Site Layout Planning using Nonstructural Fuzzy Decision Support System

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Abstract: Site layout planning can affect productivity and is crucial to project success. However, as construction is heterogeneous in the nature of its organizations, project designs, time constraints, environmental effects, etc., site layout planning for each project becomes unique. Affected by many uncertainties (variables) and variations, site layout planning is a typical multiobjective problem. To facilitate the decision-making process for these problems, a nonstructural fuzzy decision support system (NSFDSS) is proposed. NSFDSS integrates both experts' judgment and computer decision modeling, making it suitable for the appraisal of complicated construction problems. The system allows assessments based on pairwise comparisons of alternatives using semantic operators that can provide a reliable assessment result even under the condition of insufficient precise information.

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Introduction

Problem solving requires representing the problem in a language that problem solvers can understand and reason about (Li and Love 1998). However, solutions of most construction problems rely on experiential (empirical) knowledge. Li (1994) pinpointed that experiential knowledge is not codified in books and is weakly organized in memory. Furthermore, conflicting objectives and the uniqueness of construction projects make the problems difficult to conceptualize and define. As a result, project managers tend to perceive construction problems from various facets, and develop the interpretations and representational structures with an emphasis on different aspects based on heuristic judgments. As project managers are responsible for the overall success of delivering the owner's physical development within the constraints of cost, schedule, quality, and safety requirements (Edum-Fotwe and McCaffer 2000), to maintain their professional competency and enhance the quality of problem solving, decision aiding is necessary.

As defined by Roy (1996), decision aiding is the activity of the person who, through the use of explicit but not necessarily completely formalized models, helps obtain elements of responses to the questions posed by a stakeholder of a decision process. Real-world problems are rarely monocriterion based, and will incorporate a variety of criteria. Multicriteria decision aids aim to give the decision maker some tools to solve a decision problem where several, often contradictory, points of view must be taken into account (Vincke 1992).

Site layout planning, a routine task for many site staff in both precontract and postcontract stages, is one of the typical multicriteria and multiobjective construction problems. It is very much influenced by types of construction, density of development, and whether the site is level or sloping (Burges and White 1979). It also plays an important part in construction planning, which significantly affects site performance (Foster 1986; Chudley 1987; Tommelein et al. 1992a; Wrennall and Quarterman 1994; Cheng and O'Connor 1996). Although site layout planning is complex and comprises a large variety of factors such as site locations, project natures, etc., it mainly depends on planners' experience and common sense. The purpose of this paper is to present a problem-solving technique that integrates both expert judgments and a decision-aiding model to identify the planning sequence of temporary facilities in site layout planning. A decision-setting

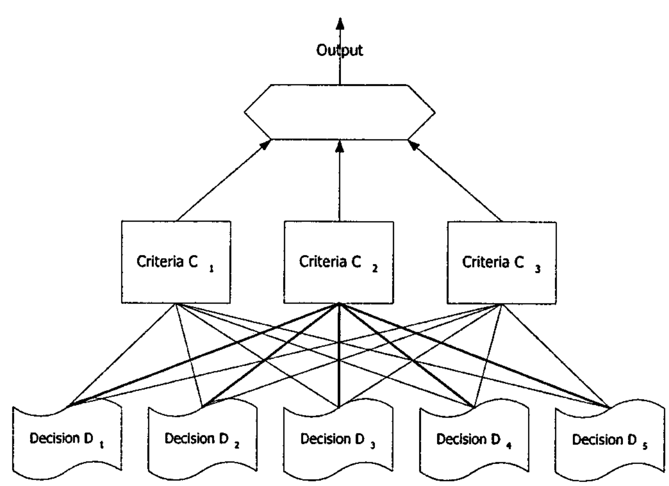

Fig. 1. Decomposition of multicriterion problem

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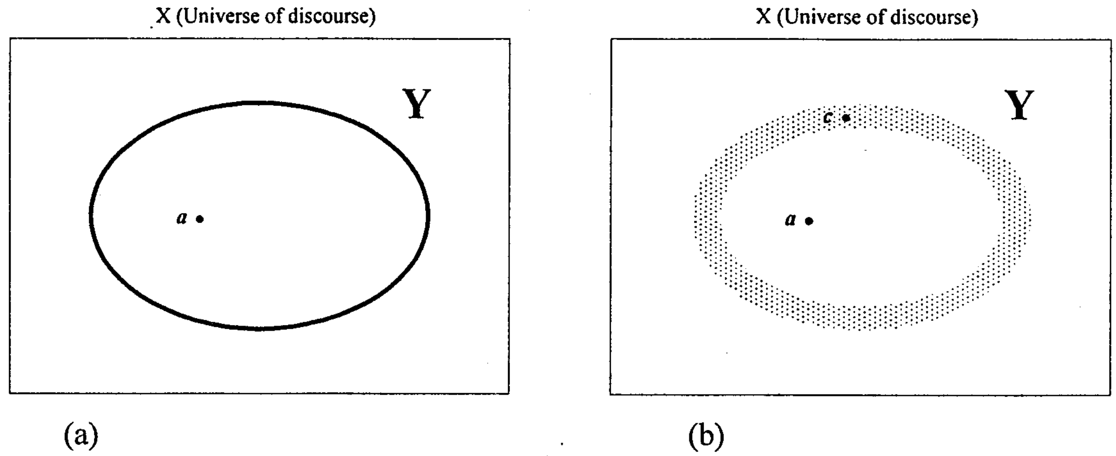

Fig. 2. Diagrammatic comparison of crisp set and fuzzy set: (a) crisp set A boundary; (b) fuzzy set A boundary

model—the nonstructural fuzzy decision support system (NSFDSS) (Chen 1998)—is applied to the priority setting process. This model delivers a method of ranking all elements on the basis of agreed-upon criteria, which facilitates resolving complicated multicriteria problems.

Significance of Site Layout Planning

Site layout shows the relationship of the proposed site with its surroundings with respect to communication, approaches, and existing facilities (Hans 1984). Good site layout planning assists in minimizing the traveling time and movement costs of plant, labor, and materials, activity interference during construction work, and site accidents, and ensures that work on buildings and other construction positions is not impeded by the thoughtless storage of materials on these locations (Hans 1984; Foster 1986; Tommelein et al. 1992a). Site layout can thus either enhance or adversely affect construction productivity and progress (Hans 1984; Foster 1986; Tommelein et al. 1992b; Cheng and O'Connor 1993).

Nonstructural Fuzzy Decision Support System

There are three steps in using the NSFDSS—decomposition, comparative judgment, and synthesis of priorities. First, decomposition structures a problem into elements of different levels, each independent of those on successive levels, working downward from the goal on the top through criteria bearing to the goal on the second level, and then to subcriteria on the third level, and so on, working from the general (and sometimes uncertain) to the more specific at the lower levels (Fig. 1).

