Decision-making in structural engineering using BHARAT-II method

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ABSTRACT

This paper presents a novel Multi-Attribute Decision-Making (MADM) method, named BHARAT-II (Best Holistic Adaptable Ranking of Attributes Technique - II), to choose the best alternatives for different structural engineering-related problems. Two case studies are provided to illustrate the suggested MADM method. The first case study deals with three problems. The three problems are: (a). selecting the best construction method for a bridge out of 04 available methods considering 07 selection attributes, (b). selecting the best structural system of the bridge out of 07 structural systems considering 11 selection attributes, and (c). selecting the best construction material out of 04 materials considering 04 selection attributes. The challenge of choosing the ideal structural system for a housing project is covered in the second case study by considering 04 alternative structural systems and 05 selection attributes involving 19 sub-attributes. The results of the proposed BHARAT-II decision-making method are compared with those of other MADM methods. The proposed method is adaptable to solve the best alternative selection problems of structural engineering.

1. Introduction

It is possible to classify the structural system selection process as a Multi-Attribute Decision-Making (MADM) problem since it is influenced by multiple compromising and conflicting attributes (i.e., criteria). Decision-makers in the fields of structural engineering and management require mathematically simple approaches that allow them to take their opinions into account. Taking into account a complete set of criteria to develop acceptable, safe, consistent, and dependable designs is a significant issue when choosing the right material, construction method, and structural system. Engineers can benefit from using MADM strategies to help them make the most out of competing criteria and alternatives from a variety of sources. A number of characteristics, including alignment concepts, design survey, geotechnical study, bridge concepts, and structural design, define the selection of materials, construction methods, and structural systems. These characteristics make MADM an appropriate approach.

Any MADM method for structural engineering selection problems involves the selection attributes, alternatives, weights of importance ascribed to the attributes, and performance data of the alternatives. The selected MADM method analyzes the provided data while taking these four factors into consideration and recommends the optimum option for the specified structural engineering application. The decision-maker uses professional judgment and knowledge to determine how important each attribute is for the specific application.

Rogers (2000) employed the Elimination Et Choix Traduisant la Realitè III (ELECTRE III) method for selecting the housing construction processes. Wong, Li, and Lai (2008) used Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP) to evaluate the intelligence of intelligent building systems. Pan (2008) used the fuzzy AHP method for selecting the best bridge construction method. A case study evaluating several bridge construction techniques was provided to show off the model's application and capabilities. Turksis, Zavadskas, and Peldschus (2009) utilized a multicriteria optimization system to make decisions about construction design and management. The normalization of the qualitative and quantitative criteria took into account the game theory's two-sided difficulties. Malekly, Mousavi, and Hashemi (2010) employed a Quality Function Deployment (QFD) approach for translating the project requirements into design requirements and for calculating the weights of the criteria. The Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) method was then used for selecting a best superstructure.

Balali, Mottaghi, Shoghli, and Golabchi (2014) used the PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations) method to create a multi-criteria decision-making model for choosing the right material, building method, and structural system for bridges. They computed the objective weights of the attributes using the entropy approach. In another work, Balali, Zahraie, and Roozbahani (2014a) suggested an integrated strategy for choosing suitable structural systems that combined the ELECTRE III and PROMETHEE II techniques. Balali, Zahraie, and Roozbahani (2014b) investigated the applicability of the AHP and PROMETHEE techniques for solving the structural system selection problem.

The AHP approach was employed by Polat, Turkoglu, and Damci (2018) to ascertain the weights of the selection attributes of a housing project's structural system, and the VIKOR (VIšekriterijumsko KOmpromisno Rangiranje) method was utilized to rank the structural system alternatives. Using a MADM approach based on q-rung ortho-pair fuzzy Aczel-Alsina aggregation operators, Khan, Wang, Ullah, and Karamti (2022) chose building materials. Pereira and Gartbatov (2022) used the TOPSIS method for the best ship structural design. The chosen ship design option had the lowest anticipated total cost, which reduced the risk and lowered the building and operating expenses while maximizing cargo capacity and energy efficiency. Asghar, Khan, Albahar, and Alammari (2023) used a complicated picture fuzzy soft set to optimize the MADM technique to construction supply chain management. Soni, Chakraborthi, Das, and Saha (2023) recycled waste plastic and agro-industrial waste for structural purposes using a fuzzy group decision-making approach for material selection of sustainable composites.

Researchers have established dependable procedures for choosing the optimum alternatives for specific structural engineering applications during the past 20 years using a variety of MADM techniques. The literature study reveals that the researchers employed various MADM techniques, including ELECTRE, TOPSIS, VIKOR, and PROMETHEE. The researchers used techniques like AHP, fuzzy AHP, and the entropy approach to find the weights of relevance of the selection attributes. The MADM methods were then used to process the data using those weights. Additionally, fuzzy scales were employed to translate the qualitative characteristics into numerical values. Fuzzy logic, on the other hand, employs several membership functions and defuzzification techniques, and the application of these techniques and functions yields various outcomes (Saaty, 2007; Rao, 2013). The aforementioned MADM techniques are helpful, but they also have disadvantages and need a lot of processing power (Rao, 2024a).

The performance data of the alternatives in structural engineering problems corresponding to various selection attributes (quantitative and qualitative) must be processed by a more logical, systematic, simple, and efficient MADM method in order to rank the alternatives according to their overall performance and logically determine the weights of importance of the selection attributes.

Recently, Rao (2024a, 2024b) developed an improved MADM method named BHARAT based on a simple ranking procedure for solving decision-making problems related to manufacturing and industrial engineering. The second version of the BHARAT method, named BHARAT-II, has been recently proposed by Rao (2024c), Rao and Lakshmi (2024). In the present work, the BHARAT-II method is extended for solving the structural engineering related selection problems. *This is the first time that the BHARAT-II method has been used for solving the decision-making problems of structural engineering*. The next section provides a detailed explanation of the suggested BHARAT-II method.

2. BHARAT-II methodology for structural engineering problems

The steps of the suggested BHARAT-II method for structural engineering issues are outlined below.

Step 1: For the above structural engineering problem, identify the alternatives *Aj* (for *j = 1, 2, ..., n*) and the relevant attributes *Si* (*i = 1, 2, ..., m*).

