Using Simulated Annealing For Layout Planning of Construction Sites

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Construction site layout is an important activity that deals with the positioning of temporary facilities that are utilized during the execution phase of a construction project. This paper presents a formulation for the construction site layout problem in terms of a combinatorial problem that is suitable for solution using simulated annealing algorithms (SA). SA is an evolutionary method motivated by an analogy to annealing in solids to avoid the solution from getting trapped in a local minimum. A case study is presented to demonstrate the efficiency of the Simulated Annealing heuristic algorithm in solving the construction site layout problem and illustrates its essential features.

Key Words: Construction Management, Construction Sites, Layout planning, Simulated Annealing

Introduction

Planning for construction site layout depends on a number of factors such as the adjacency of permanent facilities, distance between facilities, facility resources and the location of the facilities (Hans 1984). Over the past 20 years, researchers have developed many constructive heuristics for the construction site layout problem. Recently, evolutionary optimization techniques such as genetic algorithms have been used extensively (Tong and Tam, 2003; Osman et al, 2003; Cheung et al., 2002). The common approach shared by all evolutionary techniques is the avoidance of gradient-based search, thus reducing the possibility of getting stuck in local optima. Li et al. (1998) used an improved crossover and mutation to minimize the total traveling distance of site personnel. Cheung et al. (2002) used the swap method for crossover and mutation in their genetic algorithm model to search for the least cost during pre-cast concrete layout planning.

Layout planning indicates the location and numbers of temporary and permanent facilities, travel distances, facility resources, material and personnel site access, and pathways for material delivery, and safe egress from the construction site. This problem can be represented mathematically as “n” facilities located at “n” locations. These “n” facilities will be located based upon an objective function. Many forms of objective function(s) have been developed for the construction site layout planning problem. The pseudo models of these objective function(s) are given in Table (1).

Each placement of a facility compared to another will increase or decrease the objective function value. The total cost can be defined as follows:

$$\text{Total Cost= minimize}\left(\sum_{k=1}^{n}\sum_{i=1}^{n}\ \sum_{j=1}^{n} TCL_{QKi,j}\right) \tag{1}$$

Subject to

$$TCL_{QK_{i,j}} = L_{LQ_{i,j}} \times C_{QK} \qquad M_{QK_{i,j}} = FL_{QK_{i,j}} \times D_{ij}$$

$$FL_{QK_{i,j}} = \begin{bmatrix} FL_{QK_{1,1}} & FL_{QK_{1,2}} & . & . & FL_{QK_{1,q}} \\ FL_{QK_{2,1}} & FL_{QK_{2,2}} & & & FL_{QK_{2,q}} \\ . & & & & \\ . & & & & \\ FL_{QK_{q,1}} & FL_{QK_{q,2}} & . & . & FL_{QK_{q,q}} \end{bmatrix}$$

Where

n	the number of facilities;
C_{QK}	the cost per unit distance between facilities i and j
$D_{i,j}$	the distance between the facilities i and j
$TCL_{QK_{i,j}}$	the total cost of resource flow between facilities i and j
$Q_{LQK_{i,j}}$	the traveled distance per unit time between facilities i and j
$FL_{QK_{i,j}}$	the frequency of resource flow between facilities i and j

Table1: Objective Functions used in the literature

No.	Pseudo model of the objective function	Reference
1	To minimize the cost of facility construction and the interactive cost between facilities	Yeh, 1995
2	To minimize the frequency of trips made by construction personnel	Li and Love, 1998
3	To minimize the total transportation costs of resources between facilities	Hegazy and Elbeltagi, 1999
4	To minimize the total transportation costs of resources between facilities and the total relocation costs.	Zouein and Tommelien, 1999
5	To minimize the total transportation costs of resources between facilities	Tam et al., 2001& Cheung et al., 2002

It is assumed that the number of predetermined places should be equal to or greater than the number of predetermined facilities. If the number of predetermined places is greater than the number of predetermined facilities, then a number of dummy facilities will be added to make both numbers equal.