Comparative judgment is applied to construct pairwise comparisons of the relative importance of elements on some given levels with respect to the shared criterion or property on the level above, giving rise to the corresponding matrix. The third step is the synthesis of priorities. In NSFDSS, priorities are synthesized from the second level down by multiplying local priorities with the priority of their corresponding criterion on the level above, and weighting each element on a level according to the criteria it affects (the second-level elements are multiplied by unity, the weight of the single top-level goal). This gives the composite or global priority of that element, which is then used to weight the local priorities of the elements on the level below, and so on, repeating this procedure to the bottom level.

In addition to the above principles, Chen (1998) incorporated the relative fuzzy set theory to strengthen the model by integrating the underlying power of fuzzy set theory that uses linguistic variables, rather than quantitative variables, to represent imprecise concepts. Fuzzy logic was first introduced by Zadeh (1965), who laid down the following definition for fuzzy sets: ''*A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function which assigns to each object a grade of membership ranging between zero and one*.''

The beauty of a fuzzy set is its ability in handling classes of objects, which do not have precisely defined criteria of membership. Such classes of objects do not have a clear boundary of belonging, as in the traditional sense of set theory (crisp set). The concepts of the traditional crisp set and fuzzy set are compared diagrammatically in Fig. 2.

In Fig. 2, the belonging of ''a'' to Y is clearly defined by the sharp boundary of the crisp set A. In the fuzzy environment, however, the belonging of ''c'' to A is not certain nor clearly defined, where c is in the region of the ''blurred'' boundaries. The

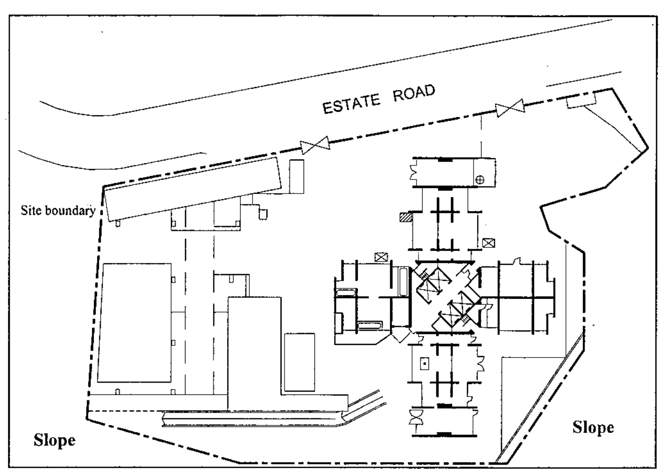

Fig. 3. Site layout for residential development in urban area

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Table 1. Checklist of Decision Criteria for Case Study

	Part I: Factors checklist		Part II: Project related details	Part III: Impact on planning	
Category	Factor Number	Factor Description	Detail Description	Significant	Not Significant
Physical features					
External	A1	Proximity of highways, roads, streets, overpasses	Main road in front of the site		
	A2	Possibility of upgrading, widening adjoining roads or streets, and future impact on the site	As checked with relevant departments, no future road work will involve		
	A3	Site access limitation	No limitation, but parking may cause trouble during peak hour, from 8.00 a.m. to 10:30 a.m.		
	A4	Availability to the site of power, water, gas, sewers, roads, rail and related easements	Details as shown in site investigation report ref.: SIR997		
	A5	Neighbors, adjoining land	Site surrounded by existing 4 blocks of public housing		
	A6	Storm water runoff to or from adjoining properties	N/A		
	A7	Proximity of river, creek, bridges; flood plain situation	N/A		
On site	B1	Topography: lay-of-the-land; high and low points; natural drainage	No obvious level difference on site, as detailed in site investigation report ref.: SIR997		
	B2	Soil conditions	Good soil condition, as detailed in site investigation report ref.: SIR997		
	B3	Existing buildings and foundations: size, condition	N/A		
	B4	Site space	Generally enough space for planning		
	B5	Existing utilities, substations, water tower, etc.	No existing utility underground, as detailed in site investigation report ref.: SIR997		
	B6	Proposed buildings: shape, size, height	3 harmony blocks of 31 storeys, size 53×48 m each block		
	B7	Nature, weight and quantity of material	Precast facades involved		
Intangible factors					
External	C1	Environment Protection Department's requirements	Air, sound, and water control is required		
	C2	Easement restrictions	N/A		
	C3	Police and fire protection	N/A		
	C4	Historical, archeological	N/A		
On site	D1	Appearance, landscaping, image	N/A		
	D2	Personnel considerations—benefits, recreation	Latrine only		
	D3	Managerial philosophy	N/A		
	D4	Cost to set up	Initial set-up cost will affect tender price and long term running cost		
	D5	Floor cycle of structural frame	5 days cycle is proposed		
	D6	Security	Employ security guard services		
	D7	Safety	Should comply with current legislation		

Note: Project: Proposed residential blocks in urban areas. Ref: R9654/Y2000; Date: 6-Sept 2000; Prepared by: Project Manager and Planning Engineer, ABC Construction Company Ltd.

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Table 2. Selected Decision Criteria (C_n) for Case Study

Decision criteria	Description
C_1	Building shape, size, and height
C_2	Cost of mechanical plant
C_3	Environmental Protection Department's requirements
C_4	Floor construction cycle of structural frame
C_5	Roads proximity
C_6	Safety
C_7	Site access limitation
C_8	Site space
C_9	Weight and quantity of material

sense of belonging of c to A in the latter case is therefore a continuum of grades of membership (Zadeh 1965). This concept of belonging, as stated by Zadeh (1965), provides a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria of class membership.

In NSFDSS, fuzzy sets provide the ability to model the ambiguity and impreciseness of human classification in dealing with vague words and expressions for comparison and expert judgments. It is used to describe vague terms, such as ''the same,'' ''marginally different,'' ''significantly different,'' and so on. Incorporating the fuzzy set theory, NSFDSS possesses the following strengths:

- Breaking the problem down into many pairwise comparisons among the alternatives can reduce the difficulty of making a judgment;
- Applying logical consistency checks to the pairwise comparison and the consideration of the comparison's magnitude can enhance the accuracy of problem solving; and
- Using semantic operators that integrate the strength of fuzzy set theory further enhances the analysis of expert judgments.

NSFDSS is similar to the analytical hierarchy process (AHP), a widely used decision-making operational research technique (Saaty 1994; Shen et al. 1998; Alhazmi and McCaffer 2000; Fong and Choi 2000). The similarity of the two is that both of them apply the three basic principles as mentioned above, then break down the problem into multilevels and compare each pair, one by one. They simplify the comparison of multicriteria problems. Also, both offer consistency checks to the pairwise comparison matrix, ensuring the rationalization of the final decision. However, in the pairwise comparison, NSFDSS is obviously superior to AHP by adopting ''logical checking,'' which only consists of three options:

1. ''D1'' is better than ''D2;''
2. D1 is equally important as D2; and
3. D1 is worse than D2.

