Theme:

Title:

Genetic Algorithm Modeling Aided with 3D Visualization in Optimizing Construction Site Facility Layout

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Abstract: *Site layout planning is a complicated issue due to the existence of the vast number of trades and inter-related planning constraints. Researchers have tried to use artificial intelligence (AI) to solve this kind of complex problems, which, however, needs a certain degree of problem simplification in order to suit the models. The simplified models cannot always present a full picture of the problem to the decision makers. To overcome this, 3-dimensional (3D) visualization technology is proposed that gives a virtual construction site layout based on solutions generated from the AI models. In the paper, a genetic algorithm (GA) optimization model for the tower crane and supply locations is generated, which is then supplemented with 3D visualization to build up a virtual construction site layout from the solutions generated from the GA model. An illustrative example is used to demonstrate the way that the use of 3D visualization in supplementing GA models in optimizing tower crane layout problems.*

Keywords: *Site layout planning, Genetic algorithms model, 3-dimensional visualization*

Introduction

Construction site facilities layout planning (FLP), which defines the types, quantities and positioning of the mechanical plant, storage areas and fabrication yards has significant impact on productivity, costs and duration of construction. Although FLP is such a critical process in construction planning, a systematic analysis of construction site layout is always difficult because of the existence of the vast number of trades and inter-related planning constraints. Practitioners of the building industry lack a well-defined approach in construction site layout planning, especially for high-rise building construction.

Site conditions, such as the topographical layout, building tower layout and the adjacent environment, are unique for each site. Consequently, they result in a great variation in site layout strategies and approaches. For high-rise building construction, the allocation of temporary facilities keeps changing and is inter-related with the progress of construction work, which further complicates the planning process. Optimization of FLP (which is a non-linear and discrete system) using the scientific approach is difficult, if not impossible, to achieve. Hence, FLP of construction sites in Hong Kong has been carried out mainly through human judgement. Because of human involvement, there are no conditions that lead consistently to the same result.

To overcome the above problems, researchers have used mathematical and computation techniques, hoping to arrive at an optimal solution. However, these scientific techniques normally require a certain degree of simplification from the reality. Thus, the simplified model may provide misleading solutions to the users that cannot let the users capture or view the complexity of the solutions. To this, 3-dimensional visualization technology is proposed, which may provide a possible tool to bridge the gap between AI models, practical problems and solutions.

The objective of this paper is to investigate and analyse the feasibility of using the VR technology to hybridise the total information of site conditions into a visualised model. An example of using results produced from a genetic algorithm (GA) model in optimising the layout of tower cranes to generate a virtual site facility layout using 3D studio MAX is used to illustrate the objective.

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Application of Genetic Algorithms in Site Facility Layout

In site facilities layout optimization, there exist many problems to be solved; for example, the non-linearity of the site facilities layout planning system, the discreteness of the number and positions of facilities, and so on. Among these problems, one of the important issues is the optimal placement of facilities in sites, on the condition that all facilities are considered simultaneously.

Genetic algorithms (GAs) are heuristic random search techniques based on the concept of natural selection and natural genetics of a population (Holland 1975, Goldberg 1989). Genetic algorithms presume that the potential solution of any problem can be represented by a set of parameters. These parameters are regarded as the genes of a chromosome and can be structured by a string of values, normally in binary form. A positive value, generally known as a fitness value, is used to reflect the degree of "goodness" of the chromosome for the problem. Due to the distinctive features, such as domain independence, non-linearity, robustness and parallel nature, GA has been proven to be a versatile and effective approach for solving optimization problems. The successful application of genetic algorithms to both combinatorial and discrete optimization problems (Koumousis and Georgiou 1994) motivated the application of GAs for solving mixed-discrete non-linear optimization problems (Jenkins 1997).

Reason for Using 3D Visualization Technology

Virtual reality is a technology to create virtual environments by computer in order to simulate the physical world (Smith and Heim, 1999). The modeller can share his/her experiences with the virtual world and give a realistic compression of the simulated world. Thus, it enables people to experience the outcomes of a variety of choices at a minimal investment of cost and time. They are allowed to play 'what if' and test alternative scenarios with relative ease.

