Application of Electimize in Solving the Construction Site Layout Planning Optimization Problem

Conference Paper · May 2012

DOI: 10.1061/9780784412329.113

2 authors:

Mohamed Abdel-Raheem
University of Texas Rio Grande Valley

Ahmed Khalafallah
Kuwait University

Application of Electimize in Solving the Construction Site Layout Planning Optimization Problem

Mohamed Abdel-Raheem[1] and Ahmed Khalafallah[2]

[1]Assistant Professor, Department of Engineering Technology, Missouri Western State University, St. Joseph, MO 64507; email: maraheem@knights.ucf.edu
[2]Assistant Professor; Department of Architectural and Manufacturing Sciences, Western Kentucky University, Bowling Green, KY 42101-1066; email: ahmed.khalafallah@wku.edu

ABSTRACT

In any construction project, site layout planning (SLP) is a critical step that maximizes the efficiency in executing different project activities. The allocation of different facilities on site is often a complicated problem that requires extensive effort in computer modeling and long processing time to find the optimum solution. The main objective of a SLP problem is minimizing the travel distance between facilities and material handling, which in turn minimizes the overall time and cost of executing the project. The SLP is a cumbersome problem as it is classified as an NP-hard problem that belongs to the class of dynamic optimization.

This paper presents the testing and the application of a newly developed evolutionary algorithm – named Electimize- in solving NP-hard dynamic optimization problems in construction engineering. Electimize simulates the phenomenon of the electric current conduction through the flow of electrons in the branches of the electric circuit. The basic advantage of Electimize over other evolutionary algorithms (EAs) lies in its ability to evaluate the quality of each value in the solution string independently. This paper primarily focuses on: 1) The basic steps of optimization using Electimize; 2) SLP problem modeling using Electimize; and 3) Testing the capability of the Electimize in solving NP-hard dynamic optimization problem in construction engineering. Electimize was applied to a benchmark SLP problem from the literature. The problem was attempted in the past using mathematical techniques, and evolutionary algorithms. The results showed that Electimize outperformed other algorithms by identifying a new optimal site layout of the facilities of the problem.

INTRODUCTION

Construction optimization problems are very sophisticated and hard to solve due to the enormous number of variables involved in a single problem. The majority of these problems belong to the non-deterministic polynomial-time hard (NP-hard) class of optimization. This rendered the majority of mathematical optimization techniques inadequate for solving construction optimization problems (Abdel-Raheem 2011).

Alternatively, evolutionary algorithms (EAs) have been used extensively to make up for the limitation of mathematical techniques, which are characterized by their complexity of modeling, long time consumption, and inability to reach the optimum solution most of time. Examples of these EAs are Genetic Algorithms (GAs), Memetic Algorithms (MA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO) and many others. Several application of EAs in solving different engineering optimization problems were discussed in [Feng et al. 1997; Leu and Yang 1999; Haidar et al.1999; Hegazy and Ersahin 2001; Hegazy and Wassed 2001; Lu 2002; Maier et al. 2003; Solimanpur et al. 2004; Christodoulou 2005; Elazouni and Metwally 2005; Elbeltagi et al. 2005; El-Rayes and Kandil 2005; Khalafallah and El-Rayes 2006; Abdel-Raheem 2007]. EAs were favored due to their ability of finding a high quality solution in a relatively short time. However, the major limitation of EAs is that they do not guarantee reaching optimality. In most cases, the solution achieved is believed to be a near optimal solution.

Electimize is a new evolutionary algorithm that was introduced to overcome the limitations mentioned above. Electimize simulates the phenomenon of the flow of electrons in multi-branch electric circuits, where the maximum current intensity is produced in the wire with the least resistance. The primary advantages of Electmize over other EAs are: 1) the ability of the algorithm to assess the quality of the each value in the solution string individually and independently; and 2) the utilization of actual mathematical scientifically proven equations for the quality assessment of values, which are Ohm's rule and Kirchhoff's Law (Abdel-Raheem and Khalafallah 2011).

The main objective of developing Electimize was to provide the construction industry with a reliable optimization tool that is capable of solving a variety of problem domain in construction engineering. Previous studies showed the successful application of Electimize in solving a number of NP-hard combinatorial construction optimization problem mainly: the cash flow problem (Khalafallah and Abdel-Raheem 2010); and the time-cost tradeoff problem (Abdel-Raheem and Khalafallah 2011).