This approach greatly simplifies the nine levels of comparison in AHP. During the consistency check, it is assumed that the upper rows of the matrix are more reliable than the lower rows and the system will reset the values of the lower rows if inconsistencies are found. In other words, the earlier comparisons made are assumed to be more accurate, which resembles human beings' cognitive behavior. AHP gives a consistency index that has an upper limit of 0.1; if that is exceeded, users should check the inputs manually and restructure the matrix, and run the procedures again. However, NSFDSS has another procedure of ''priority ordering'' to measure the difference in magnitude of the first ordered decision and others. It has 21 semantic operators, compared to nine of AHP.

Table 3. General Classification of Temporary Facilities (Hans 1984; Cormican 1985; Foster 1986; Chudley 1987; Foster 1989; Calvert et al. 1995)

Temporary facilities	Description
Access road and exit	Needs vary with the type of project and the stage of the job. It will normally be linked with the plan of construction and in some cases may actually control the progress of construction. Ideally, short direct routes and one-way traffic are encouraged.
Location of plant and equipment	Choice of the major items of the plant is of real consequence on most sites. Correctly chosen and well operated and maintained equipment enables a construction project to be completed efficiently and economically.
Material storage and handling area	Areas must be set aside for the storage and handing of material. The objective here is to minimize waste and losses arising from careless handling, bad storage, or theft, and to reduce costs by obviating double handling or unnecessary movement.
Site accommodations and welfare facilities	Consideration should always be given to the possibility of ensuring that the site accommodations are kept at a suitable distance from the construction work and are in such a position to enable the site staff to conduct their duties (welfare facilities also)
Temporary services	This includes water supply, electricity supply, gas, telephones, and drainage—the requirements of which may vary between different projects in Hong Kong.
Workshop position	Position should be indicated to enable the site supervisor to arrange for the erection of the following types of workshops: (1) fitter's shops and work area; (2) joinery shop and machinery area; (3) reinforcement and bar bending areas; and (4) concrete mixing.

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Table 4. Selected Temporary Facilities (TF_n) for Case Study

Temporary facilities	Description
TF_1	Access road
TF_2	Material hoist
TF_3	Material storage area
TF_4	Precast units storage area
TF_5	Read-mix concrete discharge point
TF_6	Refuse chute and discharge point
TF_7	Site accommodations
TF_8	Steel bare bending yard
TF_9	Tower crane

Decision Criteria and Site Facilities Adopted in Site Layout Planning

Although each site layout is unique, site layout planning can be resolved into a repetitive selection-evaluation process. Several analysis techniques can be used for the selection process—for example, the dominant factor analysis and Parker's judgment technique, which can be used to screen out available decisions in choosing facilities, and identify key decision factors and locations for each particular facility. NSFDSS can provide an additional function—synthesizing the priorities among the decisions. The following case study illustrates the application of NSFDSS in site layout planning.

Case Study: Residential Development Site in Urban Area

This case study demonstrates how the decision-aid model is applied to an actual construction project in Hong Kong to improve the site layout planning process. The subject is a residential development site in the urban area, consisting of one 30-story residential block with a height of about 87 m, a site area of 2,890 m^2, a total gross floor area of 32,076 m^2, and an overall construction period of 100 weeks. The construction site also accommodates other facility buildings, which will be sublet in other contracts; however, site coordination is necessary among various contractors. Slope treatment will be carried out by the Highway Department, one of the government departments, where adequate access should be provided. Hoarding layouts and the position of the site entrance are prescribed by the architect. The construction site layout is shown schematically in Fig. 3.

In allocating the facilities for the project, the following constraints have been identified:

1. Narrow site access. This is a typical problem of confined sites in Hong Kong, in which space for vehicular movement needs to be minimized to provide sufficient areas for site fabrication and storage yards.
2. Prescribed space for concrete placing and storage of precast units. Concreting and fixing of precast units are the key site operations for public housing construction in Hong Kong. Loading areas that are reachable by tower cranes have to be allocated for handling material delivery.

