [13] employed an ACO algorithm to solve the CSLP problem where the proximity of the facilities was calculated through the application of fuzzy reasoning and the entropy technique. Ning et al. [14] used continuous dynamic searching to guide the MMAS algorithm developed in [8] to solve the dynamic CSLP problem under the objectives of minimizing safety concerns and reducing construction cost. Gharaie et al. [15] presented an ACO algorithm to compare the results with the ones in [4] (further discussion in section 3 of the current paper). Calis and Yuksel [16] proposed an ACO algorithm with local analysis (ACO-LA) to improve the quality of the solution. They have also presented an improved ACO algorithm with parametric analysis (ACO-PA) with the potential to assess appropriate parameter values within the predefined parameter range [1]. Zhang and Wang [17] presented a PSO-based methodology to solve the construction site unequal-area problem, formulated as a quadratic assignment problem (QAP). Finally, Lien and Cheng [18] proposed a hybrid swarm algorithm (namely particle-bee algorithm - PBA) that aims to integrate the respective advantages of honey bee and bird swarms.

The literature review indicates that the majority of existing studies focus mostly on the solution method itself rather than on developing a realistic representation of the problem. As a result, they typically analyze the CSLP problem in a rather elementary manner ignoring important parameters (such as layout costs, either transportation or construction ones) or making simplifying assumptions that result in a rather theoretical solution. The present work aims to improve the realistic representation of the problem incorporating cost and safety parameters in the model and to explore the potential impact of these parameters in site layout planning. A secondary objective is to examine whether new developments in optimization models (represented by recent advancements of commercial evolutionary algorithm software) can be more effective in attaining higher accuracy solutions in such problems compared to older methodologies and tools.

2. Proposed model

The problem presented in this study can be modeled as a quadratic assignment problem (QAP) in which equal numbers of facilities and locations exist. If the number of locations exceeds that of facilities, dummy (fictitious) facilities can be added to the model (with zero distances or frequencies to existing real facilities so that they do not affect the layout planning). The optimization model incorporates the following decision parameters which contribute to the total cost to be minimized:

- Frequencies of trips made between pairs of facilities (per day).
- Distances between the predetermined locations (in meters).
- Transportation cost between locations (in cost unit/meter).
- Construction cost facilities at alternative locations (in cost units).

The cost concept is introduced to the optimization process in order to reflect the geography or other particularity of the construction site area. Two types of costs are considered:

- The construction cost represents the required expenditure for placing a facility at a certain location. Small variations (e.g., ±10%) of the normal construction cost may be expected depending on the surface of the chosen location which may require extra work (surface preparation, excavations, and embankments).
- The transportation cost represents the cost of resource movement along facilities and locations. The transportation cost between two facilities can be generally considered constant (as it characterizes the movement of specific resources), however, it can vary depending on the location and path characteristics between the facilities (e.g., inclined terrain, construction site development along a river bank or other traffic-restraining conditions).

Besides pure economic parameters, the decision for facility placement in practice may depend on other criteria as well. One of them is safety which imposes certain facilities to be close to each other and others to be as far away from others as possible (e.g., storeroom of hazardous materials). The safety enhancement goal is facilitated by means of preference in proximity or remoteness between two facilities. For example, the project manager may decide to place the site office or the labor residence facility close to a side gate in order to avoid large interference of the personnel with the main gate, which primarily serves machinery entrance and exit, and also to provide prompt evacuation in case of emergency. Such preferences can be modeled by increasing artificially the frequency or the cost of movements between the chosen facilities.

The fitness of a solution chromosome is assessed by the total cost associated with the above components. The optimization objective is then to minimize the total cost as indicated by the following relationships:

$$MinTC = \sum_{i=1}^{n}\sum_{x=1}^{n}\sum_{j=1}^{n}\delta_{xi} f_{xi} u_{ij} d_{ij} + \sum_{x=1}^{n}\sum_{i=1}^{n}\delta_{xi} c_{xi} \tag{1}$$

subject to

$$\sum_{x=1}^{n}\delta_{xi} = 1, \mathrm{i} = 1, 2, 3, ..., \mathrm{n} \tag{2}$$

where TC is the total cost; n is the number of facilities and locations, δ_{xi} is the permutation matrix variable (δ_{xi}=1 if facility x is assigned to location i, δ_{xi}=0 otherwise); f_{ij} is the trip frequency between facilities i and j; d_{ij} is the distance between locations i and j; u_{ij} is the transportation cost between locations i and j; c_{xi} is the construction cost if facility x is placed in location i.