Conventional site layout planning usually uses two-dimensional representation of sites and positions of elements. However, there may have some situations that are not adequately described by two-dimensional approaches. In this case, a VR representation with three-dimensional environment can offer sufficient information for the designer to improve the process like interaction between site elements.

Virtual Reality Tools

To produce a virtual environment, there are many computer tools available like VRML, 3D Studio MAX, AutoCAD, Raystream, Poser, Bryce 3D, Maya, Lightware, etc. Different software offers different functions. Some require programming techniques like VRML, a computer language to produce the virtual 2D or 3D environment, which can run on different operation systems like UNIX, LINUX, MS WINDOW NT or MS-DOS. 3D Studio MAX and AutoCAD are also commonly used in industries like manufacturing, computer animation, etc.

3D Studio MAX and AutoCAD are more popular than VRML because they are user-friendlier. Both are displayed in Graphical User Interface (GUI), so users with less programming background are capable to create the virtual environment; both are compatible to each other. Hence, in this study, 3D Studio MAX R3 is used.

Model Description

Three steps are involved in optimizing the locations of the tower crane and supply points (load picking-up locations). First, the permissible locations of the supply points $\{S_i \mid$ coordinates of all available supply point locations, $S_i (XS_i, YS_i, ZS_i), \forall_i \in [1, 2,…, n]\}$ are determined from the site map with the consideration of the length of the tower crane jib l_{cr} and its capacity, the required size of the supply points, and other site constraints. The demand points (unloading or load discharging locations) $D_i (XD_i, YD_i, ZD_i)$ are fixed by the geometric shape of the permanent building. Then the possible locations of tower crane $Cr_i(XCr_i, YCr_i, ZCr_i)$ are plotted, which are dependent on the structural design layout, space provisions of the permanent structure, convenience for other site activities, etc. Finally, a GA model is applied to optimize two outputs: the tower crane and the supply points locations for various trades.

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It is assumed that the geometric layout of all demand points is predetermined and fixed. For each supply and demand pair, demand levels for transportation are known, e.g., total number of lifts, number of lifts for each batch, maximum load and so on. Besides, the material transported between a supply-demand pair is handled by one crane only.

For the crane operations, the horizontal simultaneous movement of crane operations in lifting objects for experienced crane operators is assumed to be 76% of the total duration of the cycle (Kogan 1976). Hence the coefficient, α, that represents the degree of coordination of hook movement in radial and tangential directions in the horizontal plane is assumed to be 0.25 (Zhang et al 1999). The vertical simultaneous movement of crane operations is assumed to be small for high-rise building construction where the object needs to be lifted to such a level that is clear of the building before radial movements can be activated. Hence, the coefficient, β, that represents the degree of coordination of hook movement in vertical and horizontal planes is assumed to be 1, i.e. the hook moves consecutively in two planes (Zhang et al 1999).

Finally, the feasible locations for tower crane and supplied points are limited by the site conditions and the shape of the permanent building. The area of each supplied point needs to be large enough to accommodate the storage requirements.

The reach of a crane tower is determined by the length of its jib and its lifting capacity is decided by a radius-load curve where the greater the load, the smaller the crane's operating radius. Hence, the locations of both the supply and demand points must fall within the permissible weight-radius circle of the tower crane. Since the demand points are fixed, attention is focused on the permissible locations of supply points.

Setting values for the various parameters

The setting of population size, probability of crossover and mutation is a trial and error process. This process relies heavily on the knowledge and experience of the researchers. The initial parameters are often set at figures that are perceived as sensible based on previous work (Al-Tabtabai et al 1999). In general, if the problem involves a large search space and many chromosomes, a large population size is also warranted. The probability of crossover and mutation adopted used are those default values adopted by the software used. In addition, the rate of convergence and avoidance of local maxima/minima traps should also be considered.

