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A multi-attribute model for construction site layout using intuitionistic fuzzy logic

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ABSTRACT

Most researchers have concentrated on studying optimization models to produce optimal construction site layout plans using different algorithms, while the overall method for evaluating and selecting the best site layout generated from optimization models has received less attention. In an optimization model, construction cost is generally considered in the objective function. However, several objectives, such as security and tie-in with external transportation, are difficult to quantify in the objective function and were not considered in previous studies. This paper focuses on evaluating and selecting the construction site layout considering qualitative objectives. An intuitionistic fuzzy multi-attribute decision-making model is developed that combines intuitionistic fuzzy set theory and the technique for order preference by similarity to the ideal solution (TOPSIS). This model overcomes the shortcomings of a traditional fuzzy set when describing ambiguous and unclear circumstances by using membership functions. The application of this model for site layout selection is shown to be reasonable and effective based on data from a real construction project.

1. Introduction

Construction site layout planning (CSLP) is a decision-making process in which available site facilities are assigned to free locations in order to satisfy multiple objectives, such as minimum cost, maximum construction site safety level and efficient material handling. In practice, project managers need to choose the best construction site layout, which is a compromise between all the objectives and their criteria, after evaluating all site layout alternatives. From a research perspective, this decision-making process can be separated into three stages: the design stage to develop site layout alternatives, the evaluation and selection stage to choose an alternative and the output stage to implement the selected site layout plan.

In previous studies, most researchers addressed CSLP in the design stage, formulated as either a single-objective or multi-objective optimization problem. For single-objective CSLP optimization, minimizing construction cost often determines the site layout [1]. Other typical single objectives include the total travel distance [2–5]; the overall cost of resource transportation per day [6]; the sum of construction costs in the site layout considering material handling, facility erection, re-handling and working area personnel facilities [7]; and the relation of distance (work flow, information flow, level of safety and environment, personnel preference) between the facilities [8,9]. A multi-objective optimization CSLP problem includes objectives other than construction cost, such as safety [10,11], security [12], total potential energy [13], debris and wildlife control criteria [14]. The types of objective functions used by different researchers vary considerably. To find optimal solutions of site layout, different advanced algorithms, such as the genetic algorithm [15] and ant colony optimization algorithm [10], are used to consider preset quantitative objective functions.

This paper focuses on the evaluation and selection stage that has previously received little attention. In a previous study of the design stage, site layout plans were generated using optimization algorithms that considered quantitative objective functions such as cost and travel distance. Qualitative objectives, such as the tie-in with external transportation, are difficult to quantify and were therefore not considered in the design stage; however, these objectives should be considered as criteria for selection. With pre-defined criteria, the cardinal class method, which can be used for evaluating and selecting the final site layout among the solutions derived by the optimization algorithms according to qualitative attributes, needs further study. Therefore, this paper presents a study of a multi-attribute decision making (MADM) model that includes the cardinal class method to identify cardinal preferences for site layout alternatives with pre-defined qualitative attributes.

This research aims to develop a MADM model to identify the best site layout plan based on many optimal solutions of site layouts from the design stage. The technique for order preference by similarity to

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the ideal solution (TOPSIS) combined with the intuitionistic fuzzy set (IFS) theory are applied in the model [16–18]. IFS is superior to a traditional fuzzy set for assessing a fuzzy environment when decision-makers have difficulty describing an attribute's degree of 'excellence' or for more readily expressing why they dislike an attribute. The proposed model uses linear programming to deduce the attributes' weights by conducting an intuitionistic fuzzy assessment of the attributes' importance. Within the established model framework, ten key attributes were selected from 23 attributes collected from a literature review. The proposed model and the key attributes can help site managers select construction site layout plans. The final output of the model will fulfill the required attributes for an efficient site plan. This paper treats site layout planning as a decision-making model and focuses on the evaluation and selection stage, which has received little attention in previous research.

First, the cardinal class method used in the MADM model is reviewed to illustrate the reason for adopting TOPSIS. Second, the model and the process of applying the model in site layout selection are described in detail. Finally, the model is applied to a real construction project.

2. Cardinal class method used in decision-making

Cardinal class methods are required if decision-makers can offer cardinal preferences of attributes. These methods include the analytic hierarchy process (AHP), TOPSIS, simple additive weighting, ELECTRE (i.e., elimination et choix traduisant la réalité), median ranking and the weighted product method. However, there is no special rule for the selection of MADM methods, which is itself a problem [16].

In construction management, AHP is the most widely used cardinal class method because of its simplicity, ease of understanding and ease of implementation. AHP can help decision-makers when they are confronted with different choices during the management process. In AHP, the decision-makers estimate ranking priorities for alternatives by conducting pair-wise comparison judgments [19].

During the application process, decision-makers do not need to formulate goal equations and do not need to be knowledgeable about goals and priorities [20]. The key element of AHP is to build a judgment matrix by determining the relative importance of each criterion and indicating preferences regarding the importance of each alternative. The disadvantage of this method is the use of pair-wise comparison to evaluate alternatives. It is very difficult to accurately determine relative importance when comparing one factor to another, and it is difficult to quantify degrees into a nine-scale table or other mutually reciprocal table [20].