In this paper, simulated annealing (SA), which is an optimization technique based on the annealing process of physical systems in thermodynamic, is proposed to better address the construction site layout problem. SA has the advantages of simple structure, efficient operation and less sensitivity to initial condition (Liang and Xu 2009). The paper refers to the issues related to the development and adaptation of an SA algorithm for solving the construction site layout problem. The success of the proposed solution algorithm in solving the construction site layout problem is demonstrated using a case study.

Simulated Annealing Technique

Simulated Annealing (SA), also known as Monte Carlo Annealing, borrows from the gradual cooling process of metal annealing after having been heated to the melting point. At high temperature, the atoms are embodied with great amounts of energy, and move arbitrarily in any state space. As the temperature drops, the energy of the atoms decreases and gets close to the minimum point of the energy in the whole state space. When the cooling process is completed, the whole state space energy is at its lowest point. The simulated annealing acts like a random search at the beginning and gradually turns into a more traditional local search algorithm at the end, which will not accept a worse solution than the current one. The basic algorithm of simulated annealing was described by Russell (1995) as shown in Figure 1.

Function SIMULATED-ANNEALING (problem, Schedule) returns a solution state
Inputs : problem, a problem schedule, a mapping from time to temperature
Local variables: Current, a node Next, a node T, a "temperature" controlling the probability of downward steps

Current = MAKE-NODE (INITIAL-STATE [Problem])
For t=1 to ∞ do
T= Schedule [t]
If T=0 the return Current
Next = randomly selected successor of Current
ΛE = VALUE [Next] – Value [Current]
If ΛE > 0 then Current = Next

Figure 1: Simulated annealing algorithm (Russell, 1995)

The algorithm customarily starts with the random creation of initial construction layouts to be used as the starting point and current solution for the optimization process. Then, the choice of an appropriate cooling schedule is selected; Cooling schedule formulations used in this study were originally set forth by Balling (1991) and are given in the following equations. These equations formulate the cooling schedule parameters based on assumed acceptance probabilities and thus allow them to be chosen automatically irrespective of problem type. Otherwise, an arbitrary choice of these parameters exhibits problem dependency and entails an extensive numerical experimentation.

Starting Temperature, $t^s = -\dfrac{1000}{\ln(P^s)}$ (2)

Where, P^s is the starting acceptance probability.

Final Temperature, $t^f = -\dfrac{1}{\ln(P^f)}$ (3)

Where, P^f is the assumed final acceptance probability.

Cooling Factor, $\rho = \left[\dfrac{\ln(P^s)}{\ln(P^f)}\right]^{1/(N_c-1)}$ (4)

Where, N_c is the number of cooling cycles?

In the following step, an inner loop is performed, where each time the current layout is given a small perturbation to create a candidate layout as an alternative solution to the problem considered. The underlying principle related to the inner loop is associated with a thermodynamics concept, which states that a physical system attains its lowest energy provided that it acquires the least possible energy required at each temperature during the successive cooling process.

In the final step, the temperature is reduced to a slightly lower value and the inner loop is activated again with the new temperature. The process is repeated until the whole cooling cycle is iterated. Finally, the algorithm is terminated if: a) the cooling temperature is less than the final temperature; b) the number of the quenching times reaches the preset number; or c) the target function is not changed after continuous and repetitive executions for a preset number of cooling times (Wong and Fung, 1993.)

Case Study

The Hypothetical Site

A hypothetical construction site was created for the application of Simulated Annealing in order to find the optimal site layout, under a set of given conditions. Again, the intent is to create a planning conversation amongst the project team that is informed by a systematic process in lieu of ad-hoc and informal methods. A mid-size University Building was assumed. The hypothetical project is a traditional 4-story reinforced concrete school block; construction work includes site work and utilities, substructure, superstructure, enclosures, and interior finishes. The contract period is 14 months. To facilitate the example, the site was simplified as shown in a Figure 2.

