Construction Management and Economics

ISSN: 0144-6193 (Print) 1466-433X (Online) Journal homepage: https://www.tandfonline.com/loi/rcme20

Schedule-dependent evolution of site layout planning

Emad Elbeltagi , Tarek Hegazy , Abdel Hady Hosny & Adel Eldosouky

Construction Management and Economics (2001) **19**, 689–697

Schedule-dependent evolution of site layout planning

EMAD ELBELTAGI[1], TAREK HEGAZY[2*], ABDEL HADY HOSNY[3] and ADEL ELDOSOUKY [4]

[1]*Faculty of Engineering, Mansoura University, Mansoura, Egypt*

[2]*Department of Civil Engineering, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1*

[3]*Faculty of Engineering, Ain Shams University, Cairo, Egypt*

[4]*Faculty of Engineering, Tanta University, Tanta, Egypt*

Received 27 August 1999; accepted 15 February 2001

The appropriate layout of temporary facilities on a construction site has a large impact on construction safety and productivity. For the duration of a project the site layout may need to be efficiently re-organized at various intervals to satisfy the schedule requirements and to maintain site efficiency. This paper presents a practical model for schedule-dependent site layout planning in construction. The proposed model uses a combination of artificial intelligence tools (knowledge-based systems, fuzzy logic, and genetic algorithms) to generate, optimize, and re-organize the site layout plan at frequent intervals during the project. The model incorporates flexible representation of irregular site shapes and several options for placing facilities. Based on the proposed model, an automated system is developed, fully integrated with widely used scheduling software. At each schedule interval, the system recalculates the space requirements and, for the convenience of congested sites, can utilize parts of the constructed space to accommodate temporary facilities. Details of the schedule-dependent model are described, and its application in an actual case study project is presented to demonstrate its capabilities.

Keywords: Site layout, quantitative evaluation, material flow

Introduction

Site space is a resource that is as important as money, time, material, labour and equipment. Like any resource, the amount of site space demanded by the various activities changes with the schedule of the work. Therefore, during the project the site layout may need to be efficiently re-organized at various intervals to satisfy the upcoming schedule requirements and to maintain site safety and productivity. Thus, efficient planning is needed to facilitate the re-organization of the site as the schedule evolves.

Since the early 1970s, several researchers have applied various heuristics or mathematical optimization techniques to solve the static site layout planning problem in construction (e.g. Warszawski and Peer, 1973; Popescu, 1981; Rodriguez-Ramos, 1982; Rad and James, 1983; Tommelein, 1989). In late 1990s, non-traditional techniques based on artificial intelligence (AI) were applied to solve the problem (e.g. Yeh, 1995; Dweiri and Meier, 1996; Li and Love, 1998; Elbeltagi and Hegazy, 2000). These models generated static layouts that span the entire project duration.

Models that deal with dynamic layout planning in construction are limited. Cheng (1992) developed a system called ArcSite, a knowledge-based system integrated with a geographic information system (GIS) to locate the temporary facilities on construction sites. In this model, facilities are placed one-by-one on the site and, accordingly, the resulting layout solution is sensitive to the facility order. Also, the one-by-one placement of facilities may not yield the optimal site layout

*Author for correspondence. e-mail: tarek@uwaterloo.ca

Construction Management and Economics
ISSN 0144–6193 print/ISSN 1466-433X online © 2001 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/01446190110066713

plan. In another model, Tommelein and Zouein (1993) developed a dynamic layout planning system that later was expanded in Zouein and Tommelein (1999). Similar to traditional resource allocation, their models tried to modify the schedule at various intervals so that the site space is not overallocated. The latter model used linear programming to dynamically allocate space to resources one-by-one, so that total cost is minimized. Similar to the previous model by Cheng, however, optimum layout may not be obtained. Also, in most of the models presented in the literature, the site and the facilities are rectangular in shape with each facility being represented as a single block. In addition, facilities are assumed to be predetermined, and the models provide few guidelines regarding necessary facilities and their area requirements.

This paper presents a practical model for schedule-dependent site layout planning in construction. The proposed model provides direct integration with a scheduling tool to determine the schedule-dependent site needs. Accordingly, it optimizes the site plans needed at various intervals along the construction process. The proposed model is developed using a hybrid of artificial intelligence tools that provide guidance for facility identification, determining facilities' spatial relationships, and layout optimization. The developments made in this paper add dynamic capabilities to a previous model for static layout planning (Elbeltagi and Hegazy, 2000). Details of the schedule-dependent model are described in the following sections and include developments related to: facility identification; definition of the site space needs that vary with the project schedule; and layout optimization. A practical case study is used then to demonstrate the capabilities of the proposed system.