Step 2:

Determine the selection qualities' priority in order to determine the weights *wi* (for *i = 1, 2, ..., m*). Depending on how important they are in relation to one another, they are ranked 1, 2, 3, 4, 5, and so on. In cases where two or more traits are deemed equally significant, an average rank will be assigned. Let's take an example where there are five selection criteria (*U, V, W, X*, and *Y*) and they are assigned ranks of 1, 2, 3, 4, and 5. The rank relations are shown in Matrix *M1*.

$$M1 = \begin{array}{c} \\ U \\ V \\ W \\ X \\ Y \end{array} \begin{array}{c} \begin{array}{ccccc} U & V & W & X & Y \end{array} \\ \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ 1/2 & 1 & 3/2 & 4/2 & 5/2 \\ 1/3 & 2/3 & 1 & 4/3 & 5/3 \\ 1/4 & 2/4 & 3/4 & 1 & 5/4 \\ 1/5 & 2/5 & 3/5 & 4/5 & 1 \end{bmatrix} \end{array}$$

Note that in matrix *M1*, the diagonal elements are 1, and the elements below the diagonal are the reciprocals of the rank relations of the attributes given above the diagonal. Every row of the *M1* matrix has its arithmetic mean determined; they are 3 (or 15/5), 1.5 (or 7.5/5), 1.0 (or 5/5), 0.75 (or (15/4)/5), and 0.6 (or (15/5)/5) in that order. 6.85 is the grand total of these row sums, or 3 + 1.5 + 1.0 + 0.75 + 0.6. The *M2* matrix, which represents the weights of the five attributes taken into consideration, is now obtained by dividing each row sum by the total of 6.85.

$$M2 = \begin{bmatrix} 0.4379 \\ 0.2190 \\ 0.1460 \\ 0.1095 \\ 0.0876 \end{bmatrix}$$

The consistency check-as in the AHP and BWM approaches-is carried out to verify the consistency of the rank relations given in matrix *M1*.

$$M3 = M1*M2 = \begin{bmatrix} 2.1900 \\ 1.0950 \\ 0.7300 \\ 0.5475 \\ 0.4380 \end{bmatrix}$$; *M3*/*M2* is now used to compute the *M4* matrix.

$$M4 = M3/M2 = \begin{bmatrix} 2.1900/0.4379 \\ 1.0950/0.2190 \\ 0.7300/0.1460 \\ 0.5475/0.1095 \\ 0.4380/0.0876 \end{bmatrix} = \begin{bmatrix} 5 \\ 5 \\ 5 \\ 5 \\ 5 \end{bmatrix};$$

Largest Eigenvalue (λ_{max}) = Average of *M4* = (5+5+5+5+5)/5, or 5. Consistency index (CI); (λ_{max}–*m*)/(*m*-1) = (5-5)/(5-1) = 0. *m* is the number of attributes; the size of the M1 matrix is 5. The CI value indicates whether there is an error present in the rank relation judgments. The rank relations provided in the *M1* matrix are entirely consistent, as indicated by the CI value of 0. Consequently, the attributes *U*, *V*, *W*, *X*, and *Y* can be assigned weights of 0.4379, 0.2190, 0.1460, 0.1095, and 0.0876, respectively.

Step 3: Instead of utilizing a fuzzy scale, convert the qualitative attribute data into numeric data using a simple ordinal scale. Rao (2024a) demonstrated that regular, basic scales can accomplish the same goals as fuzzy ones, negating the requirement for fuzzy scales. Fuzzy scales developed by various scholars to address linguistic or qualitative characteristics utilizing various membership functions can be easily replaced by simple conventional scales. Table 1 illustrates how a linguistic or qualitative attribute can be converted into a numeric attribute using an 11-point rating system.

Step 4: Normalize the data for a selection attribute. The term "best" designates the highest value that can be found for a beneficial attribute and the lowest value that can be found for a non-beneficial attribute. The performance measures of alternatives require normalization. For a beneficial attribute, the normalized value $(x_{ji})_{norm}$ is $x_{ji}/x_{i\cdot best}$; and it is $x_{i\cdot best}/x_{ji}$ for a non-beneficial attribute. The value $x_{i\cdot best}$ represents the *i*-th attribute's best value.

Table 1

Conversion of a qualitative attribute on an 11-point scale into a quantitative attribute

Linguistic or qualitative description	Fuzzy scale value for a beneficial attribute	Simple scale value for a beneficial attribute	Fuzzy scale value for a non-beneficial attribute	Simple scale value for a non-beneficial attribute
Exceptionally low (or similar term)	0.0455	0.0	0.9545	1.0
Extremely low (or similar term)	0.1364	0.1	0.8636	0.9
Very low (or similar term)	0.2273	0.2	0.7727	0.8
Low (or similar term)	0.3182	0.3	0.6818	0.7
Below average (or similar term)	0.4091	0.4	0.5909	0.6
Average (or similar term)	0.5	0.5	0.5	0.5
Above average (or similar term)	0.5909	0.6	0.4091	0.4
High (or similar term)	0.6818	0.7	0.3182	0.3
Very high (or similar term)	0.7727	0.8	0.2273	0.2
Extremely high (or similar term)	0.8636	0.9	0.1364	0.1
Exceptionally high (or similar term)	0.9545	1.0	0.0455	0

Source: Rao (2024a)

Step 5: The overall score of an alternative is ∑ wi*(xi)norm. It comes from multiplying the weights of the selected attributes by the matching normalized data of the attributes for the alternatives.

Step 6: Based on the total scores, arrange the alternatives in decreasing order. The solution that comes out on top overall for the specific structural engineering problem under investigation is the one that is chosen.

Figure 1 depicts the flowchart of the suggested decision-making method.