Construction site facilities usually have varying shape and space requirements. Consequently, some locations may not be appropriate to accommodate certain facilities because of their size or other physical constraints (this is known as the unequal-area CSLP problem). The proposed model incorporates this aspect by considering very high construction cost in case that a facility cannot fit to a location. Furthermore, the location of certain facilities, such as the gates to the site, is often crucial for the operability of the construction mechanism in term of access and transport. These facilities are typically set to predefined locations and are not subject to change but still affect the overall layout planning through their interaction with the rest of the facilities. In other cases, certain facilities may be allocated within a subset of the available locations but not everywhere. The model can meet these expectations and provide the best allocation either by introducing constraints which prohibit the placement of certain facilities to unwanted locations or by adjusting artificially the cost of placement in line with the degree of preference or avoidance of certain locations.

The CSLP problem falls within the NP-problems meaning that as the problem size (number of facilities, locations, and constraints) increases, the set of possible solutions grows exponentially. For this reason, a genetic algorithm has been employed for the optimization process. Genetic algorithms represent one of the most popular meta-heuristics that efficiently address hard NP problems because of their ability to escape from local optima during the optimization search. The proposed GA model was implemented through Palisade Evolver software which runs as an add-in of the Microsoft Excel software.

3. Case studies

The goals of this analysis are (a) to compare the proposed formulation and the solving method with existing ones from the literature and (b) to illustrate how the enhanced model with additional parameters and decision modules perform in comparison to simpler ones. Three benchmark case studies were selected from the literature to serve as the model evaluation basis [4, 5, 15]. These studies analyze the CSLP problem employing varying meta-heuristics to obtain the optimal solution. However, all these studies confine their analysis to consider only input regarding frequencies of movement and distances with the fitness function to express the total distance traveled between location pairs. For the comparative analysis of models, therefore, the transportation and construction costs of the proposed model are initially set equal to one and zero respectively. Following, each new parameter is successively added to the model and the results are compared.

The case study project refers to the construction of two buildings. The construction site consists of 11 facilities which are to be assigned to 11 available locations within the construction area (Figure 1). The frequencies of daily trips between facilities are listed in Table 1 while the distances between the available locations are shown in Table 2. The facilities of this case study are:

1. Site office
2. Falsework workshop
3. Labor residence
4. Storeroom 1
5. Storeroom 2
6. Carpentry workshop
7. Reinforcement steel workshop
8. Side gate
9. Electrical, water and other utility control room
10. Concrete batch workshop
11. Main gate

Table 1. Case study trip frequencies between facilities

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	0	5	2	2	1	1	4	1	2	9	1
2	5	0	2	5	1	2	7	8	2	3	8
3	2	2	0	7	4	4	9	4	5	6	5
4	2	5	7	0	8	7	8	1	8	5	1
5	1	1	4	8	0	3	4	1	3	3	6
6	1	2	4	7	3	0	5	8	4	7	5
7	4	7	9	8	4	5	0	7	6	3	2
8	1	8	4	1	1	8	7	0	9	4	8
9	2	2	5	8	3	4	6	9	0	5	3
10	9	3	6	5	3	7	3	4	5	0	5
11	1	8	5	1	6	5	2	8	3	5	0

Table 2. Case study distances between site locations

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	0	15	25	33	40	42	47	55	35	30	20
2	15	0	10	18	25	27	32	42	50	45	35
3	25	10	0	8	15	17	22	32	52	55	45
4	33	18	8	0	7	9	14	24	44	49	53
5	40	25	15	7	0	2	7	17	37	42	52
6	42	27	17	9	2	0	5	15	35	40	50
7	47	32	22	14	7	5	0	10	30	35	40
8	55	42	32	24	17	15	10	0	20	25	35
9	35	50	52	44	37	35	30	20	0	5	15
10	30	45	55	49	42	40	35	25	5	0	10
11	20	35	45	53	52	50	40	35	15	10	0

In accordance to existing case studies from the literature, three test cases are examined with regard to facility placement constraints:

- *Case 1 (C1)*: All locations can accommodate every facility.
- *Case 2 (C2)*: The main gate and the side gate are assigned to locations 10 and 1 respectively.
- *Case 3 (C3)*: In addition to C2, three facilities (# 1, 3, and 10) are too large to fit to locations 7 and 8.

In terms of the proposed method, four versions are developed which differentiate in terms of the parameters that are incorporated in the decision making process:

- *New-1*: The simplest algorithm form with decision parameters the trip frequencies and distances.
- *New-2*: It additionally incorporates the transportation costs.
- *New-3*: It additionally incorporates the facility construction costs.
- *New-4*: It additionally incorporates a safety preference parameter (site office close to the side gate).