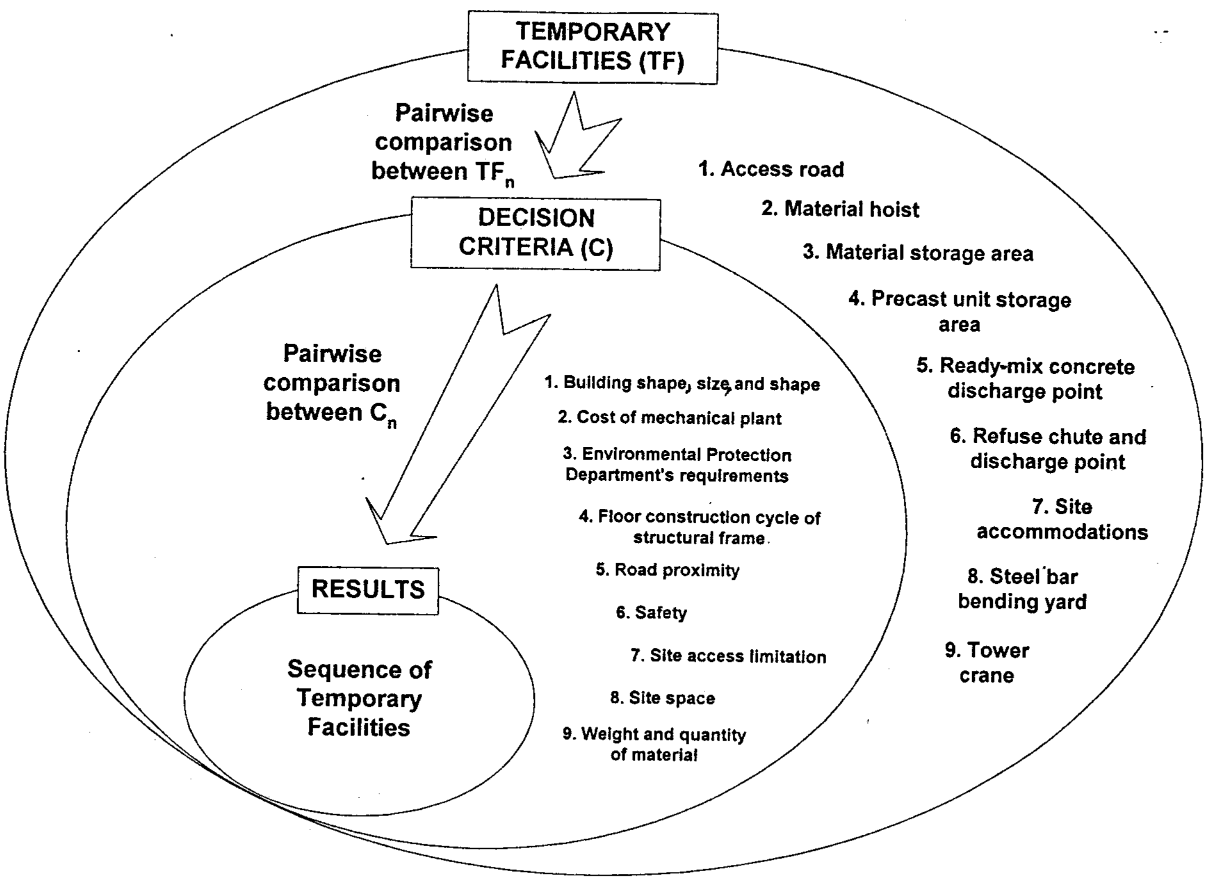

Fig. 4. Overall structure of site layout problem

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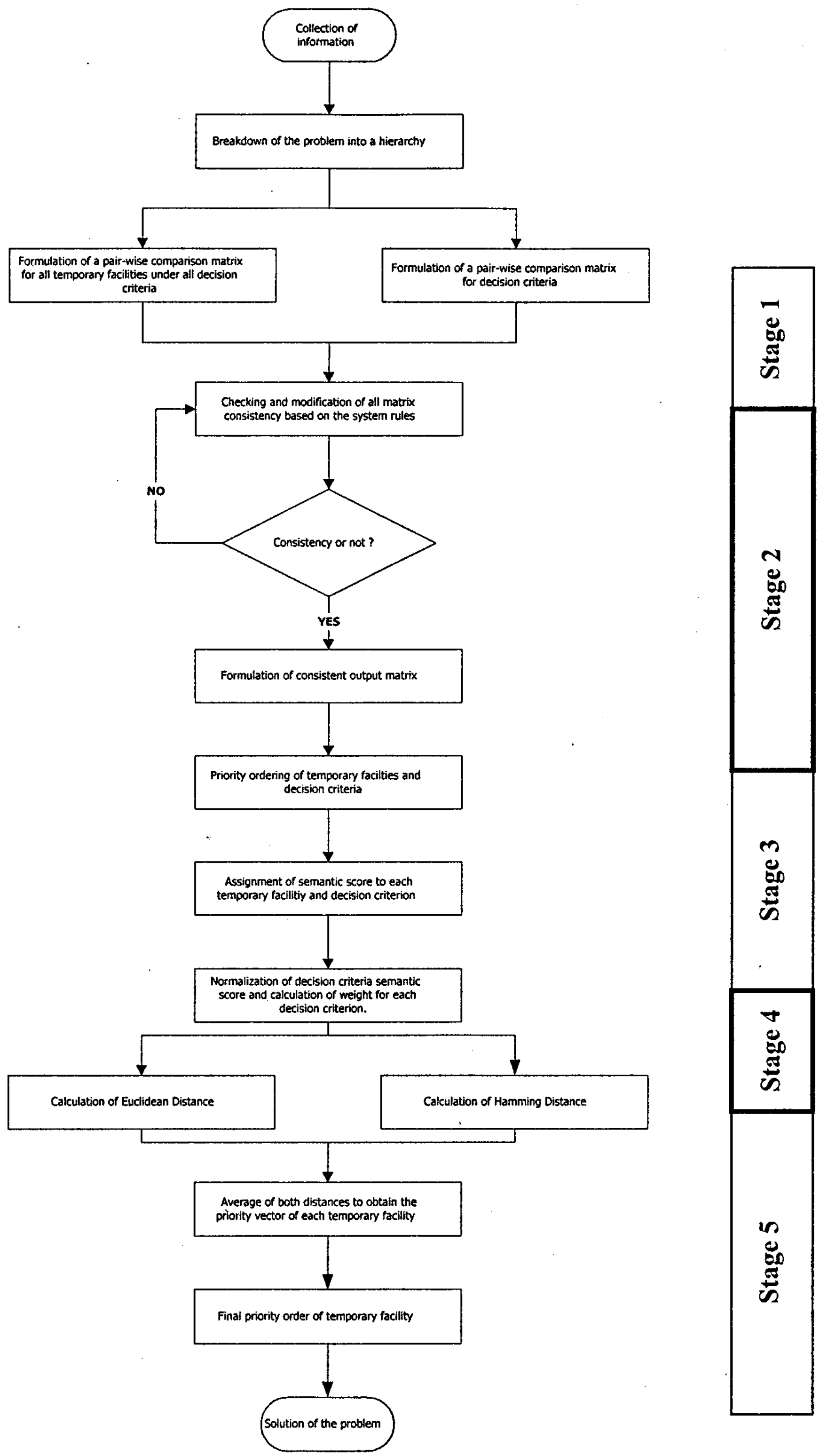

Fig. 5. Flowchart of nonstructural fuzzy decision support system

3. Three-dimensional site layout planning. Finishing/decorative works will be started when concrete frame construction has reached certain levels. Delivery and storage of finishing materials and disposal of debris at the upper levels further complicate site layout planning and impose additional constraints on site space. Proper positioning of material hoists and refuse chutes is required to avoid ''bottlenecking'' site traffic.

The above, coupled with the time constraint for the project planning exercise, make it impossible to conduct a detailed study before initialization of the work. Further, the available site information is always imprecise and fuzzy in nature, based upon which

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Table 5. Input Evaluation Matrix Form

For C_1	Input values					
TF	1	2	3	4	5	6
1	0.5	1	1	1	0.5	0.5
2	—	0.5	0.5	0.5	0	0
3	—	—	0.5	0.5	0	0
4	—	—	—	0.5	0	0
5	—	—	—	—	0.5	1
6	—	—	—	—	—	0.5

Note: 0 = one is less important than the other; 0.5 = both are equally important; 1 = one is better than the other.

project engineers need to make planning decisions. This paper, thus, introduces NSFDSS, which may help planning engineers arrive at a rational decision.

Decision Criteria

A multicriteria problem is one having a set of actions and a consistent family of criteria. Decision makers are required to determine the course of action considered to be the best with respect to each criterion by prioritizing the actions and solutions.

To systematically evaluate these decision criteria, the concept of dominant factor analysis (Wrennall and Quarterman 1994) is adopted. The dominant factor analysis summarizes site physical and nonphysical features to produce a checklist that embraces all of the possible criteria. Then a very experienced planner is required to check those factors having a significant impact on the decision. The process asks for decision-makers' profound knowledge on the subject. An example of the checklist for facility layout planning is shown in Table 1. Similarly, by adopting the dominant factor analysis, nine key significant factors have been analyzed and selected for the case project (Table 2).

Temporary Facilities in Site Layout Planning

All space-planning problems consist of a set of activities to be located and a space in which to locate them (Liggett 2000). Site layout planning consists of identifying the facilities needed to support construction operations, determining their size and shape, and positioning them within the boundaries of the site (Tommelein et al. 1992a). After summarizing previous studies on site layout (Hans 1984; Cormican 1985; Foster 1986, 1989; Chudley 1987; Calvert et al. 1995), temporary facilities are classified into six important categories, which are tabulated in Table 3. However, as each construction site has its own peculiarities, the list is not exhaustive and the requirements of temporary facilities may differ from one site to another. In our case study, the necessary temporary facilities determined by the project manager are shown in Table 4.