Facility identification

An integral feature of the proposed model is the support of the project manager's judgement in identifying the required temporary facilities needed to facilitate construction operations. Since their decisions are based largely on experience, a knowledge-based system was developed to provide support. The knowledge base incorporates 139 'IF-THEN' rules related to 22 temporary facilities (Table 1) and their size requirements (Elbeltagi and Hegazy, 2000). Sources of knowledge include construction safety and health manuals (e.g. ILO, 1992), company handbooks (e.g. Obayashi Corporation, 1975), published dissertations (e.g. Cheng, 1992; Tommelein, 1989), and technical articles (e.g. Popescu, 1981; Rad and James, 1983). The rules determine the size of the facilities based mainly on the manpower requirements, estimated quantity of work, the production rate of resources, availability of site space, and cost considerations. An example of such a rule is:

Table 1 List of temporary facilities

No. (1)	Facility name (2)	No. (3)	Facility name (4)
1	Offices	12	Batch plant
2	First aid	13	Sampling/ Testing lab
3	Information and guard	14	Piping yard
4	Toilet on site	15	Parking lot
5	Engineers/staff dormitory	16	Tank
6	Labour's dormitory	17	Long term laydown yard
7	Labour's rest area	18	Machine room
8	Maintenance shop	19	Shops
9	Rebar fabrication/ storage yard	20	Scaffold storage yard
10	Carpentry shop	21	Material warehouse
11	Cement warehouse	22	Welding shop

IF	Contractor owns, can rent, or can buy a batch plant = true
AND	Required concrete production = high
AND	Site has enough space for a batch plant = true
AND	A batch plant is more economically than ready mix concrete = true
THEN	Area of batch plant in m^2 = batch plant capacity $\times$ 10

Each temporary facility is allocated a site area as determined from the knowledge base, then placed on site as shown in Figure 1. For flexibility, each facility is represented as a number of small grid units that can take irregular shapes. The area of each grid unit is calculated as the greater common divisor (GCD) of the areas of all facilities that need to be placed on any irregular site. A facility is placed on the site grid, starting from its location reference, in three ways (Figure 1), horizontal, vertical, or rectangular, where the location reference is:

$$\text{Location reference} = (\text{Facility row position} - 1) \times \text{Site columns} + \text{Facility column position} \tag{1}$$

For example, facility i (having an area of 5 grid units) is placed horizontally starting at the fourth site row and first column (location reference = $(4 - 1) \times 11 + 1 = 34$). It is noted that facility i is a multi-unit facility that can be placed on site around site obstacles. When facilities are placed on site, distances to other facilities can be measured readily.

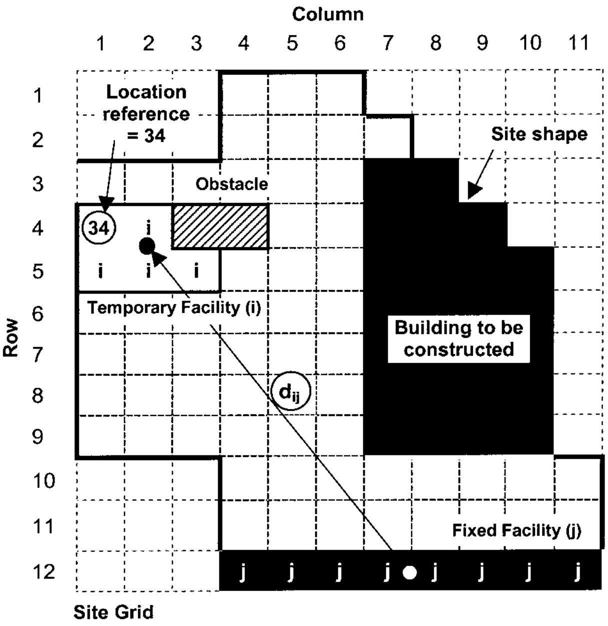

Figure 1 Site and facilities representation

Schedule-dependent site needs

Along the construction schedule, the requirements for site space change, and the layout of temporary facilities needs to be changed. Thus, schedule-dependent site layout planning is the generation of intermediate layouts that respond to the schedule needs at various intervals along the construction schedule.

To facilitate schedule-dependent layout planning, various steps need to be carried out.

1. The list of temporary facilities needed for every activity must be identified and sized, as discussed in the previous section.
2. A detailed schedule of the construction work has to be available. Techniques such as resource leveling and time–cost trade-off analysis can be applied to this schedule so that it becomes as realistic as possible.
3. The activities' requirements of the temporary facilities need to be defined in a similar way to the requirement of labour, equipment, and other resources. In this sense, the selected temporary facilities are dealt with as resources that can be assigned to activities.
4. After step 3 is accomplished, the service times (between facility start time (FST) and facility finish time (FFT)) of each temporary facility become readable from the schedule.
5. Based on step 4, the facilities that serve between any two given dates of the schedule can be defined and considered as the site needs in this interval.