Initial Population

The initial population was prepared with continuous chromosome representation. Continuous chromosomes are used because each chromosome is mapped to a special selected position. They are independent to one another and GeneHunter™ - the software used in this study – suggested using this type of chromosome. There are two sets of chromosomes. Chromosomes δ_i {δ_i | Random numbers, $\forall_i \in [1, 2, …, n]$} are mapped to location number i for each element A_j where $S_{Aj} = \{S_i \mid S_i \in A_j\}$.

Chromosome $\varepsilon_i \in (0, 1)$ are mapped to location number Cr_i for tower crane positions. A mixed integer program (MIP) is used to denote the selected tower crane location where N to be the integer to indicate the state of selection.
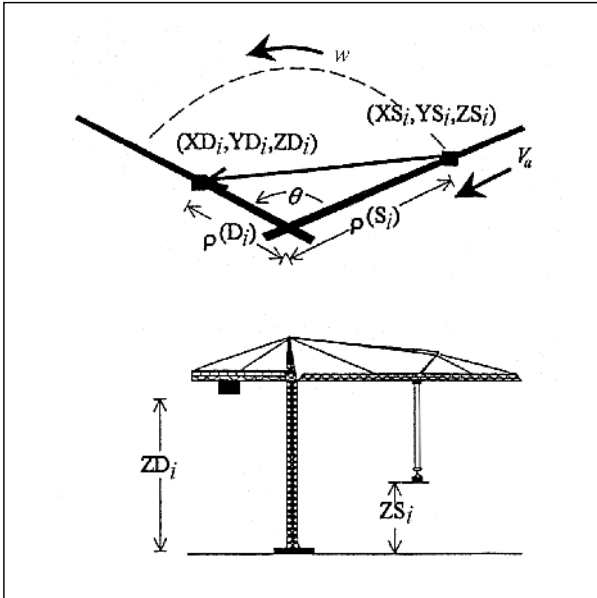
$$[N \mid Cr_i] = \begin{cases} 1 & \text{selected to be tower crane position} \\ 0 & \text{otherwise} \end{cases}$$

$$\forall i \in [1, 2, …, n]$$

The function of the GA is to find the optimal location of tower cranes and supply points with the above chromosomes.

Rating the population in terms of their fitness

In this study, the fitness of the chromosome is assessed by the total transportation costs. According to the model for calculation of hook travel time (Zhang et at 1999), the fitness function is given by:

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$$\min TC = \min\{N * [\sum_{j=1}^{n}\sum_{k=1}^{n} T_{jk} Q_{jk} C_{jk}]\}$$

$T = \max(T_h, T_v) + \beta * \min(T_h, T_v)$

$T_v = |ZS_i - ZD_i| / V_h$

$T_h = \max(T_a, T_w) + \alpha * \min(T_a, T_w)$

$\rho(D_i) = \sqrt{(XD_i - XCr_i)^2 + (YD_i - YCr_i)^2}$

$\rho(S_i) = \sqrt{(XS_i - XCr_i)^2 + (YS_i - YCr_i)^2}$

$l_i = \sqrt{(XD_i - XS_i)^2 + (YD_i - YS_i)^2}$

where l_i is the distance between supply and demand points

Time for trolley radial movement:

$$T_a = \frac{|\rho(D_i) - \rho(S_i)|}{V_a}$$

Time for trolley tangent movement:

$$T_w = \frac{1}{V_w} * Arc\cos\left(\frac{l_i^2 - \rho(D_i)^2 - \rho(S_i)^2}{2 * \rho(D_i) * \rho(S_i)}\right)$$

$$(0 \le Arc\cos(\theta) \le \pi)$$

w	possible and available supply locations	TC	total cost
j	element number	$Cr_i (XCr_i, YCr_i, ZCr_i)$	coordinate of tower crane
i	location number of each position	l_{cr}	jib length of tower crane
A_j	all supply locations available for element j	T	hook travel time
S_i	supply point at location number i	T_h	hook horizontal travel time
$S_i (XS_i, YS_i, ZS_i)$	coordinate of supply point i	T_v	hook vertical travel time
D_i	demand point for element j	T_a	time for trolley radial movement
$D_i (XD_i, YD_i, ZD_i)$	coordinate of demand point i	T_w	time for trolley tangent movement
S_{Aj}	the selected supply location number of element j	V_h	hoisting velocity of hook (m/min.)
k	number of times that the transportation of element j needs to repeat	V_a	radial velocity
Q_{jk}	quantity of material flow from S_i to D_j	V_w	slewing velocity of jib (r/min.)
C_{jk}	cost of material flow from S_i to D_j per unit quantity and unit time		