The comparison between the proposed model and representative results from the literature for the benchmark case study indicates that the continuing experimentation with evolutionary algorithms over the years is justified by the improvement potential in the optimization results of such problems. In particular, Table 3 summarizes the optimization results of six different solution methods in one or more of the three case scenarios. It can be observed that as solution methods become more rigorous, there appears notable improvement of the results. Further, the proposed model outperforms almost all previous formulations. In comparison to the best known solution from the literature ([1]), the present solution is identical in the C1 and C3 cases and slightly better (both in layout arrangement and in optimization value) in case C2.

Table 3. Result comparison among existing studies and the proposed GA model.

Test case	*GA (1998)*[4]	*GA (2000)* [5]	*ACO (2006)*[15]	*ACO (2010)* [16]	*ACO (2015)* [1]	*New-1 GA* (2016)
C1	-	-	-	-	12,150	12,150
C2	15,090	-	12,546	-	12,578	12,546
C3	-	15,160	-	12,628	12,606	12,606

In terms of facility arrangement as a result of the decision parameters involved, considerable changes are observed among different formulations. Figure 1 illustrates the facility placement resulting from two existing methods and the four new formulations for the C2 case. Aside from the main gate (#11) and side gate (#8), which have been placed in accordance with the constraints by all methods, the arrangement of the other facilities differs considerably, especially among the four versions of the proposed method, indicating that the transportation and construction costs as well as the inclusion of safety concerns influence the optimal layout decisively. The proposed model also presents acceptable flexibility to existing problem constraints and manager preferences. Figure 2 indicates notable differences in facility arrangement following the constraints associated with the three test cases C1, C2, and C3. In all cases, the model provides solutions that satisfy existing constraints, prioritize given preferences and ensure economic efficiency.

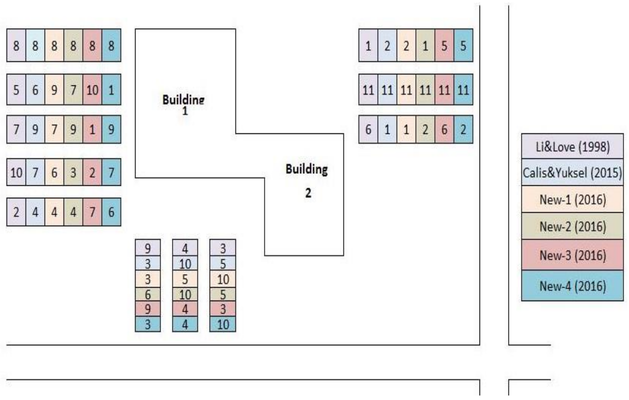

Figure 1. Facility assignment results for test case C2

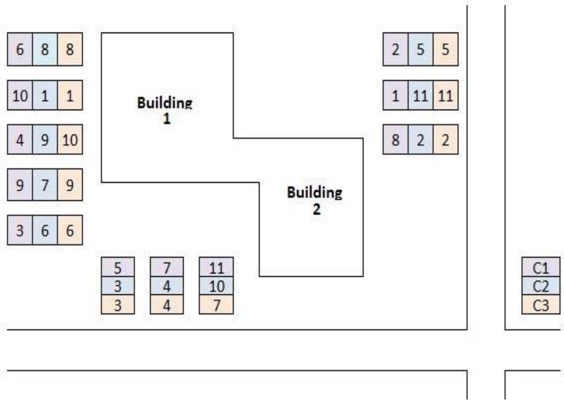

Figure 2. Constraint-driven facility assignment results (New-4)

4. Conclusions

The construction site layout planning (CSLP) optimization problem intends to produce optimal layouts regarding the positioning of temporary project facilities within the construction site boundaries. The problem can realistically be modeled in a multi-objective optimization formulation aiming at minimizing the total traveled distance among facilities and the corresponding transportation cost, the facility construction cost depending on location characteristics, and existing safety concerns resulting from the proximity or remoteness of certain facilities to others. The CSLP problem is among the most challenging ones in project planning process especially as the number of facilities and constraints increases.

In this study, an optimization model is proposed for the unequal-area CSLP problem incorporating transportation and construction costs combined with safety concerns. Several alternative model forms have been analyzed with different mix of decision parameters and constraints in order to investigate the influence of each parameter and constraint. A genetic algorithm has been employed for the optimization as a result of its capability to effectively search within a large set of possible solutions. The proposed model was tested on several test cases and results were compared with previous studies from the literature. The evaluation indicates that the proposed model provides effective and rational layout planning solutions, in response to input parameters and problem constraints, more robust representation of the actual problem structure, and even better performance (in terms of the optimization parameter value) than most existing methods, when compared on the basis of the same decision parameters and model structure.

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