Methodology of Evaluation

The overall structure of the problem is formulated as shown in Fig. 4. Then NSFDSS is applied to systematically evaluate each temporary facility (TF_n) under various decision criteria (C_n). The flowchart of the model is illustrated in Fig. 5.

Stage 1—Pairwise Comparisons

In the process of prioritization, pairwise comparisons are conducted between any two temporary facilities, forming a matrix form shown in Table 5. In this pairwise comparison, there are three scales—better, the same, and worse, as follows (note that the 0, 0.5, and 1 refer to the comparison of x to y). In considering particular decision criteria (C_n), 0 = element X is worse than element Y, 0.5 = the two are the same, and 1 = element X is better than element Y.
The same evaluation is repeated 10 times (nine for comparing the temporary facilities TF_n under each decision criterion C_{1-9} and one for comparing the nine decision criteria).

Stage 2—Consistency Checking

The principle of logical checking of the input matrix is presented in Eqs. (1) and (2). With respect to decision criteria C_n, the matrix of the pairwise comparison of the corresponding element is

$$\mathbf{iE}=\begin{bmatrix} ie_{11}, & ie_{12}, & \ldots, & ie_{1n} \\ ie_{21}, & ie_{22}, & \ldots, & ie_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ ie_{n1}, & ie_{n2}, & \ldots, & ie_{nn} \end{bmatrix} =(ie_{kl});\ k=1,2,\ldots,n;\ l=1,2,\ldots,n \tag{1}$$

where ie_{kl} = logical indicator of pairwise comparison of elements k and l; and n = number of elements to be considered.

The evaluation matrix in Table 5 is transformed into the **iE** form of the output matrix in Table 6. The priority matrix **iE** of the pairwise comparison is derived under the following conditions:

Table 6. **iE** Form of Output Matrix

For C_1	Output values					
TF	1	2	3	4	5	6
1	$ie_{11}=0.5$	$ie_{12}=1$	$ie_{13}=1$	$ie_{14}=1$	$ie_{15}=0.5$	$ie_{16}=0.5$
2	$ie_{21}=0$	$ie_{22}=0.5$	$ie_{23}=0.5$	$ie_{24}=0.5$	$ie_{25}=0$	$ie_{26}=0$
3	$ie_{31}=0$	$ie_{32}=0.5$	$ie_{33}=0.5$	$ie_{34}=0.5$	$ie_{35}=0$	$ie_{36}=0$
4	$ie_{41}=0$	$ie_{42}=0.5$	$ie_{43}=0.5$	$ie_{44}=0.5$	$ie_{45}=0$	$ie_{46}=0$
5	$ie_{51}=0.5$	$ie_{52}=1$	$ie_{53}=1$	$ie_{54}=1$	$ie_{55}=0.5$	$ie_{56}=1$
6	$ie_{61}=0.5$	$ie_{62}=1$	$ie_{63}=1$	$ie_{64}=1$	$ie_{65}=0$	$ie_{66}=0.5$

Note: 0 = method X is worse than method Y; 0.5 = the two methods are the same; 1 = method X is better than method Y.

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For C1

TF	1	2	3	4	5	6	7	8	9	Sum
1	0.5	0	0	0	0.5	0	1	0	0	**2**
2	1	0.5	1	1	1	1	1	1	0	**7.5**
3	1	0	0.5	0.5	0	0	1	0.5	0	**3.5**
4	1	0	0.5	0.5	0	0	1	0.5	0	**3.5**
5	0.5	0	1	1	0.5	0.5	1	1	0	**5.5**
6	1	0	1	1	0.5	0.5	1	1	0	**6**
7	0	0	0	0	0	0	0.5	0	0	**0.5**
8	1	0	0.5	0.5	0	0	1	0.5	0	**3.5**
9	1	1	1	1	1	1	1	1	0.5	**8.5**

For C2

TF	1	2	3	4	5	6	7	8	9	Sum
1	0.5	0	0	0	0	0	0	0	0	**0.5**
2	1	0.5	1	1	1	1	1	1	0	**7.5**
3	1	0	0.5	0.5	0	0	0	0	0	**2**
4	1	0	0.5	0.5	0	0	0	0	0	**2**
5	1	0	1	1	0.5	0	0	0.5	0	**4**
6	1	0	1	1	1	0.5	0.5	1	0	**6**
7	1	0	1	1	1	0.5	0.5	1	0	**6**
8	1	0	1	1	0.5	0	0	0.5	0	**4**
9	1	1	1	1	1	1	1	1	0.5	**8.5**

For C3

TF	1	2	3	4	5	6	7	8	9	Sum
1	0.5	0	1	1	0.5	0	1	0.5	0	**4.5**
2	1	0.5	1	1	1	0.5	1	1	0.5	**7.5**
3	0	0	0.5	0.5	0	0	1	0	0	**2**
4	0	0	0.5	0.5	0	0	1	0	0	**2**
5	0.5	0	1	1	0.5	0	1	1	0	**5**
6	1	0.5	1	1	1	0.5	1	1	0.5	**7.5**
7	0	0	0	0	0	0	0.5	0	0	**0.5**
8	0.5	0	1	1	0	0	1	0.5	0	**4**
9	1	0.5	1	1	1	0.5	1	1	0.5	**7.5**

For C4

TF	1	2	3	4	5	6	7	8	9	Sum
1	0.5	0	0.5	0.5	0.5	1	1	0.5	0	**4.5**
2	1	0.5	1	1	1	1	1	1	0	**7.5**
3	0.5	0	0.5	0.5	0	1	1	0	0	**3.5**
4	0.5	0	0.5	0.5	0	1	1	0	0	**3.5**
5	0.5	0	1	1	0.5	1	1	0.5	0	**5.5**
6	0	0	0	0	0	0.5	0	0	0	**0.5**
7	0	0	0	0	0	1	0.5	0	0	**1.5**
8	0.5	0	1	1	0.5	1	1	0.5	0	**5.5**
9	1	1	1	1	1	1	1	1	0.5	**8.5**

For C5

TF	1	2	3	4	5	6	7	8	9	Sum
1	0.5	1	0.5	0.5	0.5	1	1	1	1	**7**
2	0	0.5	0.5	0.5	0.5	0.5	1	1	0.5	**5**
3	0.5	0.5	0.5	0.5	0.5	0.5	1	0.5	0	**4.5**
4	0.5	0.5	0.5	0.5	0.5	0.5	1	0.5	0	**4.5**
5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.5	0	**4.5**
6	0	0.5	0.5	0.5	0.5	0.5	1	0.5	0	**4**
7	0	0	0	0	0	0	0.5	0	0	**0.5**
8	0	0	0.5	0.5	0.5	0.5	1	0.5	0	**3.5**
9	0	0.5	1	1	1	1	1	1	0.5	**7**