This paper presents further application of Electimize in solving another NP-hard problem, which is the site layout planning problem (SLPP). The SLPP belongs to the class of dynamic optimization.

SITE LAYOUT PLANNING PROBLEM (SLPP): BACKGROUND

Site layout planning is an important step in any construction project. Good site layout planning minimizes the travel distance between facilities, materials handling, and maximizes the efficiency in executing different construction activities (Hegazy and Elbeltagi 1999). There are two types of facilities allocated in any construction site: a) Fixed facilities, which are the actual construction, and b) Temporary facilities, which are secondary facilities that are needed for a limited amount of time for construction purposes. The SLPP can be categorized as dynamic versus static and tightly versus loosely packed, and the classification of the problem can be any combination of them (Hegazy and Elbeltagi 1999).

There are various objectives for the SLPP. In this research, the main objective is to minimize the total travel distance between facilities. The allocation of facilities in site is also based on desired closeness relationships between facilities, which referred to as proximity. These relationships present a certain preference in having the facilities close or apart from each other. Such relationships can be determined quantitatively by calculating the transportation cost between facilities per unit time or qualitatively by using proximity weights that are determined subjectively based on prior experiences (Hegazy and Elbeltagi 1999). For example, it is very desirable to allocate the concrete batch plant as close as possible to the concrete structures in the project, while the power generator in site should be allocated as far as possible from the water tank. As such, there are two main factors that determine the optimum layout of the construction project facilities: 1) Distance between facilities; and 2) Desired closeness between them. The two factors are then incorporated in one minimization objective function given in Equation (1).

$$\text{Minimize: (Total Travel Distance} = \sum_{i=1}^{T-1} \sum_{j=i+1}^{T} D_{ij} \times P_{ij} \text{)} \qquad (1)$$

where, T: total number of facilities in the project (permanent and temporary), D_{ij}: travel distance between facilities (i) and (j), P_{ij}: desired proximity (closeness) between facilities (i) and (j).

The SLPP is one of the most sophisticated construction problems due to the incorporation of many parameters that are needed to define the problem. For example, Khalafallah and El-Rayes (2006) presented a model for optimizing airport construction site layout. In their model, they incorporated specific parameters related to the aviation safety regulation and proceedings. In general, there is no specific site layout planning model that is generic enough to accommodate all the settings of different construction projects.

ELECTIMIZE: OPTIMIZATION STEPS

A framework for the development of Electimize was first introduced by Abdel-Raheem and Khalafallah (2009), then it was followed by the presentation of the basic optimization steps (Abdel-Raheem and Khalafallah 2010). However, further modifications were introduced to enhance the performance of the algorithm in Abdel-Raheem and Khalafallah (2011); and Abdel-Raheem (2011). Solving combinatorial optimization problems using the modified version of Electimize involve nine main steps as follows:

1. **Fabrication of wires:** A number (N) of solution strings (wires) are fabricated. Each wire is composed of a number of segments (M) that store possible values (l_{ml}) for the different decision variables of the problem. Each value (l_{ml}) in the solution space has a designated resistance (r_{ml}). The value of resistance (r_{ml}) is calculated based on: 1) Value Resistivity (ρ=1): It is assumed to be of the same for all values (l_{ml}) in the solution space ; 2) Value Cross-sectional Area (a_{ml}): It is a constant value calculated relative to other values of the same decision variable; and 3) Value Length (b_{ml}): It is estimated after determining the local resistances in step 6.

$$r_{ml} = \frac{\rho \times b_{ml}}{a_{ml}} \qquad (2)$$

$$a_{ml} = \frac{U}{\sum_{l=1}^{L} U}$$

   Where U = a value representing a piece of information that reflects the user knowledge or certain preference. For example, in a cost minimization optimization problem, the initial preference will be given to selecting alternatives with the least cost.

2. **Construction of the electric circuit:** The fabricated wires are connected in parallel to an imaginary electric source of voltage (V). The voltage (V) is an arbitrary value

that is used to differentiate between the qualities of the solutions. Electimize is designed to determine a suitable value for (V).