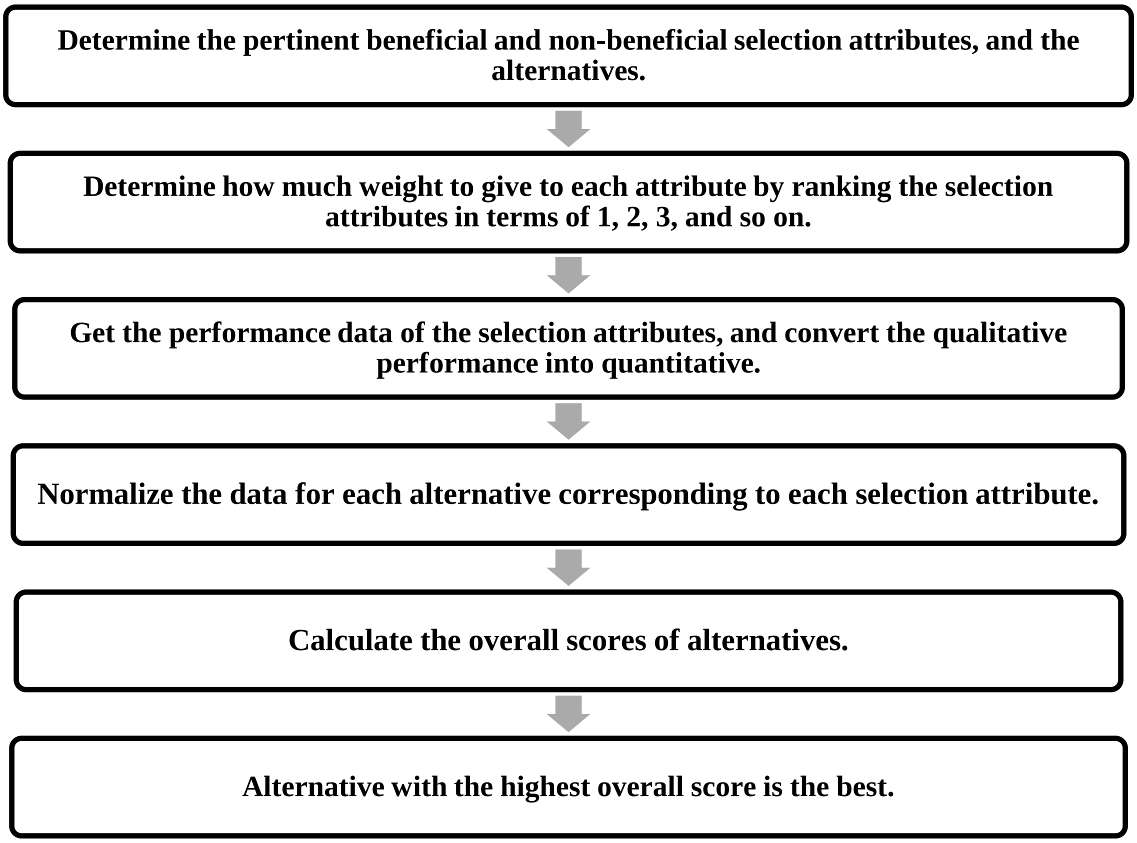


Figure 1. Flowchart of the proposed BHARAT-II method

3. Structural engineering applications of the proposed BHARAT-II method

3.1. Case study 1: Choosing the best alternative for a structural system of bridges

Balali et al. (2014) presented a case study of the Kashkhan Bridge in Iran. The bridge measured 1,050 feet in length and 33 feet in width at the deck. At the site of the proposed bridge, the river was 230 feet wide under normal circumstances and 558 feet wide during a 100-year flood. The bridge could have a minimum span of 230 feet and a maximum span of 345 feet. The data of the pertinent selection attributes was collected for the different alternative construction methods, alternative structural systems, and alternative construction materials. The project engineers, managers, and designers of bridges were contacted to complete a questionnaire and the necessary information was thus collected. The alternatives considered under each stage are shown in Figure 2. While deciding the best alternatives during the three stages of decision-making, the first stage was deciding about the construction method, second stage was deciding about the structural system, and the third stage was deciding about the construction material.

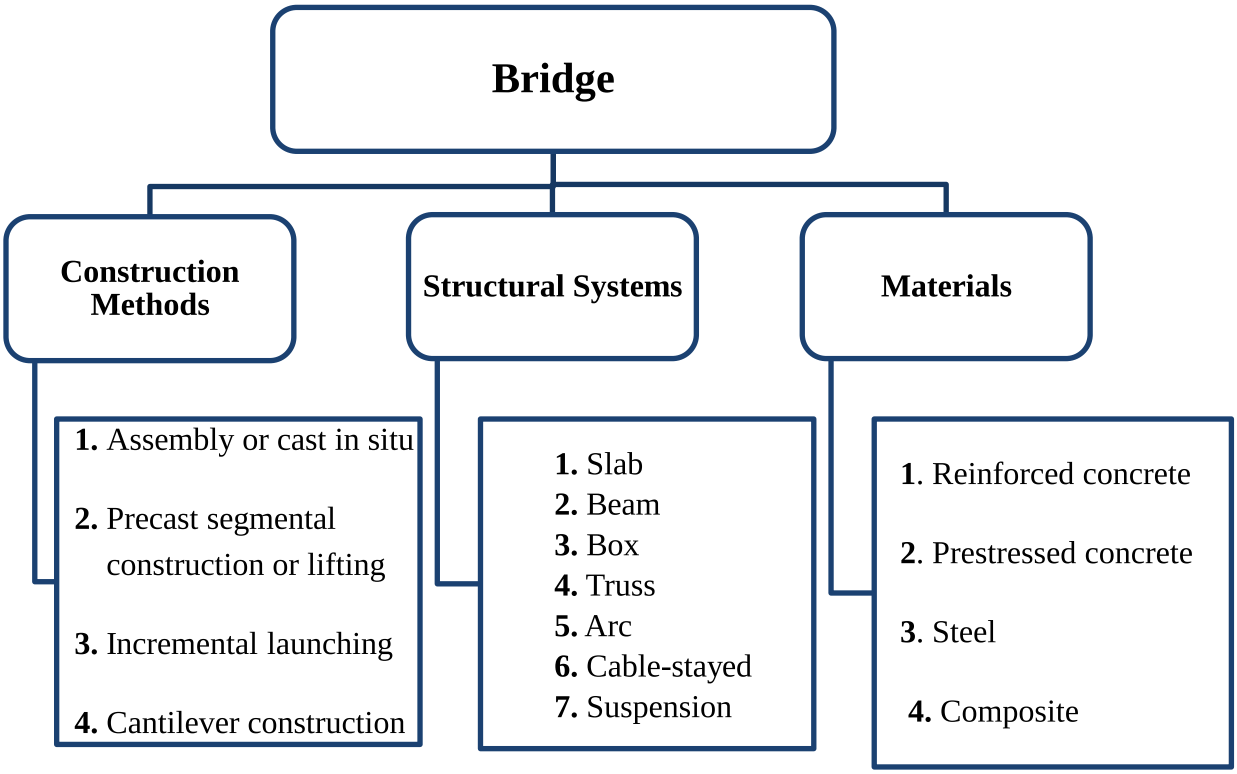


Figure 2. Alternatives available for (a). construction methods, (b). structural systems, and (c). materials

Now, the steps of choosing the right (i.e., best) alternative for each stage using the BHARAT-II method are explained below.

3.1.1. Case study 1(a): Choosing the best alternative construction method

This stage of the decision-making problem considered 04 alternative construction methods and 07 selection attributes. The 7 selection attributes included: Cost (C), Usability in Height (UH), Construction Speed (CS), Environmental Issues (EI), Quality of Construction (QC), Module Installation of Deck (MID), and Traffic Interference (TI). The attributes C, EI, and TI are non-beneficial attributes, and the remaining are beneficial attributes. The attributes EI, QC, MID, and TI were described qualitatively (i.e., linguistically). To select the best constructive method out of the 04 available construction methods, the steps of the BHARAT-II method are given below.

