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Comparison of Modern Structural Systems based on a Fuzzy Analytical Hierarchy Process

Seyedreza Siadati* and Vahid Shahhosseini

Construction Engineering and Management, Department of Civil and Environmental Engineering, Amirkabir University of Technology, Iran; siadati@aut.ac.ir,

Abstract

This article aims at comparison of three advanced construction methods to choose the appropriate one in four-storey buildings which could be suitable in mass construction. Comparison of modern structural systems is a qualitative and ambiguous notion, because there are numerous criteria in deciding a better method based mainly on expert's experience of implementing, constructing and designing under complex conditions. The analytical hierarchy process is used here and remarks of experienced experts are collected by questionnaires. Comparison of three construction systems is undertaken: three-dimensional panels, lightweight steel frames, and reinforced insulating concrete formworks. This field research has involved reviewing the relevant literature, collecting questionnaires from experts, and based undertaking statistical analysis. Choosing structural system is complex especially for engineers and owners within new technologies because they hold new unknown criteria with them. When decision making has to be involved aesthetics, economic, environmental issues and social sides which are called sustainability, it becomes more important, so this result informs investors and owners to have a practical investigation by comprehensive and reliable research. By, Analytical Hierarchy Process AHP calculations, the best structural system has been chosen in which sustainability criteria affected. The result considered for four-storey building and it offers a useful guidance for mass construction.

Keywords: AHP, Decision-Making, Insulating Concrete Formwork, Lightweight Steel Frame, Sustainability, Three Dimensional Panel

1. Introduction

Considering the rapid growth of population and continually increasing needs for housing, traditional methods of constructing housing cannot meet annual demand; moreover, these methods are in many ways not optimal. In today's world there is growing use of nonrenewable resources to prevent the depletion of energy and material supplies. All modern construction systems have their advantages and drawbacks, and understanding these by considering the necessary infrastructure and determination of appropriate methods is an effective step toward optimum project implementation.

To select the construction projects, the fuzzy analytic hierarchy process[1] is used, while the model for the equipment selection is based on the hierarchical method described. A typical MADA method, Analytical Hierarchy Process (AHP) was developed to assist in the making of decisions that are characterized by a great number of interrelated and often contending factors. To make such decisions, the relative importance of the factors involved must be properly assessed in order to enable trade-offs among them. The main feature of AHP is its inherent capability of systematically dealing with a vast number of intangible and non quantifiable attributes, as well as with tangible and objective factors. AHP allows for the incorporation into the decision-making process of subjective judgments and user intuition by producing a common formal and numeric basis for solution. Over the years, AHP has been implemented successfully in various areas but only a few AHP applications in the area of construction[2].

*Author for correspondence

2. Definitions

The technologies evaluated in this paper are three-dimensional panels, lightweight steel frames, and insulating concrete formworks. First, a brief description of the properties and structure of each of them is provided.

2.1 Lightweight Steel Frames

Lightweight steel frames of cold formed steel sections have been used to manufacture a wide variety of office, commercial, and residential buildings in recent years. This system has been used in the construction industry since 1946[3], but did not at first prevail due to competition from cheaper materials. However, it has become widespread as a result of the changes to the price of raw materials of other types of common structural systems and other mentioned advantages. The environmental benefits of this system include reduced carbon dioxide emissions, waste generation on site, resulting in savings to the system and consumables; also it is possible to produce the system from recycled materials and to recycle it after lifetime. Steel modules have excellent robustness, which usually means that they can meet international seismic standards[4]. Buildings made from steel modules can easily be disassembled and modules can be relocated to create new buildings quickly and economically. Steel modules can be grouped vertically and horizontally with good load resistance. Because of various benefits including a rapid speed of implementation, quality, its economical and environmentally friendly nature, plus energy savings and low consumption of materials in its structural function, the lightweight steel frame system is frequently seen in many countries including the United States, Canada, Australia, and Japan in short - and medium-height residential and commercial buildings[5,6].

2.2 Three-dimensional Panels

The second technological system discussed in this paper is the three-dimensional or sandwich panel, a semi-prefabricated system for the construction of reinforced concrete structures. The system is characterized by its use as a covering structure, durability, relative resistance against heat, sound and moisture, creation of more useful spaces, weight, reduced energy consumption, desirable resistance against lateral forces due to the integrity of the structure, and ease of transportation and installation. It comprises a polystyrene core with steel grids at both ends that are eventually covered with shotcrete concrete.