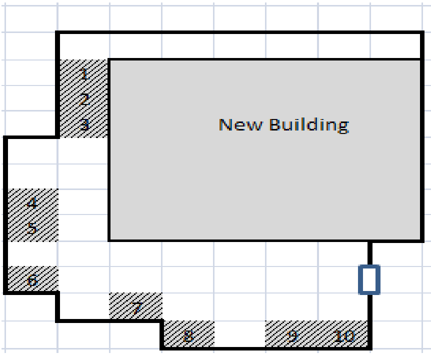


Figure 2: Layout of the Hypothetical site

Site Facilities and site representation

The number and the type of facilities depend on the size and the nature of the construction project. Some site facilities are essential, such as trailer city, portable toilets (e.g., Porta-Johns™), a laydown and storage area for materials, a refuse storage area, etc. In order to simplify the complexity of the construction site, some facilities have been neglected and the number of facilities is assumed as in Table 2.

Within the site boundary, the area for locating site facilities is limited by many constraints, such as maintaining access. Apart from that, 10 available locations were predetermined in the construction site for allocating the remaining six facilities as listed above. Four dummy facilities were added. It was assumed that each facility could be placed into any location and that the area of the location was large enough for each facility.

Table 2: Assumed Facilities on the case study construction site

Site Facilities			
1	Site Office	4	Carpentry shop
2	Debris Storage Area	5	Portable Johns
3	Bending/ Storage Yard	6	Storage Area

As presented before, the optimization objective is presented as

$$MinZ = \sum_{i,j=1}^{n} f * d_{ij}$$

Where f was assumed to be the frequencies of trips (in 1 day) made between facilities (see Table 3), and Dij is the travel distance between facility i and facility j (see Table 4). However, the travel distance between locations was measured using rectangular distances that represent actual operations and resource movements on the site in order to simplify the scenario.

Table 3: Travel Frequencies between Facilities

Facility	1	2	3	4	5	6	D 1	D 2	D 3	D 4
1	0	29	87	90	102	108	0	0	0	0
2	29	0	40	46	44	22	0	0	0	0
3	87	40	0	61	54	68	0	0	0	0
4	90	46	61	0	76	80	0	0	0	0
5	102	44	54	76	0	94	0	0	0	0
6	108	22	68	80	94	0	0	0	0	0

D 1	0	0	0	0	0	0	0	0	0	0
D 2	0	0	0	0	0	0	0	0	0	0
D 3	0	0	0	0	0	0	0	0	0	0
D 4	0	0	0	0	0	0	0	0	0	0

Table 4: Travel Distance between Locations

Distance to	1	2	3	4	5	6	7	8	9	10
1	-	1	2	6	7	9	12	14	16	17
2	1	-	1	5	6	8	11	13	15	16
3	2	1	-	4	5	7	10	12	14	15
4	6	5	4	-	1	3	7	9	11	12
5	7	6	5	1	-	2	6	8	10	11
6	9	8	7	3	2	-	3	5	7	8
7	12	11	10	7	6	3	-	2	4	5
8	14	13	12	9	8	5	2	-	2	3
9	16	15	14	11	10	7	4	2	-	1
10	17	16	15	12	11	8	5	3	1	-