β degree of coordination of hook movement in vertical and horizontal planes (0 for simultaneous movement & 1 for consecutive movement)

α degree of coordination of hook movement in radial and tangential directions in the horizontal plane (0 for simultaneous movement & 1 for consecutive movement)

Population evolution through genetic operators

Crossover and mutation are used as genetic operators for the evolution of the population. A single point continuous crossover is selected as the crossover operator because this is a resource allocation problem as suggested by GeneHunter™- the software used in this study.

Mutation of enumerated chromosomes

After the crossover stage has finished, the mutation begins. Mutation is a very important operator as it injects new genetic information into the population to change a gene of a chromosome randomly. The population resulting from the mutation stage then overwrites the old population (the one prior to selection), completing one generation. Subsequent generations follow the same cycle of selection, crossover, and mutation.

Optimal solution

The near optimal solution emerges when the pre-determined termination condition is met.

From GA to VR

To construct a 3D virtual construction site, the information given by the GA model is insufficient. The expert should collect the relevant information as shown below:

- Site architectural plan and structural plan (building information);
- Site formation plan: information on adjacent slopes and flat areas;
- Environmental conditions: extreme and normal conditions; and
- The site photos covering the whole areas with suitable details.

All of the above are the necessary information to construct a virtual site under a computer environment. Then, according to the background information being collected and the result from the GA model, the following stepwise procedures are initiated:

Step (1)   A site landscape with respect to the site formation plan needs to be constructed. The 3D coordinate points in a grid of appropriate scale then need to be plotted to form the virtual site.

Step (2)   Each element should then be plotted separately and saved as objects to form a library.

Step (3)   Building structures need to be constructed separately and saved.

Step (4)   Combine the elements formed from Step (2) and (3) onto the virtual site formation plan in absolute coordinates.

Step (5)   Determine the viewing positions and set up the direction of light source.

Step (6)   Render the virtual site and generate the views.

Step (7)   Repeat Step (5) and (6) based on different locations and angles to obtain a virtual tour.

Illustrative Example

As the site layout for high rise building construction keeps changing at different stages of construction, this study has defined a particular construction stage: the use of tower crane at concrete frame construction. The major materials transported by tower cranes are i) large panel formwork; ii) precast concrete façade units; and iii) reinforcing bars. While concrete is normally transported by concrete hoists or concrete pumps, only the positioning of the bending yard, the façade storage yard and the assembling area of large panel formwork are considered in the model.

Suppose the three storage areas including large panel formwork, precast façade units and the bending yard are denoted as A_1, A_2 and A_3. For A_1, there are six possible locations (S_1, S_2, S_3, S_4, S_5 and S_6) after

considering its size, shape and other constraints. For A_2, there are four possible locations (S_1, S_2, S_3, S_4); for A_3, five possible locations (S_5, S_6, S_7, S_8, S_9). For tower crane positions, site layout planners prefer locating a climbing crane within the structure where the crane must not obstruct other site activities. Sometimes, a static tower crane may be located at the corner of two building wings, depending on the preference of site planners. Hence, it gives twelve possible locations of tower crane (Cr_1, Cr_2, … Cr_{12}).