3. **Determining the electric current intensity (I_n)**: The intensity of the electric current (I_n) passing through each wire (W_n) is the value of the objective function after substituting the wire segments values (l_{ml}) in its variables.
4. **Calculating the global resistance of wires (R_n):** The global resistance of each wire is calculated using Ohm's Law: $R_n = V/I_n$.
5. **Evaluating the quality of wires:** The quality of each wire (W_n) is indicated by its global resistance (R_n) from previous step. Based on the global resistance, the top (5-25)% of the wire populations, the best wire in each iteration, and the best wire in all iterations are identified.
6. **Evaluating the quality of wire segments:** The quality of each value (l_{ml}) in segment (m) of wire (W_n) is based on its length (b_{ml}). To calculate length (b_{ml}), the local resistance (r_{ml}) should be estimated first. At start, it is assumed that all resistances (r_{ml}) for the values of segments (m:1→M) appear identical since there is no prior information about how the quality of each value. Therefore, the resistances are first calculated as follows:

$$r_{lm} = \frac{R_n}{M}$$

A sensitivity analysis is then conducted to determine the actual resistances of each value (l_{ml}). The top (5-25)% of wires are selected to perform a sensitivity analysis by substituting the value (l_{ml}) of each segment in the best wire (W_b) among them in 90% of the iterations and in the overall best wire determined throughout all the iterations (W_{BEST}) in the remaining 10% of the iterations. If a better wire is identified it immediately replaces $W_{BEST.}$ The change (ΔR) in the global resistance of the Control Wire is then recorded and the resistances (r_{ml}) of values are modified according to the following equations. The modified resistances (r^*_{ml}) are then normalized so that their sum is equal to the original wire resistance (R_n). This guarantees that there is no violation to Kirchhoff's rule.

$$\Delta R = R_{CW} - R_n$$

$$H = \Delta R / R_{CW}$$

$$r^*_{ml} = [r_{ml}(1 - H)] * R_n / \sum_{m=1}^{M} [r_{ml}(1 - H)]$$

Where r^*_{ml} = modified resistance of segment (m); r_{ml} = resistance of value (l_{ml}) of segment (m) in the original wire (W_n); R_n = global resistance of wire (W_n); and R_{CW} = resistance of the control wire.

7. **Updating resistances (r_{ml}) for the generated values:** The resistance (r_{ml}) is updated for each selected value (l_{ml}) for each segment (m) according to the next equation. The length (b_{ml}) can then be calculated using Equation (2). If a certain value (l_{ml}) is used more than a specified number of times- set by the user, then the updated resistance $\hat{r}_{ml}$ is multiplied by the Heat Factor to account for the pseudo-resistance generated

due to the overuse of segments. Experimentation showed that a suitable value for the Heat Factor can be in the range of [0.4, 0.7]

$$\hat{r}_{ml} = r_{ml} + r^*_{ml}$$

Where $\hat{r}_{lm}$ = updated resistance for value (l) of segment (m), and r_{ml} = resistance for value (l_{ml}) of segment (m) from the previous iteration.

8. Selection of new values (l_{ml}) for the variables: The selection probability of new values is based on the calculated length (b_{ml}) of each value (l_{ml}). For maximization problems, it can be calculated according to the following equation:

$$P_{ml} = \frac{1 / b_l}{\sum_{l=1}^{L} 1 / b_l}$$

Where P_{ml}= probability that value (l_{ml}) is selected for segment (m).

9. Algorithm Termination: The algorithm terminates after the stipulated number of iterations is reached.

PROBLEM MODELING

As the primary objective of this paper is to test the capability of Electimize in solving dynamic construction optimization problem, rather than modeling the SLPP, the methodology used for this research work was to select one of the previously developed site layout-planning models and re-work it using Electimize. The model presented by Hegazy and Elbetagi (1999)- Evosite- was found suitable for the purpose of this paper for two main reasons: 1) The model is generic in nature and can accommodate different types of construction projects; and 2) It is EA-based, which would facilitate the application of Electimize as well as the comparison with another EA, namely GAs. However, some major modifications were introduced as will be discussed in details in the following sections.