Step 1: Table 2 displays the alternative construction methods as well as the selection criteria for construction methods. These share the same considerations as Balali et al. (2014). The attributes denoted by downward arrows are the non-beneficial attributes: C, EI, and TI. The favorable attributes are denoted by upward arrows and are UH, CS, QC, and MID. Table 1 is used to assign the corresponding quantitative values to the qualitatively indicated attributes EI, QC, MID, and TI. In Table 2, the numbers in parenthesis denote the proper quantitative values assigned using a basic 11-point scale, depending on whether they are advantageous or non-beneficial. The best values for the respective attributes are indicated by the numbers in bold.

Table 2

Information about the 04 different construction methods and the 07 attributes of case study 1(a)

Alternative construction method	**Attributes**						
	C ↓	**UH ↑**	**CS ↑**	**EI ↓**	**QC ↑**	**MID ↑**	**TI ↓**
Assembly or cast in situ	**0.1**	10	50	H (0.3)	A (0.5)	VL (0.2)	VH (0.2)
Precast segmental construction or lifting	**0.1**	10	**450**	A (0.5)	**VH (0.8)**	A (0.5)	H (0.3)
Incremental launching	0.25	**1000**	400	**VL (0.8)**	**VH (0.8)**	**VH (0.8)**	**L (0.7)**
Cantilever construction	0.15	**1000**	15	L (0.7)	A (0.5)	H (0.7)	**L (0.7)**

VH: very high; H: High; A: Average; VL: very low; L: low
Source: Balali et al. (2014)

Step 2: Ranks are assigned in order to establish the weights of the seven selection attributes. UH has been awarded rank 1 since it is deemed to be far more significant for the application. MID is assigned rank 2, and EI is assigned rank 3. It is thought that the attributes C and QC are equally important. Therefore, C and QC are given an average rank of 4.5 (i.e., (4+5)/2). CS is given position six, and TI is given rank seven. Table 3 displays the weights and rank connections for the seven attributes. Table 3's final column displays the attributes' computed weights.

Table 3

Relationships between the 7 attributes of case study 1(a)

Attributes	**Attributes**							**Average of rows**	**Attributes' weights**
	C	**UH**	**CS**	**EI**	**QC**	**MID**	**TI**		
C	1	1/4.5	6/4.5	3/4.5	1	2/4.5	7/4.5	0.88888	0.08589
UH	4.5	1	6	3	4.5	2	7	4	0.38650
CS	4.5/6	1/6	1	3/6	4.5/6	2/6	7/6	0.66666	0.06442
EI	4.5/3	1/3	6/3	1	4.5/3	2/7	7/3	1.33333	0.12833
QC	1	1/4.5	6/4.5	3/4.5	1	2/4.5	7/4.5	0.88888	0.08589
MID	4.5/2	1/2	6/2	3/2	4.5/2	1	7/2	2	0.19325
TI	4.5/7	1/7	6/7	3/7	4.5/7	2/7	1	0.57143	0.05521

Source: Balali et al. (2014)

The CI value is 0, and there is perfect consistency in the judgments.

Step 3: Table 1 is used to convert the qualitative expressions of C, EI, and TI into quantitative values without the use of fuzzy logic. Table 2 displays these numbers in parentheses. For the purpose of normalization, the values for C, EI, and TI that were assigned after this can be regarded as advantageous.

Step 4: Based on the "best" construction method for every attribute, the data is normalized. In Table 2, the attributes with the highest values are bolded. Normalized values are displayed in Table 4. For example, (10/1000) yields the normalized value of 0.01 for UH, which corresponds to “Assembly or cast in situ”. (50/450) yields the normalized value of 0.11111 for CS, which corresponds to “Assembly or cast in situ”. (0.3/0.8) yields the normalized value of 0.375 for EI, which corresponds to “Assembly or cast in situ.” In a similar manner, Table 4 presents the normalized data.

Table 4

Normalized data for case study 1(a)

Alternative construction method	Attributes						
	C	UH	CS	EI	QC	MID	TI
Assembly or cast in situ	1	0.01	0.111111	0.375	0.625	0.25	0.285714
Precast segmental construction or lifting	1	0.01	1	0.625	1	0.625	0.428571
Incremental launching	0.4	1	0.888889	1	1	1	1
Cantilever construction	0.666667	1	0.033333	0.875	0.625	0.875	1

Step 5: The weights of the selected attributes are multiplied by the corresponding normalized data of the attributes to find the overall scores of the alternatives. For example, the construction method “Assembly or cast in situ” has an overall score that is calculated as,

Overall score (Assembly or cast in situ) = 0.08589*1 + 0.38650*0.01 + 0.06442*0.111111 + 0.12833*0.375 + 0.08589*0.625 + 0.19325*0.25 + 0.05521*0.258714 = 0.262992

Step 6: The different construction methods are listed in descending order of total score.

Incremental launching: 0.941298

Cantilever construction: 0.836619

Precast segmental construction or lifting: 0.465026

Assembly or cast in situ: 0.262992

The “Incremental launching” method has the highest overall score, making it the ideal option for the application in question. Balali et al. (2014) employed the entropy technique, which determines the objective weights of the attributes by calculating their numerical values without taking the decision-makers priorities into account. The weights obtained for C, UH, CS, EI, QC, MID, and TI were 0.13, 0.23, 0.11, 0.19, 0.13, 0.20, and 0.02 respectively. Using these weights and the PROMETHEE approach, Balali et al. (2014) proposed the following alternative construction methods.

Balali et al. (2014): Incremental launching - Cantilever construction - Precast segmental construction or lifting - Assembly or cast in situ.

As a result, “Incremental launching” was recommended as the optimal option by the PROMETHEE approach, which also used the weights determined by the entropy method. Nonetheless, the construction methods can be placed in the following order for fair comparison if the same entropy weights of the attributes as used by Balali et al. (2014) are utilized in the suggested BHARAT-II method.

BHARAT-II method (using the entropy weights):

Incremental launching: 0.919778

Cantilever construction: 0.762833

Precast segmental construction or lifting: 0.624621

Assembly or cast in situ: 0.352737

The "Incremental launching" was recommended as the optimal option by the proposed decision-making approach, which also employed the same entropy weights as Balali et al. (2014). "Cantilever construction" is the second option. Once again, it should be stressed that the suggested process for making decisions consists of a straightforward normalization procedure and the computation of the overall scores of various construction methods in comparison to the computationally demanding entropy and PROMETHEE methods. Compared to the entropy weights employed by Balali et al. (2014), the ranks assignment mechanism and the decision-maker's computation of the weights of the attributes make more sense. The suggested approach considers the preferences of the decision-makers. Recall that Balali et al. (2014) said that due to project and feasibility limitations, the decision-making team ultimately decided to remove the "Incremental launching" and "Assembly or cast in situ." As a result, even if the PROMETHEE and the current decision-making procedures rank "Cantilever construction" as the second option, it ultimately wins out as the first alternative. In actuality, the design team ought to have taken these project and feasibility conditions into account in the beginning itself.

