American Journal of Civil Engineering and Architecture, 2014, Vol. 2, No. 5, 149-159
Available online at http://pubs.sciepub.com/ajcea/2/5/1

DOI:10.12691/ajcea-2-5-1

A Comparison of AHP and PROMETHEE Family Decision Making Methods for Selection of Building Structural System

Vahid Balali[1,*], Banafsheh Zahraie[2], Abbas Roozbahani[3]

[1]Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, USA
[2]School of Civil Engineering, University of Tehran, Tehran, Iran
[3]Department of Irrigation and Drainage Engineering, University of Tehran, Tehran, Iran
*Corresponding author: balali2@illinois.edu

Received July 31, 2014; Revised September 03, 2014; Accepted September 08, 2014

Abstract Introduction of new structural systems into construction industry has created a competitive environment wherein selecting the most appropriate structural system has become increasingly difficult. Some structural systems have priority over others due to their unique features,as well as the special requirements of various construction projects. The structural system's selection process is intended to show the trade-off among different alternatives when evaluated by technical and nontechnical professionals and maximize the agreement between all interested parties. This paper addresses how the best system can be selected using AHP and PROMETHEE family of multiple criteria decision-making techniques. These techniques have been utilized in this study for selecting the appropriate structural system among 3D Panel with light walls in building frames, LSF, ICF, Tunnel Formwork system, and Tronco in a low rise multi-housing project in Iran. A questionnaire has been designed to collect engineering judgments and experts' opinions on various parameters such as weight of different criteria. The team of experts who has cooperated in this research includes engineers and managers of consultants, contractors, and owners who are involved in different low rise multi-housing projects in Iran. A comparison between the two techniques has been carried out based on the consistency of the results, the required amount of interactions with the decision-makers, and ease of understanding. For the case study of this research, 3D Panel with light walls in building frames has been selected as the most appropriate structural system. The PROMETHEE II has been selected as the preferred method for the appropriate structural system selection process since its results are consistent, easy to understand, and require less information from decision-makers compared to AHP.

Keywords: *Multi-Criteria-Decision-Making, AHP, PROMETHEE, building construction, structural system*

Cite This Article: Vahid Balali, Banafsheh Zahraie, and Abbas Roozbahani, "A Comparison of AHP and PROMETHEE Family Decision Making Methods for Selection of Building Structural System." *American Journal of Civil Engineering and Architecture*, vol. 2, no. 5 (2014): 149-159. doi: 10.12691/ajcea-2-5-1.

1. Introduction

Reinforced constructions, sustainable development, improvement in the quality of life, and housing enhancement indices require a transition from traditional construction methods to new technologies. To survive in today's competitive market requires a comprehensive knowledge of new construction technologies that would improve safety, durability, quality, and the construction speed. The importance of optimal investment in housing and proper management of major national projects become more apparent when knowing that 40% of industrial investments in Iran are made in the construction industry. The major challenges in Iran's construction industry are unnecessary lengthy construction period and low delivery quality. These challenges reduce the durability and the length of the operation phase of the infrastructures and increase costs which render some projects as non-economical [1,2]. Application of scientific approaches, advanced technologies, and new materials are essential requirements for enhancing the quality of building construction and residential housing industry. Therefore, architectures and engineers have to learn about advantages and proper applications of these advanced technologies. Industrial production is the only way to meet the increasing need for housing in many developing countries such as Iran.

Since selecting an appropriate building system depends on a variety of features, Multi-Criteria-Decision-Making (MCDM) techniques can be proper tools for the selection process. Selection of a structural system is the initial task in the overall process of the structural design. In this task, general arrangement of the structure, incorporating the overall form, geometry and nomination of the principal structural elements are defined [1,3].

Decision-makers need methodologies which are not mathematically complicated and can reflect their perspectives in the decision-making processes. This interactive approach requires analysis of information obtained from different sources and their associated uncertainties. The structural system selection is a broad and ill-structured practice that requires a wide variety of expertise. MCDM techniques can be used for ranking available alternatives based on several often conflicting criteria and therefore, have recently received growing attention, particularly in construction engineering and management.

Selection of a structural system and materials is often done according to personal experiences or perceptions without being evaluated as it should be for optimum performance. Designers require multi-disciplinary knowledge and experience about the behavior of different structures and structural requirements. Over a period of time, experienced designers build up some procedures for this task; several researchers tried to embrace these procedures by MCDM techniques. In some real-world situations, it may be difficult to obtainprecise information (e.g. activity durations). In these uncertain environments, MCDM methods can be also used as a tool to deal with the process of making decisions in the presence of multiple objectives and imprecise information.

[4] used ELECTRE III MCDM method for selecting housing construction processes. Eleven structural systems using seven criteria were examined covering human resources, equipment, materials, and energy demand. [5] employed Artificial Neural Networks (ANN) to assess durability in initial design stage of construction. Input data included information related to the site such as accessible work space, access road to the site, installation speed, and conceptual designing data including type of buildings, number of floors, and net area of floors. [6] studied architectural sketches which led to the selection of feasible structural systems. They proposed an integrated approach to incorporate structural engineering concerns into architectural designs for timely and well-informed decision making. [7] used ANN for selecting the structural systems. They proposed StructNet software which analyzed 15 construction parameters such as accessible work space, budget, elevation, and then selected the appropriate system for beams, columns, and slabs. [8] used multi-criteria optimization techniques for selecting the currently used external walls of individual residential buildings.They normalized the qualitative and quantitative criteria with consideration of two-sided problems in the game theory. [9] proposed two-stage procedures and guidelines for selection of optimum structural systems and materials.

AHP (Analytical Hierarchy Process)method is widely used for solving MCDMproblems; even though the conventional AHP method is incapable of handling the uncertainty and vagueness involved in the mapping of one's preference to an exact number or ratio.AHP is known as a practical versatile approach [10]. [11] explored applications of AHP in project management for selecting project advancement systems. [12] used AHP in selecting casting processes. Two MCDM approaches, the AHP and Analytic Network Process (ANP), were employed by [13] to evaluate the intelligence level of the intelligent building systems. A total of 69 key intelligence criteria were identified for eight major intelligent building systems. [14] used AHP method to establish a model which highlights the cultural aspects of construction in the human living environment.

PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) is also a quite simple ranking method in terms of concept and application compared with many other methods for multi-criteria analysis [15]. [1] used a family of PROMETHEE MCDM methods to choose a proper structural system. They explored the commonly used new structural systems in mass housing projects by taking into account the existing uncertainties through indifference and preference thresholds. [16] used PROMETHEE method for evaluating the strategic potential of construction enterprises. Integration of ELECTRE III and PROMETHEE II with the interval approach was carried out by [3] which can also be used for group decision-making cases. Their proposed methodology considers veto threshold, provides complete ranking, exempts the preference functions, and includes conceptions such as risk, uncertainty and reliability with the interval approach. [17] used the PROMETHEE method under fuzzy environments in order to determine the critical path of network considering time, cost, quality, and safety. The PROMETHEE method also has been used by [18] to select appropriate material, construction technique, and structural system of bridges.

Some researchers tried to combine AHP and PROMETHEE to further enhance the capabilities of both techniques [19-24]. In these combined methods, AHP has been used to analyze the structure of the problem and determine the weights of the criteria, whereas PROMETHEE has been used for the final ranking.

In this paper, AHP and PROMETHEE family of methods including PROMETHEE I, II and GAIA are introduced and used to select the most appropriate building structural system among 3D Panel with light walls in building frames, LSF (Light Steel Frame), ICF (Insulating Concrete Formwork), Tunnel Formwork system, and Tronco in a low rise multi-housing project in Iran. Reviewing previous applications of AHP and PROMETHEE methods, shows that they have been frequently used for many years, both individually and integrated with other techniques, and have been considered as reliable ones. The advantages of these methods for the selection and ranking problems have been proved by many researchers in the existing literature; however their application in the selection of the structural systems is a novel application in building construction industry. In the proposed methodology, the amount of information requested from decision-makers has proved to be simple and enough to ensure the decision makers' cooperation. Expert teams from various executive areas related to building construction activities have been involved in this study to evaluate the criteria and alternatives. In the next section of the paper, the principles of AHP and PROMETHEE family methods will be described. Also, the results of the case study and the conclusions are presented in the last sections of the paper.

2. Method

In this section, we give an overview of the AHP and PROMETHEE techniques for solving multi-criteria problems. Besides, the benefits and limitations of both methods are described in brief. The proposed methodology for evaluating structural system candidates for residential buildings is presented as well.

2.1. AHP Method

AHP can increase interaction and engagement of the individuals in decision making processes. AHP approach is inspired by what happens in the human brain. The requirement for pairwise comparison in AHP is regarded as an advantage as it requires decision makers to think more deeply about weights of different factors and analyze the situations at deeper levels. Another advantage of AHP is its ability to measure quality and quantity indicators by using mental preferences, expertise, and objective information. By classifying criteria from top to bottom in a decision tree, AHP systematically assesses complex problems, particularly by incorporating opinions from experts and decision makers. AHP is a reliable method for calculating the weight of each criterion since it is based on decision makers' points of view rather than decision matrices. AHP also allows performing sensitivity analysis over criteria and sub-criteria. A unique feature of AHP is the possibility of calculating compatibility/incompatibility of decisions made by the decision makers.

In the first step, AHP breaks down a complex decision making problem into a hierarchical structure, composed of decision making components (criteria and alternatives) with at least three levels: (1) overall objective at the highest level; (2) multiple criteria which define alternatives at the intermediate level; and (3) alternatives at the lowest level. The second step involves comparison of alternatives and criteria. Once the problem is analyzed and the hierarchical levels are formed, preferences are determined at each level based on the relative importance of each criterion. At each level, pairwise comparison is made among the criteria to identify the impact of each criterion compared to certain criteria at upper levels. Pairwise comparisons are carried out using a 9-point standard scale presented in Table 1 [10].

Table 1. Standard Scale for Pairwise Comparison

Value	Equally important	Weak importance	Strong importance	Very strong importance	Absolute importance	Intermediate levels
Relevance	1	3	5	7	9	2,4,6,8

Suppose that $C=\{C_j \mid j=1,2,...,n\}$ is the set of criteria. As seen in Equation (1), the result of pairwise comparison over n criteria is summarized in an $n\times n$ matrix where elements, a_{ij} $(i,j=1,2,\ldots,n)$, represent relative weights of criteria. In AHP, pairwise comparisons are made by more than one decision maker and all of these opinions are taken into account. In this case, geometric mean can be used as seen in Equation (2).

$$A=\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{n1} \\ a_{21} & a_{22} & \cdots & a_{n2} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}, \quad a_{ii}=1, a_{ji}=1/a_{ij}, a_{ij}\neq 0 \quad (1)$$

$$a_{ij}^{'}=\left(\prod_{l=1}^{k} a_{ijl}\right)^{\frac{1}{k}}, \; l=1,2,...,k; \; i,j=1,2,...,n; \; i\neq j \quad (2)$$

Where k is the number of decision makers. In the final step, the mathematical process begins with normalizing and finding relative weights for each matrix. Relative weights are defined through eigenvector $\lambda_{\max}$:

$$A^{'}\omega=\lambda_{\max}\omega \quad (3)$$

The matrix A has the rank 1, if pairwise comparisons are completely consistent ($\lambda_{\max}=1$). Here, weights can be obtained by normalizing any row or column. It should be noted that the quality of AHP output totally depends on the consistency among judgments made based on pairwise comparisons. Consistency is defined using the relation between inputs: $A: a_{ij}\times a_{jk}=a_{ik}$. The Consistency Index (*CI*) is defined as

$$CI=\frac{(\lambda_{\max}-n)}{(n-1)} \quad (4)$$

The Consistency Index Ratio (*CIR*) is used when evaluations are completely consistent:

$$CIR={CI}/{RI} \quad (5)$$

where *RI* (from Table 2) is the Random Index.

Table 2. Random Consistency Indices (Adopted from [10])

n	1	2	3	4	5	6	7	8
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41
n	9	10	11	12	13	14	15	
RI	1.45	1.49	1.51	1.48	1.56	1.57	1.59	

The value of 10 percent is acceptable as the upper limit for *CIR*. If *CIR* is larger than this value, assessment must be repeated to improve consistency. Measurements of consistency can be used to assess consistency among decision makers as well as consistency at different levels of hierarchy.