This process of defining the site needs is illustrated in Figure 2, in which a list of temporary facilities (offices, rebar shop, batch plant, and carpentry shop) are considered as resources assigned to some activities. For example, the batch plant is assigned to activities 3 and 10. Accordingly, the service time of the batch plant on the site is between the start date of activity 3 and the finish date of activity 10. Also, the service times for the four facilities is shown in Figure 2.

Knowing the FST and FFT of each facility, it is possible to decide on the facilities that should be considered for any intermediate layout. Consider a layout j starting from time t_j and spanning a layout interval from t_j to t_{j+1} (start of next layout). Thus, for a layout to service the project between times t_j and t_{j+1}, a facility i will be considered to be placed on the site if it satisifies the following:

(a) $t_j \leq \mathrm{FST}_i < t_{j+1}$
(i.e. the facility starts sometime within the layout interval) (2)

or

(b) $\mathrm{FST}_i < t_j$ and $\mathrm{FFTi} > t_j$
(i.e. the facility exists on site and is still needed for this layout interval)

For example, the batch plant, offices, and carpentry shop facilities in Figure 2 will be considered for layout 2, which serves the project between times t_2 and t_3.

One important consideration is to minimize the cost of reallocating facilities so that minimum work disruption is achieved. Therefore, a temporary facility that was placed on the site in a previous layout and is still needed for the new layout will not change its place. Fixing a facility in its place means converting it from a normal facility to a fixed facility. For any layout j, the temporary facilities that need to be converted to fixed facilities are the ones that satisfy condition (b) of Eq. 2. The batch plant facility, for example, was used in layout 1 and will be considered to be a fixed facility in layout 2.

Facilities' change over time

For increasing construction efficiency and cost saving, a facility can be placed at the location of another one that is no longer needed at the present schedule time. In that way, the space on site can be used to accommodate different facilities at different times. Now, assuming that three layouts will be sufficient for this simple project (as shown in Figure 2), the rebar shop, for example, will not be needed for layout 2 or 3. In this manner, the space on site can be dynamically re-allocated to accommodate other facilities at different times.