3.1.2. Case study 1(b): Best alternative structural system selection for the bridge

The right structural system should be chosen after the best construction method has been determined. This stage of the decision-making problem considered 07 alternative structural systems and 11 selection attributes. The 11 selection attributes included: Cost (C), Span (S), Inspection and Maintenance (IM), Construction Speed (CS), Ease of Construction (EC), Traffic Load (TL), Dependence on Imported Technologies (DIT), Architecture Design (AD), Irregular Geometric (IG), Complexity in Construction (CC), and Symbolic and Aesthetics (SA). The attributes C, IM, DIT, and CC are non-beneficial attributes and the remaining are beneficial attributes. The attributes EC, TL, DIT, AD, IG, CC, and SA were described qualitatively.

Now, to select the best structural system out of the 07 available structural systems (i.e., slab, beam, box, truss, arch, cable-stayed bridge, and suspension bridge), the steps are carried out.

<u>Step 1:</u> The different structural systems and the selection criteria for structural systems are displayed in Table 5. These are the same as what Balali et al. (2014) took into consideration. The non-beneficial attributes are denoted by downward arrows and are C, IM, DIT, and CC. The positive attributes are denoted by upward arrows and are S, CS, EC, TL, AD, IG, and SA. The qualitative descriptions of EC, TL, DIT, AD, IG, CC, and SA are assigned the appropriate quantitative values using Table 1. The numbers in parentheses in Table 5 indicate the acceptable quantitative values assigned using an 11-point scale, depending on whether they are advantageous or not. The values in bold denote the optimal values for the respective attributes.

Table 5

Information about the 11 attributes and 07 alternative structural systems of case study 1(b)

Alternative structural systems	**Attributes**										
	C ↓	**S ↑**	**IM ↓**	**CS ↑**	**EC ↑**	**TL ↑**	**DIT ↓**	**AD ↑**	**IG ↑**	**CC ↓**	**SA ↑**
Slab	**0.7**	40	**0.3**	35	**VH (0.8)**	**VH (0.8)**	**VL (0.8)**	L (0.3)	**VH (0.8)**	**VL (0.8)**	VL (0.2)

Alternative structural systems	Attributes										
	C ↓	S ↑	IM ↓	CS ↑	EC ↑	TL ↑	DIT ↓	AD ↑	IG ↑	CC ↓	SA ↑
Beam	0.8	30	**0.3**	**80**	**VH (0.8)**	**VH (0.8)**	**VL (0.8)**	L (0.3)	L (0.3)	**VL (0.8)**	VL (0.2)
Box	1.5	150	**0.3**	25	H (0.7)	**VH (0.8)**	L (0.7)	A (0.5)	A (0.5)	L (0.7)	L (0.3)
Truss	1.8	80	0.5	45	A (0.5)	**VH (0.8)**	**VL (0.8)**	A (0.5)	VL (0.2)	L (0.7)	VL (0.2)
Arch	2.5	250	**0.3**	25	L (0.3)	**VH (0.8)**	L (0.7)	**VH (0.8)**	VL (0.2)	L (0.7)	H (0.7)
Cable-stayed bridge	3	400	0.8	15	L (0.3)	H (0.7)	H (0.3)	**VH (0.8)**	VL (0.2)	H (0.3)	**VH (0.8)**
Suspension bridge	5	**1200**	1	7	VL (0.2)	H (0.7)	H (0.3)	**VH (0.8)**	VL (0.2)	VH (0.2)	**VH (0.8)**

VH: very high; H: High; A: Average; VL: very low; L: low
Source: Balali et al. (2014)

Step 2: Ranks are assigned to find the weights of the 07 selection attributes. Rank 1 is assigned to "Ease of Construction (EC)" as it is considered much more important for the given application. The rank 2 is assigned to Span (S). The attributes IM, CS, and DIT are considered equally significant. Hence, IM, CS, and DIT are given an average rank of 4 (i.e., (3+4+5)/3). TL has been assigned Rank 6. Since the attributes C and EC are seen as equally significant, they are each given the average rank of 7.5, or (7+8)/2. AD, IG, and SA are regarded as equally important qualities. Thus, AD, IG, and SA are given the average rank of 10 (i.e., (9+10+11)/3). Table 6 displays the weights and rank relations for the 11 attributes.

Table 6

Relationships between the 11 selection attributes of case study 1(b)

Selection attributes	Attributes											Means of rows	Weights of attributes
	C	S	IM	CS	EC	TL	DIT	AD	IG	CC	SA		
C	1	2/7.5	4/7.5	4/7.5	1/7.5	6/7.5	4/7.5	10/7.5	10/7.5	1	10/7.5	0.8	0.04469
S	7.5/2	1	4/2	4/2	1/2	6/2	4/2	10/2	10/2	7.5/2	10/2	3	0.1676
IM	7.5/4	2/4	1	1	1/4	6/4	4/4	10/4	10/4	7.5/4	10/4	1.5	0.0838
CS	7.5/4	2/4	1	1	1/4	6/4	4/4	10/4	10/4	7.5/4	10/4	1.5	0.0838
EC	7.5	2	4	4	1	6	4	10	10	7.5	10	6	0.3352
TL	7.5/6	2/6	4/6	4/6	1/6	1	4/6	10/6	10/6	7.5/6	10/6	1	0.05586
DIT	7.5/4	2/4	1	1	1/4	6/4	4/4	10/4	10/4	7.5/4	10/4	1.5	0.0838
AD	7.5/10	2/10	4/10	4/10	1/10	6/10	4/10	1	1	7.5/10	1	0.6	0.03352
IG	7.5/10	2/10	4/10	4/10	1/10	6/10	4/10	1	1	7.5/10	1	0.6	0.03352
CC	1	2/7.5	4/7.5	4/7.5	1/7.5	6/7.5	4/7.5	10/7.5	10/7.5	1	10/7.5	0.8	0.04469
SA	7.5/10	2/10	4/10	4/10	1/10	6/10	4/10	1	1	7.5/10	1	0.6	0.03352

Step 3: The qualitative descriptions of EC, TL, DIT, AD, IG, CC, and SA are assigned the appropriate quantitative values using Table 1. Table 5 displays these numbers in parentheses. For

the purpose of normalization, the values assigned for EC, TL, DIT, AD, IG, CC, and SA after assignment in this manner can be deemed beneficial.