2.2. PROMETHEE Method

The PROMETHEE outranking method was adopted for this study to take the interests of various decision makers into consideration. This method is software-driven, user-friendly, provides direct interpretation of parameters, and analyzes sensitivity of results. The PROMETHEE family of outranking methods is one of the most recent MCDM methods which was developed by Brans [25] and further extended byBrans and Vincke [26].

2.2.1. PROMETHEE I

PROMETHEE I establishes a partial preorder among the alternatives. In PROMETHEE I, alternative *a* is preferred over alternative *b*, *aPb*, if alternative *a* has a greater leaving flow (ϕ^{+}) than alternative *b* and a smaller entering flow (ϕ^{-}) than the entering flow of alternative *b*:

$$\begin{aligned} aPb \text{ if}: \quad & \phi^{+}(a)>\phi^{+}(b) \text{ and } \phi^{-}(a)<\phi^{-}(b); \text{ or} \\ & \phi^{+}(a)>\phi^{+}(b) \text{ and } \phi^{-}(a)=\phi^{-}(b); \text{ or} \\ & \phi^{+}(a)=\phi^{+}(b) \text{ and } \phi^{-}(a)<\phi^{-}(b). \end{aligned} \quad (6)$$

PROMETHEE I allows indifference and incomparability situations. Therefore, sometimes partial rankings can be obtained. In the indifference situation (*aIb*), two alternatives a and b have the same leaving (ϕ^+) and entering flows (ϕ^-):

$$aIb\ if:\ \ \phi^+(a)=\phi^+(b)\ and\ \ \phi^-(a)=\phi^-(b). \qquad (7)$$

Two alternatives are considered incomparable, *aRb*, if alternative *a* is better than alternative *b* in terms of leaving flow, while the entering flows indicate the reverse:

$$\begin{aligned} aRb\ if:\ \ &\phi^+(a)>\phi^+(b)\ and\ \ \phi^-(a)>\phi^-(b);\ or \\ &\phi^+(a)<\phi^+(b)\ and\ \ \phi^-(a)<\phi^-(b). \end{aligned} \qquad (8)$$

PROMETHEE I ensures creation of indifferent and incomparable alternatives. In some ranking problems, PROMETHEE I can give a complete ranking depending on the evaluation matrix values.

2.2.2. PROMETHEE II

PROMETHEE II establishes a complete preorder among the alternatives, and consists of building a valid outranking relation. The basic principle of PROMETHEE II is based on a pair-wise comparison of alternatives. The implementation of the PROMETHEE II requires the following two additional types of information [1]:

i. **The Weights of Criteria:** determination of the weights is an important step in most multi-criteria methods. PROMETHEE II assumes that a decision-maker is able to weight the criteria appropriately, at least when the number of criteria is not too large;

ii. **The Preference Functions:** for each criterion, the preference function translates the difference between the evaluations obtained by two alternatives into a preference degree ranging from zero to one. This function is used to compute the degree of preference associated with the best action in case of pairwise comparisons.

Weighting of the criteria considered during decision making and evaluation of these criteria via preference functions are performed simultaneously. In order to facilitate this process, six types of particular preference functions have been proposed by [27]: (1) usual, (2) U-shape, (3) V-shape, (4) level, (5) V-shape with indifference and (6) Gaussian. These six types are particularly easy to define. For each criterion, the value of an indifference threshold, *q*, the value of a strict preference threshold, *p*, and the intermediate value between *p* and *q*, *s*, has to be defined. One of the important steps in utilizing this method is to select the preference function which is very difficult for most of decision makers who do not have sufficient knowledge about each criterion. In the case of how to select the best preference function for one criterion, [18,28] provided some suggestions. Some new preference functions have also been proposed by [29]. More details on these functions and how to select them for different types of criteria can be found in [18].

Figure 1 presents stepwise procedure for implementing PROMETHEE II. The procedure starts with determining deviations based on pair-wise comparisons where $d_j(a,b)$ is the deviation of criterion g_j for alternatives a and b. It is followed by using an associated preference function $P_j(a,b)$ for each criterion in Step 2. For each alternative a, belonging to the set A of alternatives, $\pi(a,b)$ is a global preference index of a over b which is calculated in Step 3. Step 4 shows the procedure for calculating the leaving and entering flows for each alternative and the partial ranking. The leaving flow $\phi^+(a)$ is the measure of the outranking character of a (how a dominates all the other alternatives of A). Consequently the entering flow $\phi^-(a)$ gives the outranked character of a (how a is dominated by all the other alternatives of A). The procedure comes to an end in step 5 by calculating the net outranking flow $\phi(a)$ for each alternative and completing the ranking. The maximum amount of net flow denotes the best alternative.

2.2.3. PROMETHEE GAIA

PROMETHEEGAIA (Geometrical Analysis for Interactive Aid) is suitable for visualization of problem characteristics through geometrical interpretations [30]. Graphical GAIA displays the relative position of the alternatives, in terms of contributions to the various criteria. Principal Components Analysis (PCA) is applied to the matrix of "*normed flows*", defined for alternative *a* and criterion *j* by:

$$\phi_j=\frac{1}{m\text{-}1}\sum_{b\neq a}[P_j(a,b)-P_j(b,a)] \qquad (9)$$

where *m* is the number of alternatives, and this is used to generate a two-dimensional plot in which the alternatives and criteria are represented in the same plot.

The information relative to a decision problem, including *n* criteria, can be represented in an *n*-dimensional space. The GAIA plane is the principal plane obtained by applying PCA to the set of actions in this space. This plane is obtained by projecting this information on a plane so that the smallest amount of information is lost. Alternatives are represented by points and criteria by axes. The conflicting character of the criteria appears clearly; criteria expressing the similar preferences on the data are oriented in the same direction, while the conflicting criteria are pointing in opposite directions.

3. Technologies in Building Construction

Effective project control and quality control systems, reduction in energy consumption, optimal use of materials, reduction in production and construction costs, and improved quality of construction parts and components are among the most important advantages of using advanced technologies in building construction industry. These technologies can be classified into four categories:

1. New technologies used in production and application of building materials, including self-compacting concrete, high-strength concrete, and fire-resistant bricks.
2. Advanced technologies used in building elements including windows and glass, thermal and acoustic insulators, and indoor/outdoor drywalls.
3. New structural systems including Lightweight Steel Framing (LSF), 3D Panels, bearing wall systems with tunnel formwork.