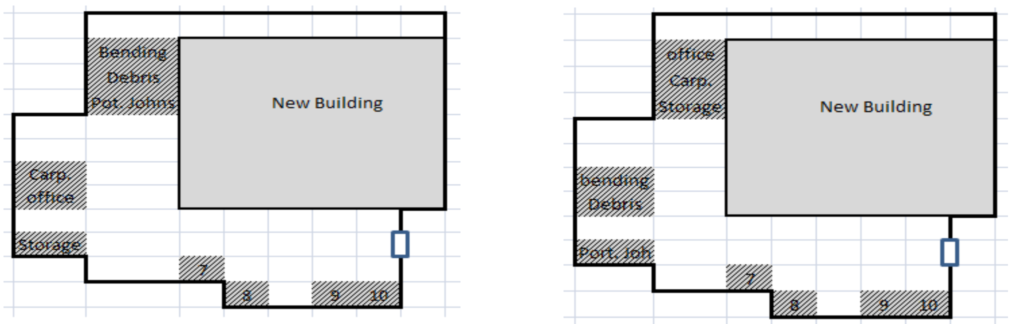
A package was written specifically to solve the problem under consideration using SA algorithm. It was written in Matlab; a commercially available developer of technical computing software. In this experiment, different heuristic parameters were investigated. Table 5 presents a partial optimum layout representation (solution) sorted by the objective function.

Table 5: Optimum layout representation

	Facility	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Objective Function**
Run #11	**Location**	5	2	1	4	3	6	10	9	7	8	4377
Run #5	**Location**	1	5	4	2	6	3	9	10	8	7	4548
Run #13	**Location**	1	3	2	6	5	4	9	10	7	8	4625
Run #9	**Location**	1	7	4	2	3	5	10	9	8	6	4893
Run #16	**Location**	1	9	5	4	3	2	10	8	6	7	5314

Discussion

In 20 trials, the optimal solutions were the layouts 5, and 11 respectively. The final optimal layouts for the hypothetical site are shown in Figures 3a and 4b. These two optimal results were then presented to three construction mangers (with a minimum 15 years of experience) for validation.



a) Run # 5 b) Run # 11

Figure 3: optimum layout representation

For both layouts, it was suggested that the site office be relocated near the main gate. For run #5, the distance between debris storage area- and Steel Bending and storage area was close enough to block the access to the Steel Bending and storage area. Run #11 was more acceptable to the construction managers, except for the location of the site office. The construction managers appreciated having this site layout planning tool but suggested including the fixed utilities such as the gate location, the material hoist and crane into consideration for future work.

Algorithm Verification

To confirm the proposed algorithm performance, Literature data for two case studies (Cheung et al 2002; Li and Love 1998), similar to the illustrated case study, were used to benchmark the algorithm results with the results provided. Cheung et al (2002) developed a Genetic Algorithm (GA) model for site pre-cast yard layout arrangement; in particular arranging the pre-cast facilities within the compound. The objective function is to minimize the total cost per day for transporting all resources necessary to achieve the anticipated production output for the pre-cast yard. The GA model yielded a near-optimum layout as presented in Table 6 while the proposed model proposed an improved layout. The Modified Objective Function for the GA model was $ 147,906. The objective function of the proposed model was $105, 362 which represents 28.76% improvement in the daily cost.

Table 6: The optimal layout solution

Facility	1	2	3	4	5	6	7	8	9	10	11
Cheung et al (2002) Location	1	11	8	10	6	4	9	5	3	2	7
Proposed Model Location	1	4	7	8	6	3	10	11	9	5	2

Li and Love (1998) presented the construction site-level facility layout problem as allocating a set of predetermined facilities into a set of predetermined places, while satisfying layout constraints and requirements. Genetic Algorithm (GA) was employed to solve this problem by minimizing the total traveling distance of site personnel between facilities. The GA model yielded a near-optimum layout as presented in Table 7 while the proposed model proposed a slightly improved layout. The Modified Objective Function was $ 12,819. The objective function of the proposed model was $12,427 which represents 3.53% improvement in the daily cost.

Table 7: The optimal layout solution

Facility	1	2	3	4	5	6	7	8	9	10	11
Li and Love (1998) Location	11	5	8	7	2	9	3	1	6	4	10
Proposed Model Location	8	5	6	9	7	11	3	1	4	2	10

The comparison to the models in Li and Love (1998) and Cheung et al (2002) underscore the advantages of using simulated annealing models to site layout planning, especially from a computational efficiency standpoint. The presented algorithm can be adapted to solve various practical problems involving spatiotemporal planning issues.