For C6

TF	1	2	3	4	5	6	7	8	9	Sum
1	0.5	0.5	1	1	1	0.5	0.5	1	0	**6**
2	0.5	0.5	1	1	1	0.5	1	1	0.5	**7**
3	0	0	0.5	0.5	0	0	0	0	0	**1**
4	0	0	0.5	0.5	0	0	0	0	0	**1**
5	0	0	1	1	0.5	0	0.5	0.5	0	**3.5**
6	0.5	0.5	1	1	1	0.5	1	1	0.5	**7**
7	0.5	0	1	1	0.5	0	0.5	0.5	0	**4**
8	0	0	1	1	0.5	0	0.5	0.5	0	**3.5**
9	1	0.5	1	1	1	0.5	1	1	0.5	**7.5**

For C7

TF	1	2	3	4	5	6	7	8	9	Sum
1	0.5	1	1	1	1	1	1	1	1	**8.5**
2	0	0.5	1	1	0.5	1	1	1	1	**7**
3	0	0	0.5	0.5	0	0.5	1	0.5	0	**3**
4	0	0	0.5	0.5	0	0.5	1	0.5	0	**3**
5	0	0.5	1	1	0.5	1	1	1	0	**6**
6	0	0	0.5	0.5	0	0.5	1	0	0	**2.5**
7	0	0	0	0	0	0	0.5	0	0	**0.5**
8	0	0	0.5	0.5	0	1	1	0.5	0	**3.5**
9	0	0	1	1	1	1	1	1	0.5	**6.5**

For C8

TF	1	2	3	4	5	6	7	8	9	Sum
1	0.5	0.5	0.5	0.5	1	1	0.5	0.5	0	**5**
2	0.5	0.5	0.5	0.5	1	1	0.5	0.5	0	**5**
3	0.5	0.5	0.5	0.5	1	1	0.5	0.5	0	**5**
4	0.5	0.5	0.5	0.5	1	1	0.5	0.5	0	**5**
5	0	0	0	0	0.5	0	0	0.5	0	**1**
6	0	0	0	0	1	0.5	0.5	0.5	0	**2.5**
7	0.5	0.5	0.5	0.5	1	0.5	0.5	0.5	0	**4.5**
8	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	**4**
9	1	1	1	1	1	1	1	1	0.5	**8.5**

For C9

TF	1	2	3	4	5	6	7	8	9	Sum
1	0.5	0	0	0	0.5	0.5	1	0	0	**2.5**
2	1	0.5	1	1	1	1	1	1	0.5	**8**
3	1	0	0.5	0.5	1	1	1	0.5	0	**5.5**
4	1	0	0.5	0.5	1	1	1	0.5	0	**5.5**
5	0.5	0	0	0	0.5	0	1	0.5	0	**2.5**
6	0.5	0	0	0	1	0.5	1	0.5	0	**3.5**
7	0	0	0	0	0	0	0.5	0	0	**0.5**
8	1	0	0.5	0.5	0.5	0.5	1	0.5	0	**4.5**
9	1	0.5	1	1	1	1	1	1	0.5	**8**

For Decision Criteria

C_n	C1	C2	C3	C4	C5	C6	C7	C8	C9	Sum
C1	0.5	0.5	0.5	0.5	0	0.5	0	0.5	0.5	**3.5**
C2	0.5	0.5	1	0.5	0.5	0	0	0	1	**4**
C3	0.5	0	0.5	0	0	0	0.5	0	0.5	**2**
C4	0.5	0.5	1	0.5	0	0	1	0.5	0.5	**4.5**
C5	1	0.5	1	1	0.5	0.5	1	0.5	1	**7**
C6	0.5	1	1	1	0.5	0.5	1	1	1	**7.5**
C7	1	1	0.5	0	0	0	0.5	0.5	0.5	**4**
C8	0.5	1	1	0.5	0.5	0	0.5	0.5	1	**5.5**
C9	0.5	0	0.5	0.5	0	0	0.5	0	0.5	**2.5**

Fig. 6. Output matrices after consistency checking

When $ie_{hk} > ie_{hl}, \quad ie_{kl} = 0$;

When $ie_{hk} < ie_{hl}, \quad ie_{kl} = 1$;

When $ie_{hk} = ie_{hl} = 0.5, ie_{kl} = 0.5 \qquad (2)$

where $h = 1,2, \ldots, n$, which is the reference element.

When matrix **iE** complies with the consistency checking of priority ordering, it is named as the priority matrix with consistent indicators. There are five conditions to check whether matrix **iE** satisfies the consistency checking of priority ordering. They are

1. If $ie_{hk} > ie_{hl}$, then $ie_{kl} \equiv 0$ (“greater than zero” condition),

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For C1		
TF	Sum	Score
9	8.5	1
2	7.5	0.818
6	6	0.6
5	5.5	0.538
3	3.5	0.333
4	3.5	0.333
8	3.5	0.333
1	2	0.212
7	0.5	0.111

For C2		
TF	Sum	Score
9	8.5	1
2	7.5	0.818
6	6	0.6
7	6	0.6
5	4	0.379
8	4	0.379
3	2	0.212
4	2	0.212
1	0.5	0.111

For C3		
TF	Sum	Score
2	7.5	1
6	7.5	1
9	7.5	1
5	5	0.6
1	4.5	0.538
8	4	0.481
3	2	0.29
4	2	0.29
7	0.5	0.143

For C4		
TF	Sum	Score
9	8.5	1
2	7.5	0.818
5	5.5	0.538
8	5.5	0.538
1	4.5	0.429
3	3.5	0.333
4	3.5	0.333
7	1.5	0.176
6	0.5	0.111

For C5		
TF	Sum	Score
1	7	1
9	7	1
2	5	0.667
3	4.5	0.6
4	4.5	0.6
5	4.5	0.6
6	4	0.538
8	3.5	0.481
7	0.5	0.212

For C6		
TF	Sum	Score
9	7.5	1
2	7	0.905
6	7	0.905
1	6	0.739
7	4	0.481
5	3.5	0.429
8	3.5	0.429
3	1	0.212
4	1	0.212

For C7		
TF	Sum	Score
1	8.5	1
2	7	0.739
9	6.5	0.667
5	6	0.6
8	3.5	0.333
3	3	0.29
4	3	0.29
6	2.5	0.25
7	0.5	0.111

For C8		
TF	Sum	Score
9	8.5	1
1	5	0.481
2	5	0.481
3	5	0.481
4	5	0.481
7	4.5	0.429
8	4	0.379
6	2.5	0.25
5	1	0.143

For C9		
TF	Sum	Score
2	8	1
9	8	1
3	5.5	0.6
4	5.5	0.6
8	4.5	0.481
6	3.5	0.379
1	2.5	0.29
5	2.5	0.29
7	0.5	0.143

For Decision Criteria		
C	Sum	Score
6	7.5	1
5	7	0.905
8	5.5	0.667
4	4.5	0.538
2	4	0.481
7	4	0.481
1	3.5	0.429
9	2.5	0.333
3	2	0.29

Fig. 7. Priority ordering and assignment of semantic score

where ie_{hk} is the logical indicator of the pairwise comparison of elements E_h and E_k, ie_{hl} is the logical indicator of the pairwise comparison of elements E_h and E_l, and ie_{kl} is the logical indicator of the pairwise comparison of elements E_k and E_l. For example, in Table 3

- $ie_{14}=1$; that is, element number 1>element number 4,
- $ie_{15}=0.5$; that is, element number 1=element number 5, and
- Therefore, element number 5>element number 4.