4. Novel technologies used in building installations and equipment including heating/cooling systems, air conditioning, intelligent systems for controlling safety and energy use, and BMS (Building Management System).

Step 1: Determination of deviations based on pair-wise comparison

$$d_j(a,b) = g_j(a) - g_j(b) \quad (9)$$

Step 2: Application of the preference function

$$P_j(a,b) = F_j[d_j(a,b)] \qquad j = 1,2,\dots,k \quad (10)$$

Step 3: Calculation of an overall or global preference index

$$\forall\, a,b \in A, \qquad \pi(a,b)\sum_{j=1}^{k} P_j(a,b)w_j \quad (11)$$

Where $\pi(a,b)$ of a over b (from 0 to 1) as defined as the weighted sum $p(a,b)$ of for each criterion and w_j is the weight associated with jth criterion.

Step 4: Calculation of outranking flows/ The PROMETHEE I partial ranking

$$\varphi^+ = \frac{1}{n-1}\sum_{x\in A}\pi(a,x) \quad (12)$$

$$\varphi^- = \frac{1}{n-1}\sum_{x\in A}\pi(x,a) \quad (13)$$

Step 5: Calculation of net outranking flow/ The PROMETHEE II complete ranking

$$\varphi(a) = \varphi^+(a) - \varphi^-(a) \quad (14)$$

Figure 1. Stepwise Procedure for PROMETHEE II

Given the importance of industrialization of mass housing projects, this paper deals with the third category of novel structural systems. The case study of this research is a mass construction project of low-rise housings in Iran. The building structural systems which are listed below have been used in the same location for the first time in Iran which provided an opportunity for comparing them. The land area of this project is 18.3 hectare, the capitation is 64.64 unit per hectare, number of blocks is 197 in 3-story, and the average area of each unit is 78 square meters. In this case study, five systems including 3D Panel with light walls in building frames, LSF (Light Steel Frame), ICF (Insulating Concrete Formwork), Tunnel Formwork system, and Tronco approved by the Iranian Building and House Research Center (BHRC) have been selected. The most important features of these systems are light weight, ease of construction, high construction speed, high structural system stability, environmental friendliness, and ease of industrial production.

3.1. Alternatives

Among the new architectural technologies, we briefly examine five systems that have been approved by BHRC to select the best system. These systems have been chosen because of their prevalence in the mass construction projects in Iran. The main specifications of these systems are briefly introduced here.

3.1.1. Light Steel Frame (LSF)

Advantages of this structural system shown in Figure 2 include:

- Extraordinary improvement in quality as a result of 90 percent fabrication in factories,
- Sixty percent reduction in dead load compared to similar structures,
- Ten percent increase in useful space of buildings due to use of thinner walls compared to traditional structures,
- Creating joints and junctions at installation sites by using bolts and nuts, saving energy under national construction code,
- Constructability at any climate due to making use of dry sites,
- Creating economic value by reducing implementation time, minimized human resources required at site,
- No requirement for heavy machineries at the construction site,
- Life cycle time of over 50 years,
- Easy installation of mechanical and electric equipment,
- Easily changeable building plans,
- Excellent diversity in materials used in façade and interior finishes,
- Environmental friendliness, and
- Minimizing waste at construction sites (green industry).

Figure 2. Light Steel Frame (LSF) in Residential Buildings

3.1.2. 3D Panels

3D Panel Building System shown in Figure 3 can be used for buildings with one or two stories. It provides light structures, no debris, resistance to heat, humidity and acoustic insulation, rapid transportation, easy installation, applicability in a wide range of buildings, increased useful space due to thinner walls, easy use for finishes, and impermeability. In addition, this system provides a clean waste-free site and a modified, ozone-friendly, fire-proof polystyrene core.

Figure 3. 3D Panel Building System

3.1.3. Insulating Concrete Formwork (ICF)

ICF includes permanent formworks used for concrete work and making reinforced concrete walls (See Figure 4). Once concrete work is done, the formwork forms a part of walls. ICFs are usually made of expanded polystyrene which should be protected by the exterior and interior envelopes and finishes. ICFs are often composed of two 5cm thick polystyrene plates connected to each other through plastic or metal connectors. In this system, walls are the main elements for bearing and transferring gravity and lateral loads that are uniformly distributed over foundation through walls and slabs. ICF has a large degree of indeterminacy and therefore, is expected to exhibit acceptable seismic behavior.

Figure 4. Preparing Insulating Concrete Formwork (ICF)

Figure 5. Tunnel Formwork System

3.1.4. Tunnel Formwork Systems

Tunnel Formwork System shown in Figure 5is a novel structural system with bearing walls and concrete roof. In this system, walls and reinforced concrete roofs arereinforced, formed, and casted continuously and simultaneously. The name comes from the form of monolithic metal formworks used in walls and roofs. Loads are largely borne by bearing walls and flat slabs. Due to the absence of beams and columns, structural walls are the main elements for bearing and transferring gravity and lateral loads. This system has excellent seismic performance because of simultaneous concrete work over walls, slabs, and roofs, and as well as integrated joints and elements. Major characteristics of this structural system include monolithic structure, improved seismic behavior due to presence of a box mechanism,spread stress instead of node-concentrated stress due to transformation from beam-and-column system to wall-and-slab system, increased degree of indeterminacy, increased delay in forming plastic joints, rapid construction due to simultaneous construction of walls and roofs, reduced concrete consumption compared to conventional concrete frames, and reduced material wastes.

3.1.5. Tronco system

This system which is shown in Figure 6 is inspired by conventional methods. Tronco combines traditional methods with new ones in construction buildings with small number of stories. The main element of this system is pipe-shaped parts made out of galvanized steel prepared on site. Door and window frames and electric and mechanical installations are installed during the construction. Given the empty space within tubes, walls, and roofs, EPS panels are used to maximize energy saving and minimize weights in Tronco systems.