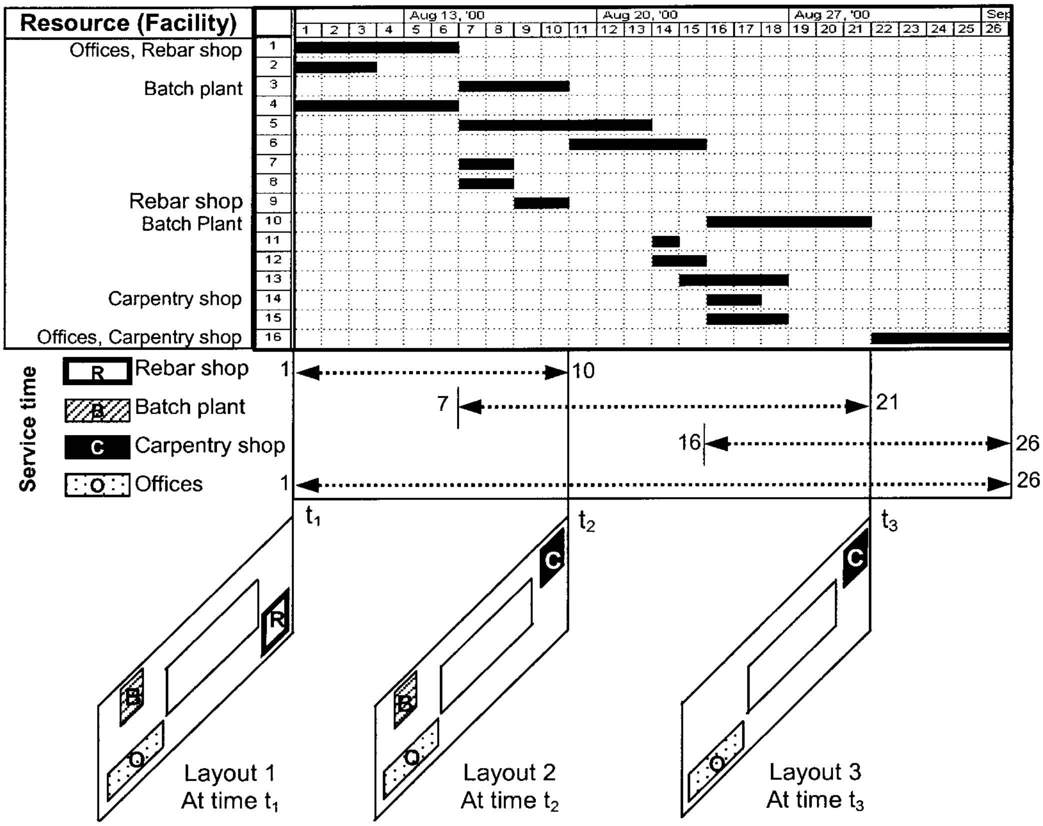

Figure 2 Schedule-dependent site layout

Consideration for restricted sites

On restricted sites, like downtown locations, the management of site space becomes more important than other resources. In many situations, construction managers use part of the constructed facility (e.g. some floors in a high rise building) for storage purposes or other uses. The present model, therefore, incorporates this important feature in its formulation. For any time interval, the user can select any part of the constructed space to be used for placing a temporary facility. Two conditions must be satisfied in this situation: (1) clearly the constructed space has to be available (i.e. its finish date is earlier than the service start date of the temporary facility required); and (2) the constructed space area has to be large enough to accommodate the temporary facility.

Schedule-dependent layout optimization

Having defined the required facilities, their areas, and service times, it is possible to optimize the generation of the various layouts at the user-decided intervals. The optimization process goes through the following steps.

1. First identify the layout intervals and the temporary facilities needed for each layout interval, as discussed in the previous section.
2. Determine the facilities' closeness relationships upon which the optimization process will take place.
3. Then perform a loop from one interval to the other to optimize the selected list of facilities in each interval.

Fuzzy closeness relationships

Effective placement of facilities within the site improves the movement of resources, or basically the interactions, among the facilities. Such interactions are referred to as the closeness relationships among the facilities, and represent the desirability of having the facilities close to or apart from each other. Due to the vagueness and ambiguity associated with such relationships (e.g. facility A should be 'as far as possible' from facility B), especially for large and congested sites, determining crisp values for these relationships is a problem that lends itself well to the fuzzy set approach (Elbeltagi and Hegazy, 2000). Background information on this technique can be found in many references (e.g. Zadeh, 1965; Ross, 1995).

The factors used in this study to determine the closeness weights among facilities are: (1) the level of work flow (WF) between two facilities; (2) the level of safety/environmental (SE) hazard; and (3) user preference (UP). The work flow between two facilities encompasses the total flow of materials, equipment, personnel, and information between the two facilities. The level of safety/environmental hazard also represents any concerns that may arise when the two facilities are close to each other. The third factor, user preference, represents the project manager's preference for having the facilities close to or apart from each other (Elbeltagi and Hegazy, 2000).

The three factors are used as fuzzy input variables: WF, SE, and UP. These three variables affect the fuzzy output variable 'closeness weight'. Each input variable is assumed to have three membership functions low (L), medium (M), and high (H), while the output variable has six membership functions (Figure 3). Using the fuzzy rule-based inferencing process described in (Elbeltagi and Hegazy, 2000), a single crisp value for the closeness weight can be calculated between the two facilities based on user input values of WP, SE, and UP. Accordingly, the closeness weights among facilities become an integral part of the site objective function that is described in the following subsection.

Layout optimization

The process of placing temporary facilities on site uses genetic algorithms (GAs) as a non-traditional optimization procedure. Researchers have reported the robustness of GAs and their ability to solve several engineering and construction management problems (e.g. Feng *et al.*, 1997; Li and Love, 1998). Background material on GAs can be found in several references (e.g. Goldberg, 1989). The procedure searches for the optimum location reference of each non-fixed facility, so that closeness relationships may be optimally maintained. As shown in Figure 4, the gene structure has been set as a string of elements, each corresponds to the location reference of a non-fixed facility, and the gene length equals the number of non-fixed facilities to be placed on the site. A representative score for the total travel distance associated with a layout is calculated based on the *dij* distances among the facilities (Figure 1), as follows.

$$\text{Objective function} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} d_{ij} R_{ij} \qquad (3)$$

where R_{ij} is the closeness weight value between facilities i and j, and n is the total number of facilities (fixed + non-fixed). Equation 3, as such, becomes the objective function to be minimized in the proposed model.

Prototype and a case study

The proposed schedule-dependent site layout planning model was implemented on a commercial spreadsheet program to simplify its implementation and automate the system. Visual Basic for Applications (VBA) macros were used to implement all components including the knowledge base, the fuzzy logic, and the GA optimization components in an integrated and automated manner. Also, other macro programs were used to link the layout planning system and a widely used scheduling software (Microsoft Project™ 1998), thus establishing a direct link to the project schedule. After implementation, testing was carried out on various hypothetical examples. Afterwards, the system was tried with actual case study projects to verify its wide applicability. A challenging case study is presented in the following section to demonstrate the system capabilities.