In the Evosite model, the construction site is represented as a two-dimensional grid composed of a number of squares of equal areas. The area of a unit grid is determined using the greatest common divisor of the areas of all facilities. The facilities are then placed with respect to their closeness relationship in an attempt of minimizing the travel distance according to Equation (1).

In Evosite, each solution string (GA chromosome) carried values of the location reference of both the permanent and temporary facilities. The location reference of any facility can be calculated using the following equation (Hegazy and Elbetagi 1999).

$$\text{Location Reference} = (\text{row no.} - 1) \times \text{no. of columns} + \text{column no.}$$

As such, if facilities A, B, and D are the permanent facilities in the project, while facilities E and C are the temporary ones, a randomly generated chromosome would look like Figure 1. The travel distances between facilities are measured between the centroids (see Figure 1). For simplicity, irregular shaped facilities are approximated to the closest rectangular shape to facilitate the calculation of the facility centroid position on the grid. The distances are then calculated using the Euclidean theorem.

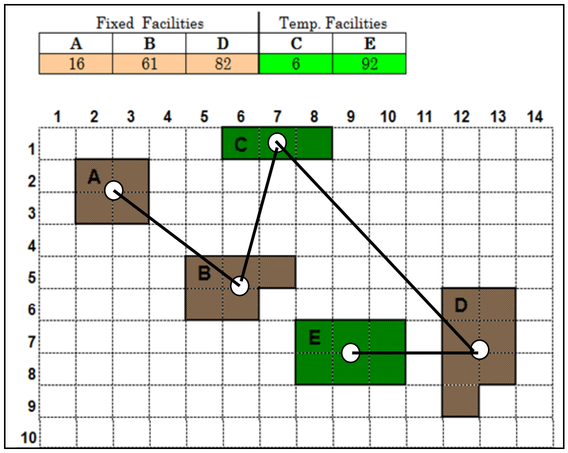

Figure 1: A Randomly Generated Chromosome & Facilities Allocation on Site according to Evosite

In modeling the SLPP using Electimize, a major modification was introduced to the generation of solution strings (wires) compared to Evosite. A number of wires (N) composed of segments (M) are generated randomly. The number of segments corresponds to the number of temporary facilities. This means that the wires segments carry the value of the location reference (k) of the temporary facilities (i) only (see Figure 2) unlike the solution strings in Evosite. Each location reference has a cross-sectional area (a_{ik}) that has a value of "1" since there is no prior information available about the quality of each location beforehand. In other words, all locations available for a single facility appear identical in terms of their contributions toward reaching the overall optimal solution.

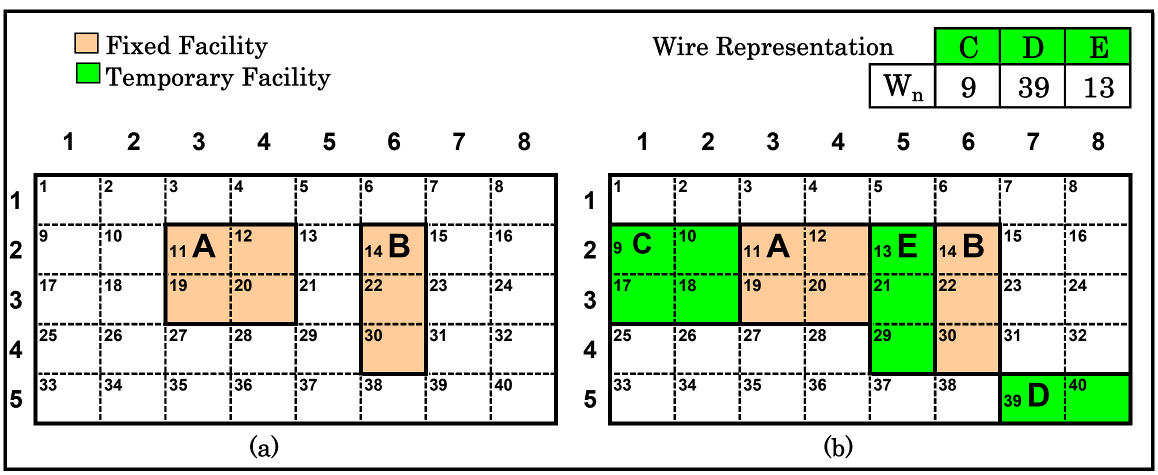

Figure 7. 1: Wire Representation of Facilities Allocation in the Construction Site Using Electimize

The distances between facilities are calculated according to their positions on site as stipulated by each wire. The intensities of the wires are then determined by substituting the distances between facilities and their closeness relationships in Equation (1). The global resistances (R_n) of the wires are then calculated using Ohm's law. The wires are ranked according to their quality, and the top 25% (highest resistances) are selected to conduct sensitivity analysis.