Step 4: The "best" structural system is used to normalize the data. In Table 5, the attributes with the highest values are bolded. Normalized values are displayed in Table 7. For instance, (40/1200) gives the normalized value of 0.033333 for S, corresponding to Slab; (0.3/0.3) gives the value of 1 for IM, corresponding to Slab; and (0.3/0.5) gives the value of 0.6 for IM, corresponding to Truss.

Table 7

Normalized data for case study 1(b)

Alternative structural systems	**Attributes**										
	C ↓	**S ↑**	**IM ↓**	**CS ↑**	**EC ↑**	**TL ↑**	**DIT ↓**	**AD ↑**	**IG ↑**	**CC ↓**	**SA ↑**
Slab	1	0.033333	1	0.4375	1	1	1	0.375	1	1	0.25
Beam	0.875	0.025	1	1	1	1	1	0.375	0.375	1	0.25
Box	0.466667	0.125	1	0.3125	0.875	1	0.875	0.625	0.625	0.875	0.375
Truss	0.388889	0.066667	0.6	0.5625	0.625	1	1	0.625	0.25	0.875	0.25
Arch	0.28	0.208333	1	0.3125	0.375	1	0.875	1	0.25	0.875	0.875
Cable-stayed bridge	0.233333	0.333333	0.375	0.1875	0.375	0.875	0.375	1	0.25	0.375	1
Suspension bridge	0.14	1	0.3	0.0875	0.25	0.875	0.375	1	0.25	0.25	1

Step 5: The overall scores of structural systems are computed by multiplying the relevant normalized data of the attributes for the alternative structural systems by the weights of the selected attributes.

Step 6: The structural systems are arranged in descending order of overall scores.

Beam: 0.763964

Slab: 0.744759

Box: 0.667852

Truss: 0.551944

Arch: 0.522636

Suspension bridge: 0.457024

Cable-stayed bridge: 0.411613

Having the highest overall score, the "Beam" structural system is the best choice. However, Balali et al. (2014) mentioned that since the beam type was unsuitable for use over large spans, it was eliminated from the list of options. Additionally, because the truss type was incompatible with the cantilever approach, it was also eliminated from the choice matrix. Similarly, the slab was also eliminated. In fact, such feasibilities should have been considered by the design team in the initial stage while screening the alternative structural systems after choosing the best construction method. The following structural systems are recommended by the suggested decision-making approach, in descending order of their overall scores, taking into account the factors mentioned by Balali et al. (2014): Box - Arch - Suspension bridge - Cable-stayed bridge

Balali et al. (2014) used the entropy method to get the weights of 0.06, 0.15, 0.13, 0.13, 0.19, 0.09, 0.13, 0.02, 0.02, 0.06, and 0.02 for C, S, IM, CS, EC, TL, DIT, AD, IG, CC, and SA respectively. Using these weights and the PROMETHEE method (and ignoring the Slab, Beam, and Truss structural systems), the alternative structural systems, in descending order, were suggested by Balali et al. (2014) as: Box - Arch - Cable-stayed bridge - Suspension bridge. For a fair comparison, if the same entropy weights of the attributes as used by Balali et al. (2014) are used in the BHARAT-II method, then the structural systems are arranged in the following order: Box - Arch - Suspension bridge - Cable-stayed bridge.

Using the same entropy weights as those used in the PROMETHEE method of Balali et al. (2014), the BHARAT-II method also suggested "Box" as the best choice. The 2nd choice is "Arch". It is to be mentioned here that Balali et al. (2014) made some calculation mistakes and suggested cable-stayed bridge as the 3rd choice and suspension bridge as the 4th choice. In fact, the right calculation suggests a suspension bridge as the 3rd choice and a cable-stayed bridge as the 4th choice.

3.1.3. Case study 1(c): Choosing the best construction material

The right construction material should be chosen after the best structural system has been determined. This stage of the decision-making problem considered 04 alternative materials and 04 selection attributes. The 04 selection attributes included: Cost (C), Life Cycle and Durability (LCD), Thermal Influence (THI), and ability to build a small and lightweight structure (AB). The attributes C and THI are non-beneficial attributes, and LCD and AB are beneficial attributes. The attributes TH and AB were described qualitatively.

Now to select the best material out of the 04 available materials (i.e., reinforced concrete, pre-or post-tensioned concrete, steel, and composite), only the important steps of the BHARAT-II method are given below for space reasons. Table 8 shows the information of the 04 attributes and 04 alternative materials; Table 9 shows the relationships of the attributes and their weights; Table 10 shows the normalized data.

Table 8

Information about the 04 attributes and 04 alternative materials of case study 1(c)

Alternative materials	**Attributes**			
	C ↓	**LCD ↑**	**THI ↓**	**AB ↑**
Reinforced concrete	**0.8**	100	**VL (0.8)**	VL (0.2)
Pre-or posttensioned concrete	1.2	**120**	**VL (0.8)**	A (0.5)
Steel	2.4	70	VH (0.2)	**VH (0.8)**
Composite	1.8	80	H (0.3)	**VH (0.8)**

VH: very high; H: High; A: Average; VL: very low
Source: Balali et al. (2014)

Table 9

Relationships between the 04 attributes of case study 1(c)

Selection attributes	**Attributes**				**Means of rows**	**Weights of attributes**
	C	**LCD**	**THI**	**AB**		
C	1	2/3	4/3	1/3	0.83333	0.16

Selection attributes	Attributes				Means of rows	Weights of attributes
	C	LCD	THI	AB		
LCD	3/2	1	4/2	1/2	1.25	0.24
THI	3/4	2/4	1	1/4	0.625	0.12
AB	3	2	4	1	2.5	0.48

Table 10

Normalized data for case study 1(c)

Alternative materials	Attributes			
	C	LCD	THI	AB
Reinforced concrete	1	0.833333	1	0.25
Pre-or post-tensioned concrete	0.666667	1	1	0.625
Steel	0.333333	0.583333	0.25	1

The overall scores of alternative materials are calculated. The alternative materials are arranged in descending order of overall scores.