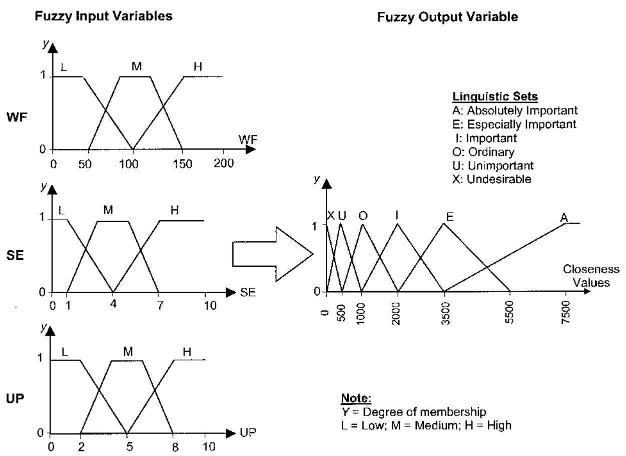

Figure 3 Fuzzy sets of the inputs and output variables

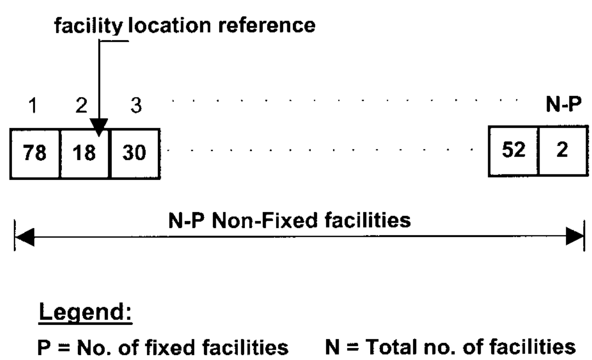

Figure 4 Gene formation

Project challenges

The case study deals with a project constructed in Mansoura, Egypt, involving: (1) a two-storey community centre (the main building); (2) a gymnasium; (3) a cafeteria; (4) a service building; (5) two swimming pools; and (6) power-room/fence/two-gates with attached utilities. The construction site area is 18 700 m^2 (170 m × 110 m). Figure 5 shows the general site plan with a layout of the buildings to be constructed.

At the time of applying the prototype to this project (autumn of 1999), construction was about 50% complete. The project at that time was experiencing some difficulties related mainly to lack of productivity, a disorganized site, and material handling problems. Originally no formal site layout plan was made for the site, and the consultant depended mainly on the general contractor's experience in organizing the site. The abundant site space gave the consultant and the contractor a mistaken impression that the site is spacious and that there was no need to spend time or money on planning the temporary facilities. The buildings to be constructed were scattered in various locations within the site, and the contractor formed material storage areas around each building perceivably to satisfy their individual needs. However, this resulted in excessive material waste, extra material handling costs, and less maneuvrability within the site. The main activities affected were the foundation piles in the main building and the swimming pools, since piling activities needed extra space for the piles, steel cages, and the piling equipment. Problems were also experienced related to crew movements and safety conditions.

After discussing such problems with the consultant and the contractor, it was decided to experiment with the prototype to investigate three aspects, which will be discussed in the next section:

1. the ability of the prototype to divide the site and the facilities into small grid units that can take irregular shapes;
2. the ability of the prototype to generate an initial layout that could have circumvented some of the experienced problems along the schedule development; and
3. the usability of the prototype to generate a modified layout in account of the actual work done on site.

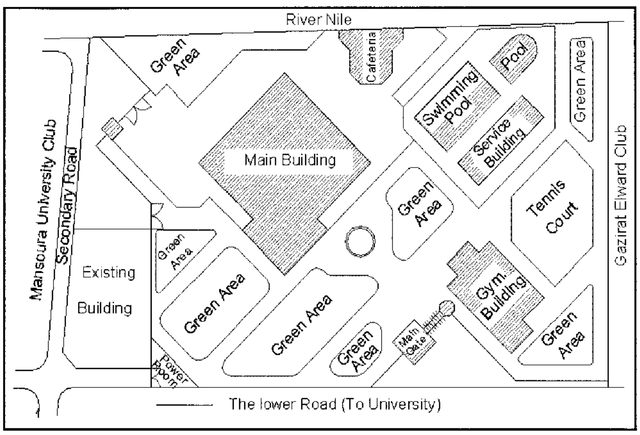

Figure 5 Case study project

Layout optimization

Based on the project information obtained from the consultant and the contractor, the prototype was used to generate an initial site layout plan. First, the necessary temporary facilities and their areas were identified through the knowledge-based module, and were confirmed by the consultant. Accordingly, the site unit area was calculated as 25 m^2, which represents the GCD of all facilities' areas.

A detailed schedule of the activities involved in the project was obtained. The schedule involves 121 activities, grouped by building types, as shown in Figure 6. After defining the temporary facilities, the prototype automatically activated the schedule to assign the identified temporary facilities to the various activities, using the software features. Once this was done, a list of the temporary facilities and their expected service times on the project became available, as shown in Figure 7.