The quality of each available position on site associated with a certain facility is then determined based on its local resistance (r_{ml}). The local resistances are determined through the sensitivity analysis step. For each of the top wires, the value of each segment (location reference) is substituted in its corresponding segment of the comparison wire (see Figure 3).

	C	D	E
W_{best}	9	39	13
W_n	33	28	15

W_C	33	39	13	
W_D	9	28	13	Infeasible
W_E	9	39	15	

Figure 3: Sensitivity Analysis Step for SLPP Modeling Using Electimize

The local resistances (r_{ik}) of site location (k) for facility (i) are then updated and the selection probability (P_{ik}) are calculated in accordance.

SLPP: COMPUTER CODING

Spreadsheet-based software was developed to model the SLPP. The software is comprised of multiple sheets to store, retrieve, and report different data about the problem like information about the sizes of the facilities, best solutions identified throughout the iterations, the wires generated, selection probabilities of values, and drawing the final site layout.

SLPP: APPLICATION EXAMPLE

Electimize was applied to a site layout planning problem from the literature. The problem was first introduced by Rodriguez-Ramos in 1982 in his PhD thesis presenting quantitative techniques for construction site layout planning based on CRAFT, which is a computer-based model for construction site layout planning (Hegazy and Elbetagi 1999). The problem was reattempted by Hegazi and ELbeltagi (1999) in their proposed model – Evosite- which is based on Genetic Algorithms. The problem is a tightly-packed construction site layout planning problem composed of 8 temporary facilities to be allocated on a construction site that has dimensions of (1,500 x 1,700) square feet. The project has nine fixed facilities (see Figure 4). The project facilities description and information is given (see Table 1 and 2). The site grid was divided into 15 columns x 17 rows. Each grid unit has an area of 100 ft^2. The objective is to minimize the total travelling distance between the 17 facilities using the closeness relationships (proximity) between them.

Table 1: Different Types of Facilities used in the Application Example

Facility	Description	Area (ft2)	Facility Type	Width	Length	No. of Options	X-Coord.	Y- Coord.
1	Field office	600	Temporary	30	20	93	-	-
2	Warehouse	600	Temporary	20	30	102	-	-
3	Reinforcing bars shop 1	600	Temporary	30	20	93	-	-
4	Reinforcing bars shop 2	600	Temporary	20	30	102	-	-
5	Excavated material	800	Temporary	20	40	88	-	-
6	Patch plant	800	Temporary	20	40	88	-	-
7	Subcontractor's office	600	Temporary	30	20	93	-	-
8	Formwork shop	800	Temporary	20	40	88	-	-
9	Project I	1,200	Fixed	30	40	-	8.5	2
10	Project J	600	Fixed	30	20	-	8.5	5
11	Project K	1,200	Fixed	30	40	-	5.5	2
12	Project L	800	Fixed	20	40	-	1	12
13	Project M	600	Fixed	20	30	-	1	15.5
14	Project N	1,500	Fixed	50	30	-	6.5	15.5
15	Project O	1,600	Fixed	40	40	-	13	12
16	Project P	1,200	Fixed	40	30	-	13	15.5
17	Project Q	1,200	Fixed	30	40	-	3.5	12

Table 2: Proximity Matrix of Relationships between Facilities in the Application Example