Figure 6. Tronco System using Galvanized Steel Pipe Elements

3.2. Evaluation Criteria

In choosing the criteria for selection between alternatives, understanding and the acceptability of the method by the decision makers should be taken into account. The theory of multi-criteria evaluation should be understood by the decision makers in order to maximize the effectiveness of the decision making process and to avoid having the method become a “*black box*”. In this study, the five selected structural systems have been ranked based on the following criteria:

- **Cost**: This criterion includes costs per square meter of building, creating the production line, transportation, construction, and maintenance.
- **Ease of Construction**: Availability of special machineries, skilled labors, easy installation, and safety are some of the important aspects affecting this criterion.
- **Energy saving**: Energy parameters and indices include requirements of exterior walls and compliance with construction standards and codes.
- **Dead load**: to reduce damages resulting from earthquakes, buildings must be designed and constructed based on seismic provisions, latest standards, and minimum weights.
- **Number of stories**: number of stories and maximum allowable height are usually among the most important factors in mass construction projects.
- **Life cycle time**: permanency of materials, resistance to corrosion, and stability are among major concerns when evaluating life cycle time.

Some of these criteria are qualitative and should be transformed to quantitative criteria. The general method in evaluation of qualitative criteria is application of bipolar scale which is denoted in Table 3 for positive and negative indices.

Table 3. Bipolar Scale for Positive Indices

	Very Low	Low	Average	High	Very High
Positive indices	1	3	5	7	9
Negative indices	9	7	5	3	1

Table 4. Pairwise Comparison Matrix

Criterion	Cost	Ease of Construction	Energy Saving	Dead load	Number of stories	Life cycle time	Criteria weight
Cost	1	4	6	8	7	9	47.48%
Ease of Construction	0.25	1	3	5	4	7	21.38%
Energy saving	0.17	0.33	1	5	4	7	15.59%
Dead load	0.13	0.20	0.20	1	0.33	3	4.73%
Number of stories	0.14	0.25	0.25	3	1	4	7.83%
Life cycle time	0.11	0.14	0.14	0.25	0.25	1	2.63%

4. Results and Discussion

Qualitative and quantitative reliability of decisions made through AHP and PROMETHEE methods highly depends on the quality of the questionnaires designed and the accuracy of the information provided by the experts, professionals, and staff of the organizations involved in the decision making process. The outputs of questionnaires in this study have been used along with other data from reliable sources to complete pairwise comparison tables. Questionnaires were completed by 10 contractors (two contractors for each system), five engineering consultants involved in designing projects, and five owners. The weights of criteria and preference functions were determined by the decision makers. An analysis of the findings revealed that consultants mainly have focused on the technical criteria including dead load and energy saving; contractors have emphasized on the ease of construction; and lastly, owners' main concerns have been life cycle time and cost of the infrastructure.

4.1. AHP Ranking Results

Based on the criteria and alternatives, a hierarchical structure was designed (Figure 7). In order to compare criteria and alternatives, transforming relative concepts into quantities is needed. In the pairwise comparison matrix, each element represents relevance of the row criterion compared to the column criterion. Table 4 presents a pairwise comparison matrix. It should be noted that the matrix was constructed using geometric mean (Equation 2) of decision makers' perspectives based on the assumption of equal decision making power. For a balanced comparison, weights must be assigned to the criteria. These weights were assigned by obtaining the weight vector for each matrix. Here we used an approximation method (arithmetic mean) for computing the matrix weights. First, elements of each column were normalized through division by sum of that column. Then, mean of the normalized values in each column was selected as the weight of the criterion. Table 4 shows the weights assigned to the criteria.

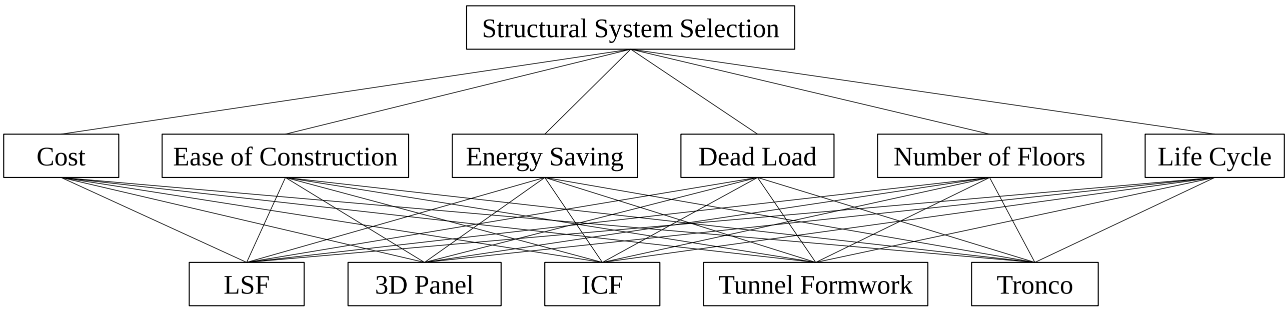

Figure 7. Hierarchical Structure for Alternatives and Criteria

Pairwise comparison matrix is a reliable base for calculations only if it is consistent. Consistency means a condition in which ratios assigned for comparing criteria and options in a matrix (based on the pairwise connection between criteria) are mutually consistent. Table 5 presents consistency ratios based on the previous equations.

Table 5. Parameters in Calculating Consistency Ratio in Pairwise Comparison Matrix

CIR	*IIR*	*CI*	λ_{max}
9%	1.24	0.117	6.585

As mentioned earlier, for applicability of pairwise comparison matrix in AHP, inconsistency in the matrices must not exceed 10 percent, as is the case here. In addition, to determine the ratios for sub-criteria and alternatives, further comparison matrices were constructed. Consistency was determined in a similar way. For example, Table 6 presents the comparison matrix for the structural systems of buildings in terms of cost.

Table 6. Pairwise Comparison Matrix for Available Options in Terms of Cost

Cost	LSF	3D Panel	ICF	Tunnel formwork	Tronco
LSF	1	3	5	7	2
3D Panel	0.33	1	2	7	0.5
ICF	0.2	0.5	1	4	0.2
Tunnel Formwork	0.14	0.14	0.25	1	0.11
Tronco	0.5	2	5	9	1

Calculations showed an inconsistency coefficient of 4.38 percent which is smaller than the maximum allowable value (10%). In the same way, alternatives for other criteria were compared to determine coefficients of inconsistency which are summarized in Table 7. Finally, relative weights of criteria were used along with respective vectors for each option to determine scores used in raking shown in Table 8. According to the scores and ranking shown in this table, the best choice has been 3D Panel followed by Tronco.