The next step was to map the irregular site shape on the prototype. Given a grid unit area of 25 m^2, the site was represented by spreadsheet cells, each cell representing one grid unit. Using coloured cells, the site was drawn on the spreadsheet as in Figure 8, showing the fixed locations of the buildings that will be constructed on the site, the access roads, and the site gates. The irregular shapes demonstrate the flexibility of the prototype to model any site and facilities.

Knowing the service time for each temporary facility, the choice was made of having three layout intervals, each covering one third of the construction period, as shown in Figure 6. Accordingly, the prototype automatically provided a list of the facilities that will be used in each layout interval (using Eq. 2). The facilities needed for the first layout are shown in Figure 9.

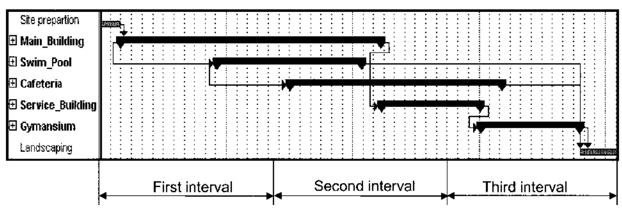

Figure 6 Case study project scheduling

				Desired arrangement		Facility type	Service time	
Code	Name	Size(m2)	Units*	Max. Units / Width	Arrangement**	Fixed (Fix=1, Non=0)	Start Date	Finish Date
1	Main Building	1600	64			1	2/26/96	3/22/98
2	Road1	1050	42			1	1/1/96	2/6/00
3	Gymnasium & Gate	850	34			1	1/4/99	10/17/99
4	Road2	750	30			1	1/1/96	2/6/00
5	Pool1	375	15			1	12/2/96	1/25/98
6	Service Building	300	12			1	3/23/98	1/3/99
7	Cafeteria	275	11			1	6/30/97	3/7/99
8	Pool2	150	6			1	12/2/96	1/25/98
9	Pipying yard	80	3			1	8/4/97	10/3/99
10	Carpentry shop	60	3			1	5/26/97	8/8/99
11	Gate1	50	2			1	1/1/96	2/6/00
12	Gate2	50	2			1	1/1/96	2/6/00
13	Information and guard	40	2			1	1/1/96	2/6/00
14	Long term laydown yard	500	20	4	0	0	1/1/96	2/6/00
15	Scaffold storage yard	300	12	3	1	0	1/1/96	2/6/00
16	Cement warehouse	250	10	4	0	0	1/1/96	2/6/00
17	Material warehouse	200	8	2	0	0	1/1/96	3/22/98
18	Rebar fab/storage yard	160	7	2	0	0	3/4/96	7/4/99
19	Parking lot	90	4	1	0	0	1/1/96	2/6/00
20	Maintenance shop	80	3	1	1	0	2/26/96	11/9/97
21	Toilet and rest area	80	3	1	0	0	1/1/96	2/6/00
22	Machine room	40	2	1	1	0	1/1/96	2/6/00
23	Offices	40	2	1	0	0	1/1/96	2/6/00
24	Tank	40	2	2	1	0	1/1/96	2/6/00
25	First aid	40	2	1	1	0	1/1/96	2/6/00
26	Sampling/Testing lab	20	1	1	0	0	3/4/96	3/22/98
27	Welding Shop	20	1	1	1	0	3/4/96	9/28/97

* Number of units = facility size / GCD = size / 25
** 0 = horizontal, 1 = vertical

Figure 7 Final list of facilities

Before starting with the first layout, the facilities' closeness weights were determined using the fuzzy logic module. Between each pair of facilities, numeric values of the work flow, safety concerns, and user preference were entered. Accordingly, the prototype automatically calculated a crisp value for the closeness weight between the two facilities. Note that, due to the

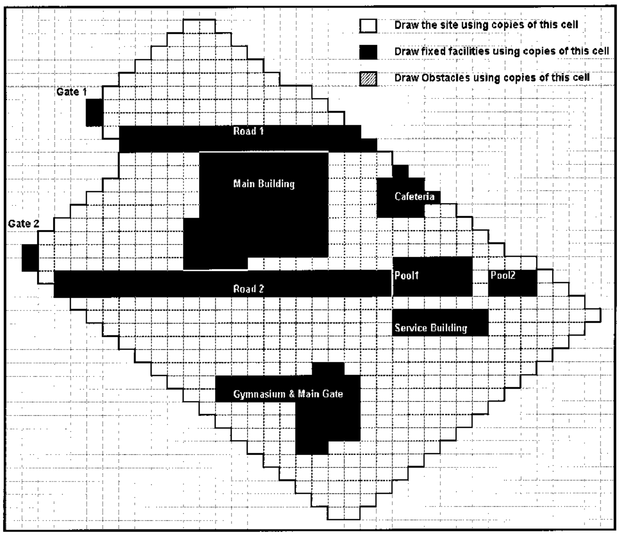

Figure 8 Site representation with fixed facilities preset

At the current time 01/01/96 :

A number of 0 facility(ies) will exit from the layout.