2. If $ie_{hk}<ie_{hl}$, then $ie_{kl}\equiv 1$ (“smaller than one” condition). For example, in Table 3
   - $ie_{25}=0$; that is, element number 2<element number 5,
   - $ie_{24}=0.5$; that is, element number 2=element number 4, and
   - Therefore, element number 5>element number 4; that is, $ie_{54}=1$.
3. If $ie_{hk}=0.5$ and $ie_{hl}=0.5$, then $ie_{kl}\equiv 0.5$ (“equal to 0.5” condition). For example, in Table 3

- $ie_{23}=0.5$; that is, element number 2 = element number 3,
- $ie_{24}=0.5$; that is, element number 2 = element number 4, and
- Therefore, element number 3 = element number 4; that is $ie_{34}=0.5$.

4. If $ie_{hk}=1$ and $ie_{hl}=1$, then $ie_{kl}=\{0,0.5,1\}$. For example, in Table 3
   - $ie_{13}=1$; that is, element number 1 > element number 3,
   - $ie_{14}=1$; that is, element number 1 > element number 4, and
   - It is possible that element number 3 > element number 4 or element number 3 = element number 4 or element number 3 < element number 4.

   Therefore, in Table 3, $ie_{34}=0.5$ is valid and does not need to be revised.
5. If $ie_{hk}=0$ and $ie_{hl}=0$, then $ie_{kl}=\{0,0.5,1\}$. For example, in Table 3
   - $ie_{45}=0$; that is, element number 4 < element number 5,
   - $ie_{46}=0$; that is, element number 4 < element number 6, and
   - It is possible that element number 5 > element number 6 or element number 5 = element number 6 or element number 5 < element number 6.

Therefore, in Table 3, $ie_{56}=1$ is valid and does not need to be revised. After consistency checking, 10 output matrices are generated for further evaluation, as presented in Fig. 6.

Stage 3—Priority Ordering and Assignment of Priority Scores to Temporary Facilities

After the consistency check, the priority matrices of the pairwise comparison among the temporary facilities with respect to decision criteria C_n are confirmed. Summing up the values of the indicators on each row, those temporary facilities are then rearranged in descending order with respect to decision criteria C_n. Based on this priority order, experts can assign a semantic operator to each temporary facility by comparing each temporary facility to the one with the highest value (the bottom-up approach). Taking the priority order for C_1 in Fig. 7 as an example, the previous step provides the temporary facility number order of {9, 2,6,5,3,4,8,1,7}. As TF_7 gets the lowest sum of 0.5, it is first compared with TF_9. Their difference is judged by experts, who then assign a semantic operator of "absolutely incomparable" to describe their relative importance. As a result, the priority score of 0.111 (see Table 7 for the mapping of scores) is assigned and the same process is repeated for all elements.

The formulation of the semantic operator is detailed in Chen's (1998) work, and is shown in Table 7. Each semantic operator (like marginally different, quite different, etc.) is assigned a score. These scores, ia_{1j}, within the range of [0.5,1] (0.5 = same; 1 = different) are mapped into a priority score, ir_j, in the range of [1,0], as shown in Fig. 8, by applying the fuzzy set theory through the following equation:

$$ir_j=\frac{1-ia_{1j}}{ia_{1j}};\quad 0.5\leqslant ia_{1j}\leqslant 1 \tag{3}$$

where ia_{1j} = semantic score; and ir_j = priority score.

Stage 4—Derivation of Weightings by Normalizing Semantic Scores

After obtaining the priority order of the decision criteria and temporary facilities in stage 3, it is necessary to measure the magni-

Table 7. Semantic Operators, Scores, and Transformed Priority Scores

Semantic operators	Step	ia_{1j}	ir_j
Same	1	0.5	1
In-between	2	0.525	0.905
Marginally different	3	0.55	0.818
In-between	4	0.575	0.739
Slightly different	5	0.6	0.667
In-between	6	0.625	0.6
Quite different	7	0.65	0.538
In-between	8	0.675	0.481
Markedly different	9	0.7	0.429
In-between	10	0.725	0.379
Obviously Different	11	0.75	0.333
In-bwtween	12	0.775	0.29
Very different	13	0.8	0.25
In-between	14	0.825	0.212
Significantly different	15	0.85	0.176
In-between	16	0.875	0.143
Very significantly different	17	0.9	0.111
In-between	18	0.925	0.081
Extremely different	19	0.95	0.053
In-between	20	0.975	0.026
Absolutely incomparable	21	1	0

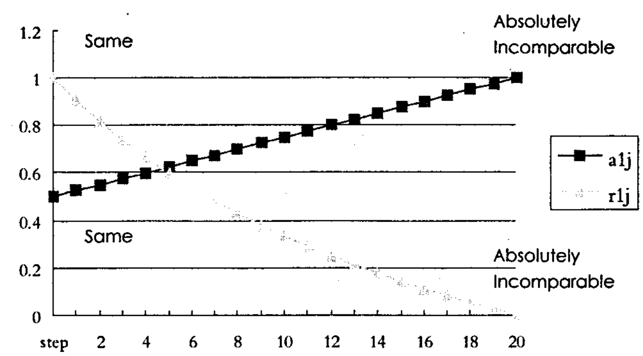

Fig. 8. Mapping of ia_{1j} to ir_j

Table 8. Normalization of Decision Criteria Priority Scores into Weighting

C_n	Semantic score	Normalization	Weighting
C_1	0.429	0.429/5.124	0.0837
C_2	0.481	0.481/5.124	0.0939
C_3	0.290	0.290/5.124	0.0566
C_4	0.538	0.538/5.124	0.1050
C_5	0.905	0.905/5.124	0.1766
C_6	1.000	1.000/5.124	0.1952
C_7	0.481	0.481/5.124	0.0939
C_8	0.667	0.667/5.124	0.1302
C_9	0.333	0.333/5.124	0.0650
[Sum]	5.124	—	—

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tude of the pairwise comparison by calculating the weightings of the decision criteria. In NSFDSS, this process is carried out by the normalization of semantic scores. Let $\omega = (w_1, w_2, \ldots, w_n)$ be the weightings of decision criteria $C_1, C_2, \ldots, C_n$. The set of weightings (ω) is then developed from the normalization of the semantic scores, as shown in Table 8.