Table 7. Coefficients of Inconsistency for Comparison of Alternative

Criterion	Coefficient of inconsistency (%)
Cost	4.38
Ease of Construction	4.20
Energy Saving	4.32
Dead load	3.72
Number of stories	6.30
Life cycle time	3.92

Table 8. Scores and Ranking of Alternatives

Criterion	Cost	Ease of Construction	Energy Saving	Dead load	Number of stories	Life cycle time	Score (%)	Rank
Weight (%)	**47.48**	**21.38**	**15.59**	**4.37**	**7.83**	**2.63**		
LSF	0.167	0.159	0.159	0.655	0.074	0.590	19.11	3
3D Panel	0.413	0.360	0.360	0.348	0.376	0.267	38.35	1
ICF	0.034	0.037	0.037	0.039	377.1	0.590	15.52	4
TSF	0.088	0.081	0.075	0.140	0.765	0.590	15.30	5
Tronco	0.298	0.382	0.374	0.141	0.177	0.094	30.59	2

4.2. PROMETHEE Ranking Results

Before using the PROMETHEE method to rank the alternatives, for each criterion, a specific preference function, with its thresholds was defined. Preference functions and threshold values have been defined by the same decision-making team consisting of contractors, consultants, and owners. Decision-making team has set these values by taking into consideration the features of alternatives and the project conditions. The preference functions and thresholds are provided in Table 9.

Table 9. Criteria Preference Functions and Thresholds

Criteria	Preference Function	Preference Threshold	Indifference Threshold
Cost	Linear	280	30
Ease of Construction	V-Shape	6	-
Energy Saving	V-Shape	5	-
Number of Stories	Linear	7	2
Max. Dead Load	Linear	300	100
Life Cycle Time	Linear	15	5

After determining the evaluation matrix and preference functions, alternatives were evaluated by using the Decision Lab software. The leaving flow (ϕ^+), entering flow (ϕ^-) and net flow (ϕ) values obtained from the evaluation process are shown in Table 10.

Table 10. PROMETHEE Flows

	ϕ^+	ϕ^-	ϕ
LSF	0.1955	0.1910	0.0045
3D Panel	0.2565	0.1158	0.1407
ICF	0.2387	0.1508	0.0878
Tunneling	0.2000	0.4800	-0.2800
Tronco	0.2430	0.1960	0.0470

By using the flow values in Table 10, firstly the partial ranking was determined via PROMETHEE I (Figure 8). PROMETHEE I used leaving and entering flow values to find the partial ranking based on strongly established preferences only. As a result, not all alternatives could be compared one-to-one with the others and some alternatives were simply incomparable. Highlighting incomparable alternatives was interesting for decision makers because it usually emphasizes on alternatives with quite different profiles.

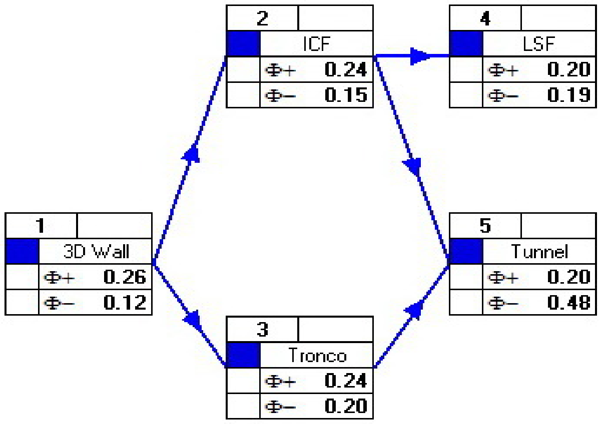

Figure 8. PROMETHEE I Partial Ranking

Tunnel Formwork system was determined as the worst alternative according to the PROMETHEE I partial ranking. LSF, 3D Panel, ICF, and Tronco systems were preferred to Tunnel Formwork system, and Tronco system was preferred to LSF system. On the other hand ICF, LSF, and Tronco systems were incomparable alternatives. As it is shown in Figure 8, PROMETHEE I selected3D Panel as the best alternative.

The net flow values, given in the last column of Table 10, were used in PROMETHEE II complete ranking to identify the best alternative (Figure 9). All the alternatives were ranked, leaving no incomparable pair of alternatives. This information is more straightforward and easier to use than the PROMETHEE I partial ranking, but it could be a reflection of less reliable preferences.

The 3D Panel was selected as the best alternative based on the provided information by PROMETHEE II, and the other ranked alternatives were ICF, Tronco, LSF, and Tunnel formwork system respectively.

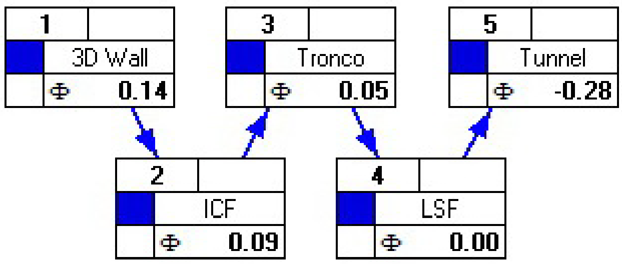

Figure 9. PROMETHEE II Complete Ranking

The GAIA plane provides the decision maker with comprehensive graphical image of the decision problem and is thus a descriptive complement to PROMETHEE rankings. The decision problem can be represented in the GAIA plane (Figure 10) where structural systems are represented by points and criteria by vectors. Through this approach, conflicting criteria may appear clearly. Criteria vectors expressing similar preferences are oriented in the same direction, while conflicting criteria are pointing in opposite directions. The length of each vector is a measure of its power in structural systems differentiation.

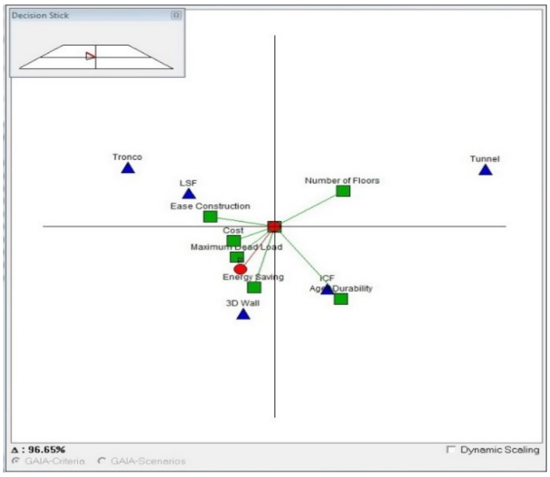

Figure 10. GAIA Plane

This plane is the result of principal component analysis (PCA), projecting the 6-dimensional space of criteria onto a two-dimensional plane. As it is shown in Figure 10, the Delta-parameter is 96.65 percent, which means only 3.35 percent of the total information is lost by the projection. It can be seen from Figure 10 that the *pi* vector is in the direction of energy saving, maximum dead load, and cost and the closest alternative to the *pi* vector is 3D Panel. This result is consistent with the complete ranking of PROMETHEE II.