A number of 22 facility(ies) will enter the layout.
1 Main Building .
2 Road1 .
4 Road2 .
5 Pool1 .
8 Pool2 .
11 Gate1 .
12 Gate2 .
13 Information and guard .
14 Long term laydown yard .
15 Scaffold storage yard .
16 Cement warehouse .
17 Material warehouse .
18 Rebar fab/storage yard .
19 Parking lot .
20 Maintenance shop .
21 Toilet and rest area .
22 Machine room .
23 Offices .
24 Tank .
25 First aid .
26 Sampling/Testing lab .
27 Welding Shop .

A number of 0 facility(ies) will be considered fixed.

Figure 9 List of facilities for the first layout interval predetermined positions of the fixed facilities, the closeness weights among them are zeros.

Having the facilities for each layout interval defined and their relationships determined, the optimization process started using GAs. Accordingly, the prototype came up with the optimum site layout for the first layout interval shown in Figure 10, given a minimum representative score of 48 855 348.

In the second scheduling period, facilities that ended in the previous interval were not considered for this interval and their site areas were used to accommodate other facilities. Also, the facilities laid out in the pervious interval and still needed for this interval were considered as fixed facilities. The full list of facilities for this layout interval is shown in Figure 11. For this interval, the main building had been completed and it could be used to accommodate temporary facilities, namely the piping yard and the carpentry shop, as its area can accommodate the two facilities (shown in Figures 10 and 12). The final optimum solution for this interval is that in Figure 12.

The optimum layout for the third interval was obtained similarly. Then the results of the site layout planning for the three intervals were shown to the consultant and the contractor, and favourable comments were received. The flexibility of the system was a major point of appeal. While processing time was longer than expected, particularly for the first site layout (2 hours on a Pentium 450 MHz personal computer), the system was able to determine layout plans that experts agreed with and did not wish to modify.

The second experiment conducted with the prototype was to try improving an existing site layout or optimally to place a new facility in a given layout. However, this is merely a special and much simpler

At the current time 14/05/97 :

A number of 0 facility(ies) will exit from the layout.

A number of 4 facility(ies) will enter the layout.
6 Change Building .
7 Cafeteria .
9 Piping yard .
10 Carpentry shop .

A number of 22 facility(ies) will be considered fixed.
1 Main Building .
2 Road1 .
4 Road2 .
5 Pool1 .
8 Pool2 .
11 Gate1 .
12 Gate2 .
13 Information and guard .
14 Long term laydown yard .
15 Scaffold storage yard .
16 Cement warehouse .
17 Material warehouse .
18 Rebar fab/storage yard .
19 Parking lot .
20 Maintenance shop .
21 Toilet and rest area .
22 Machine room .
23 Offices .
24 Tank .
25 First aid .
26 Sampling/Testing lab .
27 Welding Shop .

Figure 11 List of facilities for the second layout interval

case application. Only the storage space was to be relocated, while keeping all other facilities fixed in place. Accordingly, the prototype was used to model all the facilities other than the storage space as fixed facilities on the site map. The optimization was then conducted having only one temporary facility to optimally re-