Stage 5—Determination of Results

After the weightings of C_n are obtained, Eq. (4) is applied to calculate the Hamming distance for $p=1$ and the Euclidean distance for $p=2$ (Chen 1998)

$$u_j = \frac{1}{1+\left\{\dfrac{\sum_{i=1}^{m}[w_i(r_{ij}-1)]^p}{\sum_{i=1}^{m}(w_i r_{ij})^p}\right\}^{2/p}} \tag{4}$$

for $p=1,2$ and $\mathbf{u}=(u_1, u_2, \ldots, u_j, \ldots, u_n)$, where $\mathbf{u}$ = priority vector; u_j = average distance for $p=1$ and 2; w_i = weight of C_n; $r_{ij} = ir_j$ = semantic scores; and p = distance parameter.

The priority vector $\mathbf{u}$ of the final judgment on each temporary facility can be obtained by taking the average of the two values (Table 9). Finally, the priority vectors of the temporary facilities are rearranged in descending order and the solution of the decision problem is obtained. The result is tabulated in Table 10. In this case study, the most critical facility derived by using the NSFDSS is "tower crane." Thus, it should be planned and located in advance of other facilities.

From the above, the planning sequence of the facilities can be derived. In the case project, tower crane is ranked at the top among other facilities. The possible locations for positioning the tower crane are evaluated first, and the best location is reserved for it. In Fig. 9, locations ($L_1, L_2, L_3, \ldots, L_n$) are the possible position options. If L_n is chosen for the tower crane, the remaining locations will be freed for other facilities. The tower crane location, L_n, on the other hand, will prescribe the location options for other facilities; for example, "access road" needs to be located within the jib length of the tower crane. The site layout positions of all facilities can then be obtained by repeating the process.

Superiority of Nonstructural Fuzzy Decision Support System over Analytical Hierarchy Process

When compared with the most commonly used multicriteria decision aiding method AHP, NSFDSS has shown the following superiorities:

1. *Automatic consistency checking and correction*. At the consistency check, NSFDSS assumes that the logical indicators at the upper rows of the matrix are more reliable than those of the lower rows. The system will then reset the values of the lower rows if inconsistencies are found. In other words, earlier comparisons made (with higher concentration and focus at that stage) are assumed to be more accurate, which resembles human beings' cognitive behavior. On the other hand, AHP only provides a "consistency ratio" as a guideline for decision makers to monitor the consistency of a pairwise comparison. If there are any inconsistencies found, the whole evaluation process needs to be repeated again, which is time-consuming and unsuitable for complex construction problems.
2. *Simplified scale of comparison*. NSFDSS only uses 1, 0.5, and 0 for comparing the relative importance, whereas AHP relies on a more complicated nine-point scale for evaluation. This would be demanding, difficult, and, in some ways, beyond the human judgmental capability. Thus, this would either prolong the decision-making process and complicate the decision-making procedures, or induce inaccuracy or inconsistency in the solutions. Decision makers may be falling into judgmental uncertainties, which will jeopardize the accuracy of the results.
3. *Elimination of consistency deviation*. The global acceptance of the consistency ratio in AHP has its own shortfalls. The acceptable tolerances in using the consistency ratio may compromise the judgmental accuracy, deviating the result from the optimal. In contrast, NSFDSS gives absolute con-

Table 9. Calculation og Priority Vector for Temporary Facilities

TF_n	For $p=1$ $\mathbf{U}(j)$	For $p=2$ $\mathbf{U}(j)$	Average $\mathbf{U}(j)$
TF_1	0.692	0.733	0.7127
TF_2	0.926	0.889	0.9075
TF_3	0.265	0.290	0.2775
TF_4	0.265	0.290	0.2775
TF_5	0.410	0.420	0.4147
TF_6	0.554	0.600	0.5768
TF_7	0.154	0.217	0.1855
TF_8	0.358	0.368	0.3634
TF_9	0.999	0.992	0.9956

Table 10. Results of Site Layout Planning Problem

Calculated weight of each decision	Decision number	Description
0.9956	9	Tower crane
0.9075	2	Material hoist
0.7127	1	Access road
0.5768	6	Refuse chute and discharge point
0.4147	5	Ready-mix concrete discharge point
0.3634	8	Steel bar bending yard
0.2775	3	Material storage area
0.2775	4	Precast units storage area
0.1855	7	Site accommodations

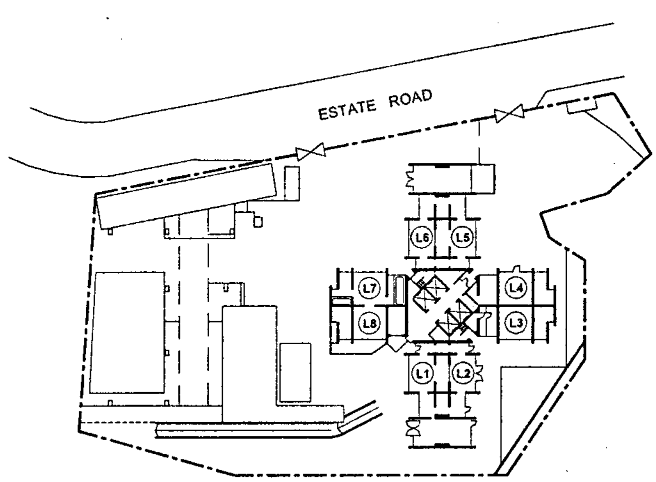

Fig. 9. Example of site map (available tower crane locations $=L_1$–L_8)

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sistency during evaluation; therefore, the priority order of the decisions is generally close to the optimum solution.

Feedback from Practitioners

In this study, five experienced project planners—one project manager, two project engineers, and two site agents—with 10–15 years of planning experience have been selected to solicit feedback concerning the model. The following are the remarks they have made:

1. NSFDSS is suitable at the initial site layout planning stage, at which time only imprecise information is available. It can help one arrive at a rational and multiobjective decision quickly;
2. The repeated evaluation and selection process is suitable for the major site facilities, such as the tower cranes, material hoists, storage areas, and likewise; and
3. The evaluation factors for considering a site facility can affect the evaluation results; thus, attention needs to be paid to the process of selecting evaluation factors.

Conclusions

In site production planning, space allocation and material transportation problems have been mainly resolved based on practitioners' past experience and knowledge, without any decision rules for guidance. In this paper, the decision-aiding model NSFDSS is introduced. NSFDSS can systematically analyze human judgments to generate the relative weightings for the decision factors and elements. NSFDSS offers some merits over traditional decision-making models. It uses a simple comparative rating scale (1, 0.5, and 0) in evaluating the relative importance of different factors, which provides a built-in consistency checking mechanism to maintain and correct discrepancies in the evaluation process. The model provides an alternative technique in decision-making for complex multicriteria problems, where multiple objectives exist. The model provides a systematic procedure to aid project managers or planning engineers in determining site facility allocations. Further development of the model can be extended to evaluate the effectiveness of the overall site layout planning.

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