4.3. AHP Sensitivity Analysis

Sensitivity analysis over the criteria indicates the extent to which variations in criteria weights and decision makers' perspective affect rankings obtained from AHP. The small difference between the scores obtained for LSF and Tronco indicates the sensitivity of these two options. Sensitivity analysis was carried out by utilizing Expert Choice 2000. The results are presented in Table 11. As seen in the table, the smallest variations are observed in the dead load criterion. It means that an increase by 25.7 percent in dead load exchanges LSF for Tronco (LSF goes down to the second place while Tronco moves up to the first rank). Therefore, dead load is the most sensitive criterion in determining the ranks of LSF and Tronco.

Table 11. Sensitivity Analysis Results on Ranks of LSF and Tronco

Criterion	Variations in weight (%)
Cost	-44.5%
Easy implementation	+54.5%
Saving energy	+68.2%
Dead load	+25.7%
Number of stories	+28.5%
Durability and useful life	+36.5%

4.4. PROMETHEE Sensitivity Analysis

For each criterion, a stability interval was computed. It indicates the range in which the weights of that criterion can be modified without affecting the PROMETHEE II complete ranking, provided that the relative weights of other criteria are not modified. This information is interesting for assessing the general robustness of the ranking. For the case of this research, it shows that if the weight of number of stories criterion changes in the range of 8.18 percent to 21.39 percent, the ranking does not change.

Table 12. Stability Intervals

	Initial Weight	Interval	
		Min	Max
Cost	0.25	0.1788	0.3111
Ease of Construction	0.20	0.0838	0.2374
Energy Saving	0.18	0.1071	1.0000
Number of Stories	0.15	0.0818	0.2139
Max. Dead Load	0.12	0.0000	0.4762
Life cycle time	0.10	0.0748	0.1705

Table 13. Ranking of Alternatives for Each Method

Alternatives	LSF	3D Panel	ICF	TSF	Tronco
AHP	3	1	4	5	2
PROMETHEE I	4*	1	2	5	3
PROMETHEE II	4	1	2	5	3

* LSF is not comparable with other alternatives – It is partially ranked 4.

The optimal system for the case study of this research based on both AHP and PROMETHEE is 3D Panel with light walls in building frames. Not only industrial production of this system is possible, but the light weight of this system reduces forces exerted as a result of earthquake, thereby improving earthquake resistance. Thus, using lightweight elements can be regarded as one solution that may improve the construction speed and costs. The systems discussed here can be used with minor modifications as appropriate systems for constructing lightweight and easily constructed buildings. Such appropriate building systems can be constructed at high speed without requirements for numerous equipment and machineries, and skillful human resources.

5. Conclusion

Application of new architectural technologies and structural systems can accelerate the construction speed in some developed countries such as Iran especially in mass residential building construction projects. Thus, selecting the appropriate structural system plays a significant role in design and construction. AHP method and PROMETHEE family of methods including PROMETHEE I, II and GAIA are well established multiple criteria decision making techniques but using them in the selection of structural systems is a novel application in building construction industry. Selection of criteria can also be an important issue in such a selection process and the case of this research can provide a recommendation for other researchers.

The weights obtained from the decision making team were included in the decision making process and the alternative priorities were determined based on these weights. Even though the same set of weights was used for both approaches, it is important to recognize that the weights in MCDM methods do not carry the same meaning. Comparison between the two methods was made based on the consistency of the results, the amount of interaction required between the analyst and the decision makers, and ease of understanding by technical and nontechnical professionals.

Decision matrix used in AHP application, introduced the decision makers’ preferences in which all relevant criteria were compared against each other. The information of this matrix was used to calculate the criteria weights. The distinct merit of AHP method is that it decomposes a decision problem into its constituent parts and builds hierarchies of criteria. As a result the decision problem is unbundled into its smallest elements which makes the importance of each element clear. But in the case of many criteria, it may become very difficult for decision makers to obtain clear view of the problem and to evaluate the results. The amount of interaction with the user increases dramatically with an increase in the number of alternatives and this increase prevents the user from continuing the analysis and leading to some inconsistencies. Complexity of the eigenvector method and the loss of information when converting the quantitative data into a 1-9 scale are other drawbacks of AHP.

PROMETHEE does not provide such structuring. PROMETHEE needs much less inputs; it takes into account the preference function of each criterion, determined by the decision-makers. By this way, each criterion is evaluated on a different basis and it is possible to make better decisions. PROMETHEE I identifies the alternatives which cannot be compared and the alternatives which are indifferent, by making a partial ranking (such as LSF), while PROMETHEE II provides a complete ranking for alternatives. The GAIA plane is proved to be a useful analytical tool for visualization of the decision problem. The GAIA plane is a powerful tool to identify conflicts between criteria and to group the alternatives.

The PROMETHEE II is the preferred method for evaluating solution alternatives for the appropriate structural system selection process. The method is consistent, easy to understand and requires little interaction with the decision makers. The linearity and the additive assumptions for the preference function is acceptable to the decision makers. By utilizing the PROMETHEE method for sensitivity analysis, the most effective criteria in decision making process are determined. These are unique features of PROMETHEE method which are not available in AHP, or other MCDM techniques such as ELECTRE and TOPSIS methods.

The proposed methodology has only been implemented on the structural system selection problem in the mass construction projects. It can be used in other construction engineering and management decision making problems such as equipment management, project delivery systems selection, and etc.

Acknowledgement

The authors would like to thank all the people contributed to the data collection process for this study.