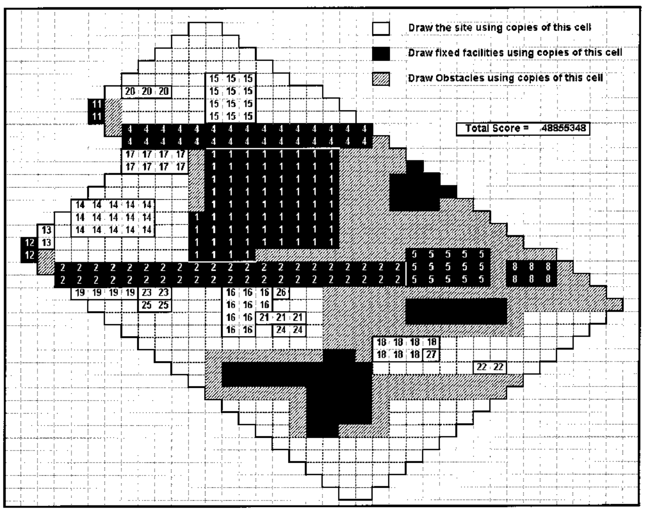

Figure 10 Optimum solution of the first layout interval

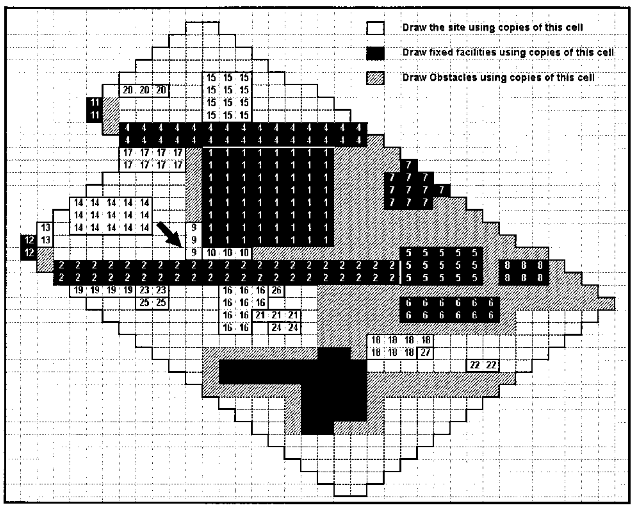

Figure 12 Optimum layout with part of the constructed space accommodating temporary facilities

allocate the storage space. This type of use is important when a crane is being located on the site.

The schedule-dependent approach for site planning presented in this paper is simple and practical, yet it can be expanded to consider the actual profile of material use within the construction activities. Also it can be linked to a geographic information system to automate the mapping of the site and the identification of site characteristics.

Summary and conclusions

A practical system has been presented for evolving a site layout plan as the project schedule progresses. The proposed model encompasses: (1) flexible representation of the site, facilities, and placement options; (2) a large knowledge-base for facility identification and area determination; (3) fuzzy-logic assessment of the vagueness in the facilities' inter-relationships; (4) a genetic algorithm search for an optimal layout solution; and (5) direct integration with a scheduling tool to determine the schedule-dependent site needs. The current layout methodology improves the site planning efficiency by the integration of the entire site layout planning tasks into a single environment. This capability not only speeds up the planning process but also ensures data integrity and accuracy. In addition, the integration of the schedule and layout information makes it easy for the project manager to track and update the layout of the site. Two important features were considered in the developed model that might help project managers in laying out restricted site space: (i) the use of the constructed space to place a temporary facility; and (ii) the use of the site space to accommodate different facilities at different times. A practical case study project has demonstrated the capabilities of the proposed system.

References

Cheng, M. Y. (1992) Automated site layout of temporary construction facilities using geographic information systems (GIS). Ph.D. thesis, The University of Texas at Austin.

Dweiri, F. and Meier, F. A. (1996) Application of fuzzy decision-making in facilities layout planning. *International Journal of Production Research*, **34**(11), 3207–25.

Elbeltagi, E. and Hegazy, T. (2000) A hybrid AI-based system for site layout planning in construction. *Computer-Aided Civil and Infrastructure Engineering*, **16**(2), 79–93.

Feng, C.-W., Liang L., and Burns, S. A. (1997) Using genetic algorithms to solve the construction time–cost trade-off problems. *Journal of Computing in Civil Engineering ASCE*, **11**(3), 184–9.

Goldberg, D. E. (1989) *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison-Wesley, Reading, MA.

ILO (1992) *Safety and Health in Construction*, International Labor Office, Geneva.

Li, H., and Love, P. E. D. (1998) Site-level facilities layout using genetic algorithms. *Journal of Computing in Civil Engineering ASCE*, **12**(4), 227–31.

Obayashi Corporation (1975) *Company Handbook for Temporary Facility Site Layout*, Obayashi Corporation, Japan.

Popescu, C. (1981) Managing temporary facilities for large projects. In *Proceeding of the Project Management Institute and INTERNET Joint Symposium*, Boston, MA, 28–30 September, pp. 170–3.

Rad, P. F., and James, B. M. (1983) The layout of temporary construction facilities. *Cost Engineering*, **25**(2), 19–26.

Rodriguez-Ramos, W. E. (1982) Quantitative techniques for construction site layout planning. Ph.D. thesis, University of Florida.

Ross, T. J. (1995) *Fuzzy Logic with Engineering Applications*, McGraw-Hill, New York.

Tommelein, I. D. (1989) SightPlan: an expert system that models and augments human decision-making for designing construction site layout. Ph.D. thesis, Stanford University.

Tommelein, I. D., and Zouein, P. P. (1993) Interactive dynamic layout planning. *Journal of Construction Engineering and Management ASCE*, **119**(2), 266–87.

Warszawski, A. and Peer, S. (1973) Optimizing the location of facilities on a building site. *Operational Research Quarterly*, **24**(1), 35–44.

Yeh, I. C. (1995) Construction site layout using annealed neural network. *Journal of Computing in Civil Engineering ASCE*, **9**(3), 201–8.

Zadeh, L. A. (1965) Fuzzy sets. *Information and Control*, **118**, 338–53.

Zouein, P. P. and Tommelein, I. D. (1999) Dynamic layout planning using a hybrid incremental solution method. *Journal of Construction Engineering and Management ASCE*, **125**(6), 400–8.