Pre- or post-tensioned concrete: 0.766667

Composite: 0.756111

Steel: 0.703333

Reinforced concrete: 0.6

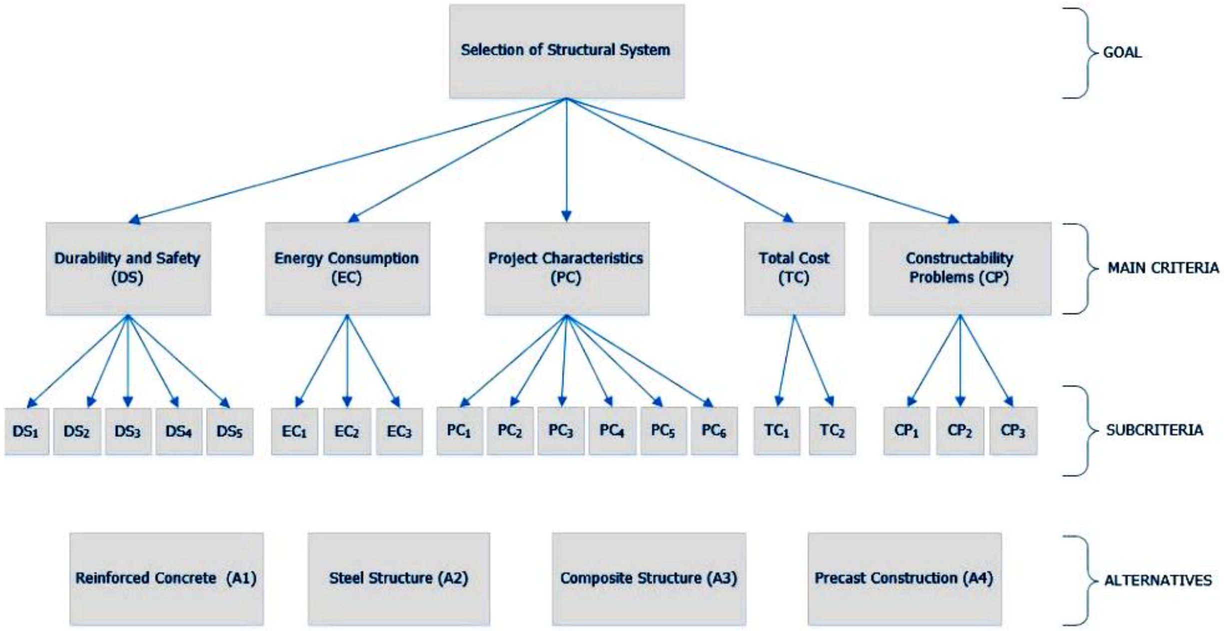
Having the highest overall score, the “Pre- or post-tensioned concrete” material is considered the best choice for the given application. Balali et al. (2014) used the entropy method to get the weights of 0.20, 0.27, 0.13, and 0.40 for C, LCD, THI, and ABB, respectively. Using these weights and the PROMETHEE method, the alternative materials, in descending order, were suggested by Balali et al. (2014) as Pre- or post-tensioned concrete - Composite - Steel - Reinforced concrete. For a fair comparison, if the same entropy weights of the attributes as used by Balali et al. (2014) are used in the BHARAT-II method, then the materials are arranged in the following order: Pre- or post-tensioned concrete - Composite - Steel - Reinforced concrete. Using the same entropy weights as those used in the PROMETHEE method of Balali et al. (2014), the BHARAT-II method also suggested “Pre- or post-tensioned concrete” as the best choice. The second choice is “Composite”.

The case study 1 containing three parts (a), (b), and (c), has illustrated the potential of the proposed method as a MADM method. Thus, *the final choice of case study 1 is Cantilever construction using a Box structure with Pre- or post-tensioned concrete as the construction material.*

3.2. Case study 2: Choosing the best alternative structural system for a housing project

Now another case study is presented to further demonstrate the BHARAT-II method. Polat et al. (2018) considered a housing project in Istanbul, Turkey, and proposed an integrated structural system selection approach using the AHP-VIKOR method. This project had a total building area of 822,000m^2, including three basement floors, a ground floor, and three regular stories. The design team, which consisted of four engineers and architects, was responsible for determining the structural system. The selection attributes (mentioned as criteria by Polat et al., 2018), the sub-attributes (mentioned as sub-criteria), and the alternative structural systems are shown in Figure 3.

The quantitative data of the "construction cost of the project" (TC1) was measured in thousands of Turkish Liras, whereas the remaining sub-criteria were qualitative and these values were collected by Polat et al. (2018) by interacting with the design team of decision-makers using 1 to 9 point scale (i.e., 1: Very Bad; 9: Very Good). The geometric means of the decision makers' individual subjective assessments of the alternatives were determined in order to create an aggregated decision matrix for the structural system selection problem.



DS1: resistance to external conditions; DS2: resistance to seismic loads; DS3: safety against fire; DS4: resistance to wind loads; DS5: lifecycle of the structure; EC1: energy used to construct the structural system; EC2: production energy of construction materials; EC3: reusability of construction materials; PC1: number of floors; PC2: need for large spans in the structure; PC3: need for huge amount of clear space; PC4: aesthetics of the structure; PC5: changeability of the internal space; PC6: modularity of the structure; TC1: construction cost of the project; TC2: operation and maintenance costs of the project; DC1: construction duration; DC2: delivery of construction materials to the site; DC3: availability of laborers and equipment

Figure 3. Structural system selection problem with alternatives, sub-criteria, main criteria, and the goal (Polat et al., 2018)

The steps of the BHARAT-II method are now followed in order to choose the best structural system from the four accessible structural systems, as explained below.

Step 1: The various structural systems and the structural system selection sub-criteria are displayed in Table 11. These are the same as what Polat et al. (2018) took into consideration. Lower values are preferred for the attributes TC1 and TC2. The remaining attributes are helpful in nature.

Step 2: Ranks are assigned to find the weights of the criteria (i.e., attributes) and the sub-criteria (i.e., sub-attributes). Table 12 shows the ranks assigned to the 05 main criteria and the calculated weights. Tables 13-17 show the ranks assigned to the sub-criteria and the calculated local weights.

Table 11

Information about the 19 sub-criteria and 04 alternative structural systems of case study 2

Sub-criteria	**Alternative structural systems**			
	Reinforced concrete (A1)	**Steel structure (A2)**	**Composite structure (A3)**	**Precast construction (A4)**
DS1	7.11	4.74	5.24	6.59
DS2	7.97	7.2	5.66	3.98
DS3	6.88	2.74	2.89	5.57
DS4	8.21	4.21	5.96	6.12
DS5	6.4	7.2	5.23	4.86
EC1	7.48	6.4	6.4	5.89
EC2	5.89	7.17	6.9	6.16
EC3	2.99	6.88	5.69	4.46
PC1	6.09	6.45	4.56	6.16
PC2	5.38	7.97	4.9	7.14
PC3	6.74	4.74	8	7.97
PC4	6.59	7.17	6.85	5.96
PC5	5.21	4.24	4.05	3.98
PC6	1.86	5.58	5.18	6.59
TC1	335	795	650	720
TC2	4.16	7.9	6.05	5.24
CP1	5	7.09	6.62	6.51
CP2	6.51	5.63	5.38	4.68
CP3	7.33	5.38	5.48	4.95

Source: Polat et al. (2018)