References

[1] V. Balali, B. Zahraie, A. Hosseini, A. Roozbahani, Selecting appropriate structural system: Application of PROMETHEE decision making method, 2nd International Conference on Engineering Systems Management and Its Applications (ICESMA), Sharjah, UAE., 2010, pp. 1-6.

[2] M. Golabchi, H. Mazaherian, “New Architectural Technologies., University of Tehran Press., Tehran, Iran, 2010.

[3] V. Balali, B. Zahraie, A. Roozbahani, Integration of ELECTRE III and PROMETHEEII Decision Making Methods with Interval Approach: Application in Selection of Appropriate Structural Systems, Journal of Computing in Civil Engineering 28 (2) (2014) 297-314.

[4] M. Rogers, Using Electre III to aid the choice of housing construction process within structural engineering, Journal of Construction Management and Economic 18 (3) (2000) 333-342.

[5] M.A.B. Tabarak, D.S. William, Artificial neural network for the selection of buildable structural systems, Journal of Engineering, Construction and Architectural Management 10 (4) (2003) 263-271.

[6] R.M. Rivard, R.J. Leclercq, FROM ARCHITECTURAL SKETCHES TO FEASIBLE STRUCTURAL SYSTEMS, in: J. Gero (Ed.), Design Computing and Cognition ’06, Springer Netherlands, 2006, pp. 675-694.

[7] J. Messner, V. Sanvido, R. Kumara, StructNet: A Neural Network for Structural System Selection, Journal of Computer-Aided Civil and Infrastructure Engineering 9 (2008) 109-118.

[8] Z. Turskis, E.K. Zavadskas, F. Peldschus, Multi-criteria Optimization System for Decision Making in Construction Design and Management, Journal of Economics of Engineering Decisions 1 (61) (2009) 7-17.

[9] O.S. Shamrani, G.G. Schierle, Selection of optimum structural systems and materials, Journal of Art in Science and Engineering 13 (2009) 91-103.

[10] T.L. Saaty, Mathematical Models for Decision Support, Springer Link, 1988.

[11] K.M.A.-S. Al-Harbi, Application of the AHP in project management, International Journal of Project Management 19 (1) (2001) 19-27.

[12] M.K. Tiwari, R. Banerjee, A decision support system for the selection of a casting process using analytic hierarchy process, Journal of Production Planning & Control: The Management of Operations 12 (7) (2001) 689-691.

[13] J. Wong, H. Li, J. Lai, Evaluating the system intelligence of the intelligent building systems: Part 2: Construction and validation of analytical models, Automation in Construction 17 (3) (2008) 303-321.

[14] L. Juhua, T. Lishou, Y. Lei, Application of AHP Method in Building Construction and Cultural Combined - By Human Living Environment Construction of PengAn as the Background, Management and Service Science (MASS), 2011 International Conference on, 2011, pp. 1-4.

[15] D.C. Morais, A.T. de Almeida, Group decision-making for leakage management strategy of water network, Resources, Conservation and Recycling 52 (2) (2007) 441-459.

[16] R. Ginevičius, V. Podvezko, M. Novotny, The Use Of PROMETHEE Method For Evaluating The Strategic Pptential Of Construction Enterprises, The 10th International Conference on Modern Building Materials, Structures, and Techniques, Vilnius, Lithuania, 2010, pp. 407-413.

[17] J. San Cristobal, Critical Path Definition Using Multicriteria Decision Making: PROMETHEE Method, Journal of Management in Engineering 29 (2) (2013) 158-163.

[18] V. Balali, A. Mottaghi, O.R. Shoghli, M. Golabchi, Selection of Appropriate Material, Construction Technique, and Structural System of Bridges by Use of Multi-Criteria Decision-Making Method, Transportation Research Record: Journal of the Transportation Research Board (TRR) (2431) (2014) 79-87.

[19] R.U. Bilsel, G. Büyüközkan, D. Ruan, A fuzzy preference-ranking model for a quality evaluation of hospital web sites, International Journal of Intelligent Systems 21 (11) (2006) 1181-1197.

[20] M. Dağdeviren, Decision making in equipment selection: an integrated approach with AHP and PROMETHEE, Journal of Intelligent Manufacturing 19 (4) (2008) 397-406.

[21] M. Fathollah, F. Taham, A. Ashouri, Developing a Conceptual Framework for Simulation Analysis in a Supply Chain Based on

Common Platform (SCBCP), Journal of applied research and technology 7 (2) (2009) 163-184.

[22] A. Kasaeian, O. Shoghli, A. Afshar, T. Narmak, Nondominated archiving genetic algorithm for multi-objective optimization of time-cost trade-off, Proc., 8th WSEAS Int. Conf. on Evolutionary Computing, 2007.

[23] J. Wang, C. Wei, D. Yang, A decision method for vendor selection based on AHP/PROMETHEE/GAIA, Journal of Dalian University of Technology 46 (6) (2006) 926-931.

[24] J.-J. Wang, D.-L. Yang, Using a hybrid multi-criteria decision aid method for information systems outsourcing, Computers & Operations Research 34 (12) (2007) 3691-3700.

[25] J.P. Brans, Lingenierie de la Decision. Elaboration DinstrumentsDaide a la Decision, Methode PROMETHEE In: Nadeau, R., Landry, M. (Eds.), Laide a la Decision: Nature, Instruments et Perspectives Davenir., de Universite Laval, Quebec, Canada, 1982, pp. 183-214.

[26] J.P. Brans, P. Vincke, A Preference Ranking Organisation Method: (The PROMETHEE Method for Multiple Criteria Decision-Making), Management Science 31 (6) (1985) 647-656.

[27] J.P. Brans, P. Vincke, B. Mareschal, How to select and how to rank projects: The Promethee method, European Journal of Operational Research 24 (2) (1986) 228-238.

[28] S.K. Amponsah, K.F. Darkwah, A. Inusah, Logistic preference function for preference ranking organization method for enrichment evaluation (PROMETHEE) decision analysis., African Journal of Mathematics and Computer Science Research 5 (6) (2012) 112-119.

[29] V. Podvezko, A. Podviezko, Dependence of multi-criteria evaluation result on choice of preference functions and their parameters, Technological and Economic Development of Economy 16 (1) (2010) 143-158.

[30] J.P. Brans, B. Mareschal, The PROMETHEE GAIA Decision Support System for Multicriteria Investigations, Journal of Investigation Operative 4 (2) (1994) 107-117.