2.3 Insulating Concrete Formworks

The insulating concrete formwork system is the final new technology compared in this paper. It was first developed in Germany and then it spread to other countries. Its high implementation speed whilst maintaining optimum energy and structural rigidity is an important feature. The system normally comprises two slow-burn polystyrene insulation layers as the frame, reinforced with shear wall structures.

3. Methodology

One of the most efficient decision-making techniques is the Analytical Hierarchy Process, or AHP, as mentioned. It is based on paired comparisons and enables managers to review various scenarios. In classic multi-criteria decision making, attempts are made to calculate the effect of different factors using mathematical concepts, but it is impossible to express many factors using mathematical logic. There is always uncertainty in the real world, including during the various stages of studying any issue. Therefore, in many cases all or parts of the data of a multi-criteria decision are fuzzy and, if a problem is formulated using definite data, no correct and accurate answer can be obtained. Consequently, a choice will not be the optimum selection; it is impossible to achieve a set target with such inaccurate decision making. Hence in decision-making models whose data are random or fuzzy, besides further calculation and operations the model should consider accuracy, logic and uncertainty. Uncertainty in decision making is modeled using fuzzy set theory, and limitations in classic multi-criteria decision-making methods have led to the introduction of fuzzy multi-criteria decision-making.

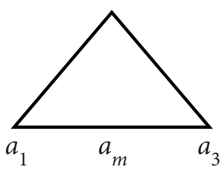
Fuzzy theory was introduced in 1965 by Professor Lotfi Zadeh in his paper, “Fuzzy sets”[7]. Fuzzy logic and fuzzy sets may be counterpoised with classic logic and classic sets. Classic sets are suitable both for concepts that are defined and determined conclusively and for fuzzy sets for which it is not possible to set definite borders or to form a classic set-based on those borders, for example the set of tall people and similar, as used routinely in real life. In a classic set the membership of elements has two states - either a member or not - while in a fuzzy set this is expressed by a membership degree of between zero and one. Fuzzy sets can take coherent or discrete forms. Coherent sets are shown by diagrams called membership functions. Those mostly used in studies include triangles, or complete or partial trapezoids. The fuzzy lingual scale is defined in Table 1.

The steps performed in the FIS are as follows[8]:

- The fuzzification process transforms each crisp input variable into a membership grade based on the membership functions defined.
- The inference engine used for applying the appropriate fuzzy rule in order to obtain the fuzzy set to be accrued in the output variable.
- The defuzzifier transforms the fuzzy output into a crisp output by applying a specific defuzzification method.

Generally, the membership function of triangular numbers is as below:

$$(1)\mu_A(x)=\begin{cases} 0, & x \le a_1 \\ \dfrac{x-a_1}{a_2-a_1}, & a_1 \le x \le a_2 \\ \dfrac{a_3-x}{a_3-a_2}, & a_2 \le x \le a_3 \\ 0, & x \ge a_3 \end{cases}$$



Questionnaires were collected from 28 construction projects that used the technologies mentioned in this article. Each project was surveyed from the perspective of three experts namely the designer, the contractor and the project manager. Of the completed forms, nine from a total of five projects lacked valuable information. In order to maintain the consistency of the comments of the three groups, the information received from the group of three respondents on those five projects was discarded, i. e., 15 questionnaires.

A paired comparison matrix of criteria was formulated according to the experts' opinions and, after assigning a weight to the main criteria, weights of sub-criteria were calculated. For each matrix, the arithmetic mean was calculated to synthesize the expert opinions based on Chang's Extended Analysis[9].

Table 1. Fuzzy lingual scales

Lingual variables	Fuzzy number	Fuzzy scale
Very low	1	(1,1,3)
A little more important	3	(1,3,5)
More important	5	(3,5,7)
High importance	7	(5,7,9)
So much importance	9	(7,9,9)

The inconsistency rate was calculated using Super Decisions software, taking into account the middle fuzzy spectrum (the rate of incompatibility in the computation of fuzzy hierarchical analysis process must be smaller than or equal to 0.1, as accomplished in this study).