Plan of site conditions
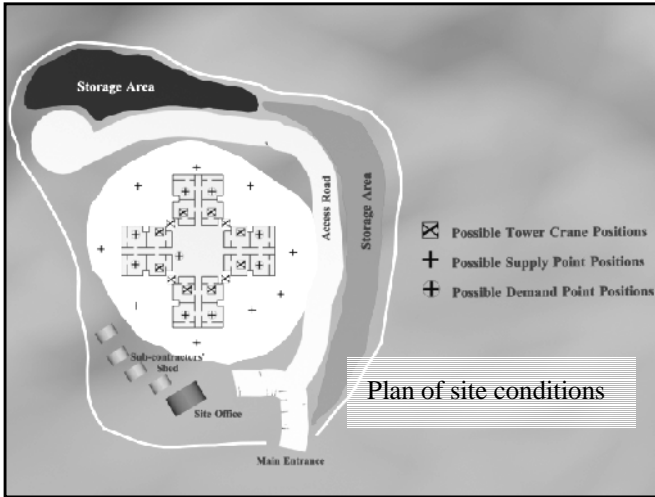
In the GA modeling, the mutation rate is 0.05 and the crossover rate used is 0.9. The results of two rounds of modeling with different initial chromosome populations are shown below.

Round 1

1. The optimized total cost

Initial total cost: HK$ 2,217.63 (US$ 284)

Final total cost: HK$ 1,880.018 (US$ 241) (Optimized)

2. The selected supply points

After optimization, three supply points in three-dimensional co-ordinates are generated from the genetic algorithm model. The points are S_2 (87, 45, 1.5), S_3 (83, 31, 2) and S_9 (55, 15, 1).

Supply Points				
No.	x	y	z	Choice
A_1	87	45	1.5	S3
A_2	83	31	2	S2
A_3	55	15	1	S9

3. Selected location of tower crane

The locations of tower crane C_r in 3D co-ordinates are shown as follows:

Location of tower crane				
No.	Choice	x	y	z
Cr_2	1 (selected)	65	36	30

Round 2

1. The optimized total cost

Initial Total Cost: HK$ 2,452.38 (US$ 315)

Final Total Cost: HK$ 1,890.863 (US$ 243) (Optimized)

2. The selected supply points

After optimization, three supply points in 3D co-ordinates are generated from the GA model. The points are S_1 (73, 26, 2), S_2 (87, 45, 1.5) and S_9 (55, 15, 1).
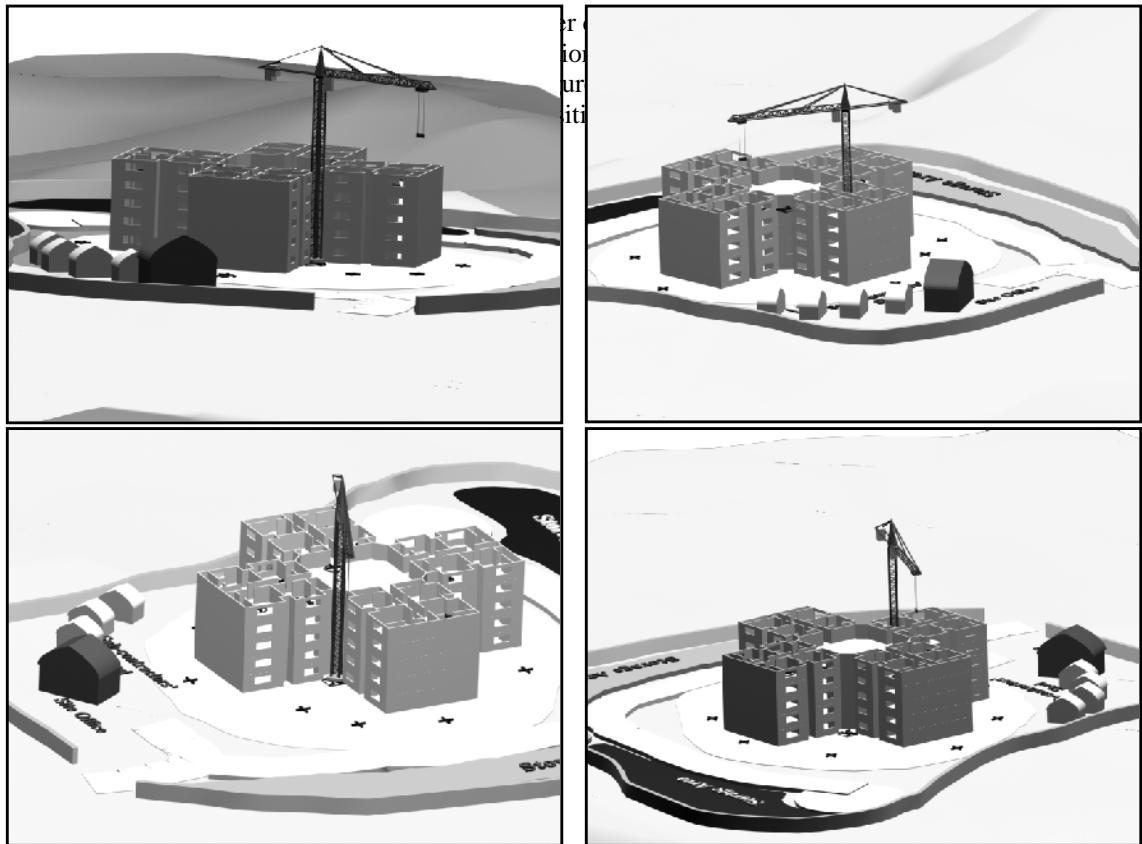
Supply Points				
No.	x	y	z	Choice
A_1	73	26	2	S_1
A_2	83	31	2	S_2
A_3	55	15	1	S_9