Conclusions

This research investigated a scheme for representing the construction site layout planning problem to suit the simulated annealing operations. The problem formulation provided in this paper can be extended to include many other costs and factors without significant increase in computation requirements.

The strength of the SA system lies in the ability to accept uphill moves with a limited probability and the non-dependence of the final solution on the initial solution. Therefore, the SA system is less likely to restrict the search to a local optimum. The paper demonstrated the robustness of the SA approach in solving layout problems as combinatorial optimization problems.

Planning for proper arrangement of a construction site layout is of paramount importance even though the final realized arrangement on site may differ. As president Eisenhower is known to have said “Planning is everything, the plan is nothing.” The planning process may uncover constraints which were unknown to the team, as well as be in a better position to handle those that they are aware of. The project will have a better chance of being executed effectively and efficiently. The SA algorithm presented will aid in the planning process, but as another planning tool should be considered as necessary but not sufficient.

References

Back T. (1996) “Evolutionary Algorithms in Theory and Practice”. New York, Oxford University Press.

Balling, R. (1991) “Optimal Steel Frame Design by Simulated Annealing”, Journal of Structural Engineering, 117 (6), pp. 1780-95.

Bennage W., Dhingra A. (1995) “Single and Multi-objective Structural Optimization in Discrete-Continuous Variables Using Simulated Annealing” International Journal of Numer Meth Engineering; (38), pp. 2553-73.

Cheung S., Tong T., and Tam C. (2002) “Site Pre-cast Yard Layout Arrangement through Genetic Algorithms”; Automation in Construction, 11 (1), pp. 35-46.

Hans, P. (1984).”Construction Management and P.W.D. Accounts”, 6th Ed., Hans Publications, Ludhiana, India.

Hegazy T., and Elbeltagi E.(1999) “EvoSite: Evolution-based Model for Site Layout Planning”, Journal of Computing in Civil Engineering, 13(3), pp. 198-206.

Li, H. & Love, P. (1998) “Site-level Facilities Layout Using Genetic Algorithms”, Journal of Computing in Civil Engineering, ASCE, 12 (4) pp. 227-31.

Liang Y. and Xu L. (2009). “Global path planning for mobile robot based genetic algorithm and modified simulated annealing algorithm”. GEC '09: Proceedings of the first ACM/SIGEVO Summit on Genetic and Evolutionary Computation.

Metropolis N., Rosenbulth A., Rosenbulth A., Teller A, Teller, H. (1953)“Equation of State Calculations by Fast Computing Machines”, J of Chem. Phys, 21 (6), pp. 1087-91.

Michalewicz Z. (1996) “Genetic Algorithm Data Sources= Evolution Programs”, New York, Springer.

Osman H., Georgy M., and Ibrahim M. (2003) “A Hybrid CAD-based Construction Site Layout Planning System Using Genetic Algorithms”, Automation in Construction, 12 (6), pp. 749-764.

Schwefel H. (1995) “Evolution and Optimum Seeking” , New York: Wiley.

Tam C., Tong T., and Chan W. (2001) “Genetic Algorithm for Optimizing Supply Locations Around Tower Crane”, Journal of Construction Engineering and Management, 127 (4), pp. 315-320.

Tong T.; Tam C., (2003) “GA-ANN Model for Optimizing the Locations of Tower Crane and Supply Points for High-rise Public Housing Construction”. Journal of Construction Management and Economics, 21(3), pp.257-266.

Yeh, I. (1995) “Construction Site Layout Using Annealed Neutral Network”, Journal of Computing in Civil engineering, (ASCE), 9 (3), pp. 201-8.

Zouein P., and Tommelein I. (1999). “Dynamic layout planning using a hybrid incremental solution method”, Journal of Construction Engineering and Management, 125(6), pp. 400–408.