Facility	Field office	Ware h.	Reinf. shop 1	Reinf. shop 2	Exc. Material	Patch plant	Sub. office	Form. shop	I	J	K	L	M	N	O	P	Q
Field office	0	10	2	4	0	2	0	2	2	2	6	10	2	2	20	4	2
Warehouse	10	0	4	4	0	0	0	20	4	6	4	2	4	6	20	4	2
Reinforcing bars shop 1	2	4	0	0	0	0	0	0	20	20	20	0	0	0	20	20	0
Reinforcing bars shop 2	4	4	0	0	0	0	0	0	0	0	0	20	40	60	0	0	20
Excavated material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Patch plant	2	0	0	0	0	0	0	0	100	200	100	400	300	100	500	400	300
Subcontractor's office	0	0	0	0	0	0	0	0	6	6	6	6	6	6	6	6	6
Formwork shop	2	20	0	0	0	0	0	0	20	20	20	20	20	20	60	20	20
Project I	2	4	20	0	0	100	6	20	0	0	0	0	0	0	0	0	0
Project J	2	6	20	0	0	200	6	20	0	0	0	0	0	0	0	0	0
Project K	6	4	20	0	0	100	6	20	0	0	0	0	0	0	0	0	0
Project L	10	2	0	20	0	400	6	20	0	0	0	0	0	0	0	0	0
Project M	2	4	0	40	0	300	6	20	0	0	0	0	0	0	0	0	0
Project N	2	6	0	60	0	100	6	20	0	0	0	0	0	0	0	0	0
Project O	20	20	20	0	0	500	6	60	0	0	0	0	0	0	0	0	0
Project P	4	4	20	0	0	400	6	20	0	0	0	0	0	0	0	0	0
Project Q	2	2	0	20	0	300	6	20	0	0	0	0	0	0	0	0	0

SLPP: RESULTS AND COMPARISON WITH PREVIOUS ATTEMPTS

Electimize was able to find a new optimal solution (18,713.14 ft) for this problem using 50 iterations, 100 wires, and the top 21 wires in each iteration for the sensitivity analysis step.

The original solution for this problem was reported by Rodriguez-Ramos in 1982 and has a value of 22,386 ft (Hegazy and Elbetagi 1999). The second attempt was conducted by Hegazy and Elbetagi in 1999 using GAs and they obtained a new solution (22, 229 ft), which is better than the first attempt with an improvement of 0.71 percent.

Electimize was able to identify a better solution (18,713.14) than the previous attempts with improvements of 20% and 19% from the first and second attempt respectively. The final site layout reported by Electimize in comparison to Hegazi and Elbeltagi's solution is illustrated (see Figure 4).

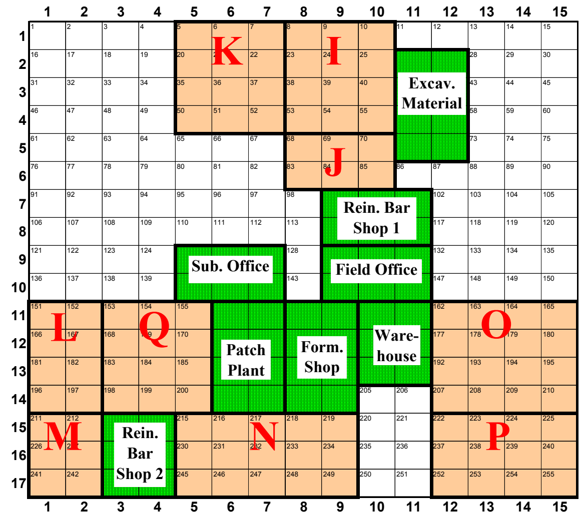

Figure 4: Final Site Layout Plan of the Application Example for Different Attempts

CONCLUSION

This paper presents testing the capabilities of Electimize as an efficient tool for solving complex construction optimization problems. The site layout planning problem was selected for this purpose as an example of a dynamic NP-hard combinatorial optimization problems. An Excel-based site layout planning prototype was developed to facilitate practical application. Electimize was coded internally as a Macro program. Electimize was then applied to a benchmark SLPP in comparison to a previous attempt made using GAs. Eletimize major contribution lied in the identification of a new optimal solution for this problem with an improvement of almost 20% from the past results. Electimize proved to be an efficient tool in solving complex construction optimization problems. The ease of its application and its fast convergence make it a reliable tool for finding the optimal solution(s) for a wide range of problems in the construction industry.

REFERENCES

Abdel-Raheem, M. (2007). Cash Management: A Computer-based Framework for Maximizing Profit Using Evolutionary Algorithms. M.Sc. Thesis, Faculty of Engineering, Cairo University, Giza, Egypt.