3. The selection location of tower crane

The selected locations of tower crane in 3D co-ordinates are shown as follows:

Location of tower crane				
No.	Choice	x	y	z
Cr_6	1 (selected)	60	33	30

Virtual site layout diagrams are then constructed for different tower crane locations as shown below:

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Application of 3D Visualization

As mentioned above, the GA models can only display the coordinates without showing the actual facility layout arrangement and site planners may be skeptical in adopting the solutions. With the assistance of the 3D visualization technology, the actual site facility layout can be simulated and reproduced for site planners to visualize the conditions and identify if there are any unidentified constraints.

3D visualization can provide the following supplementary information in the site layout planning optimization:

1. Actual site conditions: The use of the technology can mimic virtual site conditions. Thus, there may have neglected variables like the detailed ground conditions and geometrical shape of buildings, etc., which can be visualized and may help modify the plan.

2. Operational difficulty: With the 3D visualization, the operational difficulty can be revealed. Planners can view the site layout from all angles and different zooming distance. For example, crane operator's view can be simulated to identify if there are any blind spots, which facilitates a higher accuracy in the estimation of material transportation time.

3. Hybridization of additional information: Incorporating the 3D visualization technology, the information omitted in the GA model can be recovered and displayed in the virtual environment, which helps hybridize the additional information in fine-tuning the model.

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4. Risk analysis: 3D visualization enables planners to perform 'what if' estimation on potential risk matters. It enables planners understand the interactions between elements in a construction site before implementation of the layout.

Conclusions

The GA model described helps improve conventional site facility layout problems. It gives an objective, quantitative and scientific way to evaluate the effectiveness of site facility layout. Experimental results indicate that the model performs satisfactorily. It infers that a systematic approach in site facility planning is important to improve the site production efficiency.

The integration of 3D visualization technology and GA offers the following superiority over traditional approaches:

1. The supply points and possible tower crane positions are obtained realistically according to the site conditions and geometrical layout of the permanent structures. The model can, thus, generate a more realistic solution.

2. Unlike the 2-dimensional layout approach of traditional methods, the model developed can handle 3-dimensional coordinates of all supply, demand and tower crane locations.

3. A number of supply points are considered simultaneously and thus it offers a higher variability in the choice of supply points and may result in a more optimal solution.

4. Site facility layout is a non-deterministic polynomial problem that is difficult to be solved by other polynomial algorithms. GA is an effective tool in handling this kind of non-deterministic polynomial optimization.

5. The use of 3D visualization can overcome the oversimplification of AI modeling. The technology can play a substantial role in the design and analysis of complex site production systems and processes. The three-dimensional nature and the mechanisms for interacting with objects in VR environments make the enormous amount of available information much more accessible to decision makers.

The 3D visualization technology is appropriate for visualizing and assessing complicated physical site facility constraints in parallel to the determination of construction process flows. To design and analyze the site production systems, both economic and operational aspects of each facility should be considered at the same time.

Acknowledgement

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