TOPSIS was developed to find the best solution for MADM problems [16]. The solution should represent the furthest distance from the negative-ideal solution and the closest distance to the positive-ideal solution. The merits of TOPSIS include the merits of AHP, such as simplicity, ease of understanding, ease of implementation, and no goal formulation or prioritization. TOPSIS overcomes the disadvantage of tedious pair-wise comparison. In TOPSIS, the evaluator does not need to make comparisons of the alternatives' relative importance or give crisp data to describe the degree of relative importance.

In the proposed MADM system, TOPSIS is integrated with intuitionistic fuzzy set to estimate and find the best site layout among construction site layout alternatives. With the application of intuitionistic fuzzy TOPSIS, the positive-ideal solution and the negative-ideal solution are easily identified because the intuitionistic fuzzy set can be used to quantitatively describe personal preferences by simultaneously using the membership and non-membership functions. Combining IFS and TOPSIS amplifies the advantages of each. Intuitionistic fuzzy TOPSIS can improve the validity of MADM problems when facing vague perceptions in construction management.

3. Multi-attribute decision-making model for construction site layout

The intuitionistic fuzzy set (IFS) theory was introduced by Krassimir Atanassov [21] as an extension of the fuzzy set theory by Lotfi Zadeh [22]. In classical fuzzy set, each element's belonging degree to the set under consideration is expressed by a membership function, whose value can be a number in the interval [0, 1]. Decision-makers typically have difficulty describing an attribute's degree of 'excellence' and can more readily express why they dislike an attribute. Thus, it is appropriate to adopt IFS instead of a traditional fuzzy set to rate an alternative criterion.

The intuitionistic fuzzy set theory assesses elements using three functions: a membership function, $\mu(x)$ $(0 \le \mu(x) \le 1)$; a non-membership function, $\nu(x)$ $(0 \le \nu(x) \le 1)$; and a hesitation margin function, $\pi(x)$ $(0 \le \pi(x) \le 1)$ that may be appropriate in circumstance when people have opinions that include two or more answers of the type "yes", "no" and "I have no idea" or "I wonder". The hesitation margin function $\pi(x)$ is used to address a situation in which someone is uncertain of an element's degree of membership or non-membership.

The process of applying the proposed multi-attribute model is illustrated in the flowchart in Fig. 1. The model applies the IFS logic and the TOPSIS principles [23,24]. In Part 1, the IFS logic is applied to evaluate site layout alternatives. In Part 2, the TOPSIS principles are used to produce an optimized solution and select the most effective layout for a construction project.

3.1. Part 1: using IFS to evaluate construction site layout alternatives

For a given construction site, there are n alternative layouts, $x_1, x_2, \ldots, x_n$, which are represented mathematically as the set $X = [x_1, x_2, \ldots, x_n]$. The objective of the model is to find the most effective layout among the n alternatives using an optimization process. To evaluate the performance of each alternative, attributes a_1 through a_m are used in terms of an attribute set, $A = [a_1, a_2, \ldots, a_m]$. The rating of alternative x_i for attribute a_j is expressed as (μ_{ij}, ν_{ij}), where μ_{ij} and ν_{ij} are the degrees of membership and non-membership, respectively. The rating matrix of the model is given below:

$$\mathrm{R} = \begin{array}{c} \\ x_1 \\ x_2 \\ \cdots \\ x_n \end{array} \begin{array}{c} \begin{array}{cccc} a_1 & a_2 & \cdots & a_m \end{array} \\ \begin{bmatrix} (\mu_{11}, \nu_{11}) & (\mu_{12}, \nu_{12}) & \cdots & (\mu_{1m}, \nu_{1m}) \\ (\mu_{21}, \nu_{21}) & (\mu_{22}, \nu_{22}) & \cdots & (\mu_{2m}, \nu_{2m}) \\ \vdots & \vdots & \vdots & \vdots \\ (\mu_{n1}, \nu_{n1}) & (\mu_{n2}, \nu_{n2}) & \cdots & (\mu_{nm}, \nu_{nm}) \end{bmatrix} \end{array} \quad (1)$$

where $0 \le \mu_{ij} \le 1$; $0 \le \nu_{ij} \le 1$; and $0 \le \mu_{ij} + \nu_{ij} \le 1$.

In previous research, the weights of the attributes were often derived from the importance level of the attributes, which can be measured on a scale of 1–5 or by using pair-wise comparisons. The weighting method or AHP can be used to calculate final weights. However, it is difficult for the evaluator to express an attribute's degree of 'importance' or to accurately determine relative importance when comparing one factor to another in pair-wise comparisons. Thus, it is appropriate to adopt IFS instead of a traditional fuzzy set to describe importance level and to use linear programming to derive attribute weights.

Let α_j, β_j and τ_j be the membership function, the non-membership function, and the hesitation margin of attribute a_j to the fuzzy concept "importance", respectively. The hesitation margin can be used in calculating the best final results (and the worst results) that we can expect in a process; this margin leads toward a final optimal result by adding the value of the hesitation margin, τ_j, to increase the evaluation (or decrease the evaluation). An attribute in IFS can be expressed as $Z = \{<x_i, \mu_A(x_i), \nu_A(x_i), \pi_A(x_i)> | x_i \in X\}$. The attribute weight of $\tilde{w}_j$ $(\sum_{j=1}^{m} \tilde{w}_j = 1)$ is within the closed interval $[\alpha_j, \alpha_j + \tau_j]$ for $\tau_j = 1 - \alpha_j - \beta_j$. To obtain the positive