Abdel-Raheem, M. (2011). Electimize: A New Evolutionary Algorithm for Optimization with Application in Construction Engineering. Ph.D Dissertation, Colleage of Engineering and Computer Science, University of Central Florida, USA.

Abdel-Raheem, M., and Khalafallah, A. (2009). "Framework for a Multi-Level Evolutionary Algorithm for Construction Optimization." Proceedings of the 23rd European Conference on Modeling and Simulation (ECMS 2009), June 9 – 12, Madrid, Spain.

Abdel-Raheem, M., and Khalafallah, A. (2011). "Using Electimize to Solve the Time-Cost-Tradeoff Problem in Construction Engineering." Proceedings of 2011 ASCE International Workshop on Computing in Civil Engineering, June 19-22, Miami, FL, USA, pp 250-257.

Abdel-Raheem, M., and Khalafallah, A. (2011). "Introduction to a New Mechanism for Electimize." Proceedings of UKSim 13th International Conference on Modeling and Simulation (UKSim2011), March 30 – April 1, Cambridge, UK, pp 8-13.

Christodoulou, S. (2005). "Scheduling Construction Activities Using Ant Colony Optimization." Proceedings of the Tenth International Conference on Civil, Structural, and Environmental Engineering Computing, Civil-Comp Press, Stirling, Scotland, 1-12.

Elazouni, A.M., and Metwally, G. (2005). "Finance-Based Scheduling: Tool to Maximize Project Profit Using Improved Genetic Algorithms." Journal of Construction Engineering and Management, ASCE, Vol. 131, No.4, 400-412.

Elbeltagi, E., Hegazy, T., and Grierson, D. (2005). "Comparison among five evolutionary-based optimization algorithms." Advanced Engineering Informatics, Elsevier, 43-55.

El-Rayes, K., and Kandil, A. (2005). "Time-Cost-Quality Trade-Off Analysis for Highway Construction." Journal of Construction Engineering and Management, ASCE, Vol. 131, No.4, 477-486.

Feng, C.W., Liu, L., and Burns, S. (1997). "Using Genetic Algorithms To Solve Construction Time-Cost Trade-Off Problems." Journal of Computing in Civil Engineering, ASCE, Vol. 11, No.3, 184-189.

Hegazy, T., and Elbeltagi, E. (1999). "EvoSite: An Evolution-Based Model for Site Layout Planning." Journal of Computing in Civil Engineering, ASCE, 13 (3), 198-206

Hegazy, T., and Ersahin, T. (2001). "Simplified Spreadsheet Solutions. II: Overall Schedule Optimization." Journal of Construction Engineering and Management, ASCE, Vol. 127, No.6, 469-475.

Hegazy, T., and Wassed, N. (2001). "Simplified Spreadsheet Solutions. II: Overall Schedule Optimization." Journal of Construction Engineering and Management, ASCE, Vol. 127, No.3, 183-191.

Khalafallah, A., and El-Rayes, K. (2006) "Optimizing Airport Construction Site Layouts to Minimize Wildlife Hazards," Journal of Management in Engineering, ASCE, 22(4), 176-185.

Khalafallah, A, and Abdel-Raheem, M. (2011). "Electimize: A New Optimization Algorithm with Application in Construction Engineering." Journal of Computing in Civil Engineering, ASCE, 25(3), pp 192-202.

Lu, M. (2002). "Enhancing Project Evaluation and Review Technique Simulation through Artificial Neural Network-based Input Modeling." Journal of Construction Engineering and Management, ASCE, Vol. 128, No.5, 438-445.

Maier, H.R., Simpson, A.R., Zecchin, A.C., Foong, W. K., Phang, K.Y., Seah, H. Y., and Tan, C.L. (2003). "Ant Colony Optimization for Design of Water Distribution Systems." Journal of Water Resource Planning and Management, ASCE, Vol.129, No.3, 200-209.

Solimanpur, M., Vart, P., and Shankar, R. (2004). "Ant colony optimization algorithm to the inter-cell layout problem in cellular manufacturing." European Journal Of Operational Research, Elsevier, Vol.157, 592 -606.