(2) weight of vector = W

(3) Matrix pair comparison = A

(4) $\lambda_{\max} = W * A$

(5) For matrix 3*3 $\quad \lambda_{\max} = \dfrac{\lambda_{\max 1} + \lambda_{\max 2} + \lambda_{\max 3}}{3}$

(6) inconsistency index $\quad I.I = \dfrac{\lambda_{\max} - n}{n-1}$

(7) multiplication (weight of elements and I.I) = I.I.R

(8) inconsistency rate $\quad I.R. = \dfrac{I.I.}{I.I.R}$

The remarks of experts were turned into fuzzy numbers, set using the fuzzy triangle method, and the weight of criteria was assigned.

4. Analysis/Results

In this article Saaty's hierarchical method was chosen but due to the fuzzy nature of expert opinion, it was decided to find a method to achieve a better comparison against classic methods. This is achieved by combining fuzzy concept and hierarchical analysis methods. A set of 84 questionnaires was collected of which nine were invalid, covering five projects; to keep the comments consistent; the 15 questionnaires from the entire group of respondents on those five projects were omitted.

Due to calculations the weight of criteria and sub-criteria extracted in Table 2.

According to the findings the highest weight of criteria is related to economical nature (0.186) which is obvious in most construction projects, on the other hand, structure's resistance against accidents resulting from hits got the lowest weight (0.012). The resistant to side forces is in the second position in rating which shows its significance in experts view.

The items studied in this paper as criteria and sub-criteria presented below are based on sustainability.

4.1 Social Criteria

- Architectural flexibility of the interior
- Architectural flexibility of the exterior (possibility of using any material and long consoles or esthetic fractures)
- Technology and occupation localization speed

Table 2. Weight of criteria and sub-criteria

	Criteria and sub-criteria	Weight
C1	Resistant to side forces	0.143
C2	Thermal insulator and energy preservation	0.033
C3	Architectural flexibility of interior	0.053
C4	Architectural flexibility of the exterior (possible to use any material and long consoles or esthetic fractures)	0.047
C5	Technology and occupation localization speed	0.038
C6	Recycling capability	0.042
C7	Economical nature	0.186
C8	Possibility for mass construction	0.082
C9	Technology lifetime	0.041
C10	Resistant to fire	0.036
C11	Operation level comfort (shake and sound probability)	0.025
C12	Rigidity and the level of necessity to reconstruct the structure after earthquake or storm	0.037
C13	Compatibility with expectations of operators based on the insight and definitions of common structures	0.041
C14	Emission of environmental waste	0.021
C15	Disturbance during construction for humans and animals, including noise, dust, frequent transportation of materials, etc	0.029
C16	Reduced consumption of material and energy	0.021
C17	Safety of workers in operation	0.028
C18	Structure's resistance against accidents resulting from hits	0.012
C19	Passive defense and progressive destruction	0.067

- Resistance to fire
- Operation level comfort (shake and sound probability)
- Disturbance levels when constructing for humans and animals including noise, dust, frequent transportation of materials and etc.
- Safety of workers in operation
- Passive defense and progressive destructions

4.2 Economic Criteria

- Resistant against side forces
- Lower end price
- Possibility of mass construction
- Technology lifetime
- Rigidity and the necessity of levels to reconstruct the structure after earthquake or storm
- Compatibility with expectations of operators based on the insight and definitions of common structures
- Structure's resistance against accidents resulting from hits

4.3 Environment Criteria

- Thermal insulation and energy preservation
- Recycling capability
- Emission of wastes and environmental trashes
- Lower material consumption and energy saving in the world

5. Structure Systems Ranking

Structure systems rankings are listed in Table 3 in which three-dimensional panels show a small difference with insulating concrete formworks frame. Lightweight steel frame hit the highest rank that suggests expert engineers and owners prefer to use this kind of system implicitly.

6. Conclusion

Hierarchical-fuzzy calculations revealed that the lightweight steel frame building system is a better choice than other modern methods discussed in this article. Moreover, if the purpose is to construct a four-storey building especially mass construction to meet the criteria specified, this system has further benefits. This study attempted to ensure that respondents thoroughly understood the criteria, and were able to exercise their judgment freely, independent of regional issues, in completing the questionnaire.

Table 3. Weight of items

Items	Weight	Rank
Lightweight steel frame	0.36	1
Insulating concrete formworks frame	0.33	2
Three-dimensional panels	0.31	3

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