Table 12

Relationships between the 05 main criteria of case study 2

Criteria	**Criteria**					**Averages of rows**	**Criteria' weights**
	DS	EC	PC	TC	CP		
DS	1	3.5	2	3.5	5	3	0.44025
EC	1/3.5	1	2/3.5	1	5/3.5	0.85714	0.12579
PC	1/2	3.5/2	1	3.5/2	5/2	1.5	0.22012
TC	1/3.5	1	2/3.5	1	5/3.5	0.85714	0.12579
CP	1/5	3.5/5	2/5	3.5/5	1	0.6	0.08805
Total =						6.81428	1.00000

Table 13

Relationships between the 5 sub-criteria of criterion DS of case study 2

Sub-criteria	Sub-criteria					Averages of rows	Local weights of sub-criteria
	DS1	DS2	DS3	DS4	DS5		
DS1	1	1/2	3/2	5/2	4/2	1.5	0.21898
DS2	2	1	3	5	4	3	0.43795
DS3	2/3	1/3	1	5/3	4/3	1	0.14598
DS4	2/5	1/5	3/5	1	4/5	0.6	0.08759
DS5	2/4	1/4	3/4	5/4	1	0.75	0.10949
Total =						6.85	1.00000

Table 14

Relationships between the 3 sub-criteria of criterion EC of case study 2

Sub-criteria	Sub-criteria			Averages of rows	Local weights of sub-criteria
	EC1	EC2	EC3		
EC1	1	2.5	2.5	2	0.55555
EC2	1/2.5	1	1	0.8	0.22222
EC3	1/2.5	1	1	0.8	0.22222
Total =				3.6	1.00000

Table 15

Relationships between the 3 sub-criteria of criterion PC of case study 2

Sub-criteria	Sub-criteria						Averages of rows	Local weights of sub-criteria
	PC1	PC2	PC3	PC4	PC5	PC6		
PC1	1	2	4.5	4.5	3	6	3.5	0.40909
PC2	1/2	1	4.5/2	4.5/2	3/2	6/2	1.75	0.20454
PC3	1/4.5	2/4.5	1	1	3/4.5	6/4.5	0.777775	0.09091
PC4	1/4.5	2/4.5	1	1	3/4.5	6/4.5	0.777775	0.09091
PC5	1/3	2/3	4.5/3	4.5/3	1	6/3	1.166665	0.13636
PC6	1/6	1/3	4.5/6	4.5/6	3/6	1	0.583333	0.068181
Total =							8.555548	1.00000

Table 16

Relationships between the 2 sub-criteria of criterion TC of case study 2

Sub-criteria	**Sub-criteria**		**Averages of rows**	**Local weights of sub-criteria**
	TC1	TC2		
TC1	1	2	1.5	0.66666
TC2	1/2	1	0.75	0.33333
Total =			2.25	1.00000

Table 17

Relationships between the 3 sub-criteria of criterion CP of case study 2

Sub-criteria	**Sub-criteria**			**Averages of rows**	**Local weights of sub-criteria**
	CP1	CP2	CP3		
CP1	1	2	3	2	0.54545
CP2	1/2	1	3/2	1	0.27273
CP3	1/3	2/3	1	0.66666	0.18091
Total =				3.66666	1.00000

Table 18 provides the global weights of the sub-criteria, which are determined by multiplying the weights of the corresponding criterion by the local weights of the corresponding sub-criteria. For instance, DS1's global weight can be computed as follows: 0.44025*0.21898 = 0.096406.

Table 18

Global weights of the sub-criteria of case study 2

Sub-criteria	**Global weights of the sub-criteria**
DS1	0.096406
DS2	0.192807
DS3	0.064268
DS4	0.038561
DS5	0.048203
EC1	0.069883
EC2	0.027953
EC3	0.027953
PC1	0.090049
PC2	0.045023
PC3	0.020011
PC4	0.020011
PC5	0.030016
PC6	0.015008
TC1	0.083859

Sub-criteria	Global weights of the sub-criteria
TC2	0.04193
CP1	0.048027
CP2	0.024014
CP3	0.015929

Step 3: The data given in Table 11 is already quantitative.

Step 4: The "best" structural system for each of the sub-criteria is used to normalize the data. In Table 2, the qualities with the highest values are bolded. Normalized values are displayed in Table 4. For instance, (10/1000) yields the normalized value of 0.01 for UH, which corresponds to "Assembly or cast in situ." (50/450) yields the normalized value of 0.11111 for CS, which corresponds to "Assembly or cast in situ." (0.3/0.8) yields the normalized value of 0.375 for EI, which corresponds to "Assembly or cast in situ." In a similar manner, Table 19 presents the normalized data.

Table 19

Normalized values of the 19 sub-criteria and 4 alternative structural systems of case study 2

Sub-criteria	**Alternative structural systems**			
	Reinforced concrete (A1)	**Steel structure (A2)**	**Composite structure (A3)**	**Precast construction (A4)**
DS1	**1**	0.666667	0.73699	0.926864
DS2	**1**	0.903388	0.710163	0.499373
DS3	**1**	0.398256	0.420058	0.809593
DS4	**1**	0.512789	0.725944	0.745432
DS5	0.888889	**1**	0.726389	0.675
EC1	**1**	0.855615	0.855615	0.787433
EC2	0.821478	**1**	0.962343	0.859135
EC3	0.434593	**1**	0.827035	0.648256
PC1	0.944186	**1**	0.706977	0.955039
PC2	0.675031	**1**	0.614806	0.895859
PC3	0.8425	0.5925	**1**	0.99625
PC4	0.919107	**1**	0.95537	0.831241
PC5	**1**	0.81382	0.777351	0.763916
PC6	0.282246	0.846737	0.786039	**1**
TC1	**1**	0.421384	0.515385	0.465278
TC2	**1**	0.526582	0.687603	0.793893
CP1	0.705219	**1**	0.933709	0.918195
CP2	**1**	0.864823	0.826421	0.718894

Sub-criteria	**Alternative structural systems**			
	Reinforced concrete (A1)	**Steel structure (A2)**	**Composite structure (A3)**	**Precast construction (A4)**
CP3	**1**	0.73397	0.747613	0.675307

Step 5: Overall scores of structural systems are calculated. For example, the overall score of structural system constructive method "Reinforced Concrete" is computed as:

Overall score (Reinforced Concrete) = 0.096406*1 + 0.192807*1 + 0.064268*1 + 0.038561*1 + 0.048203*0.888889 + 0.069883*1 + 0.027953*0.821478 + 0.027953*0.434593 + 0.090049*0.944186 + 0.045023*0.675031 + 0.020011*0.8425 + 0.020011*0.919107 + 0.030016*1 + 0.015008*0.282246 + 0.083859*1 + 0.04193*1 + 0.048027*0.705219 + 0.024014*1 + 0.015929*1 = 0.924403

Step 6: The structural systems are arranged in descending order of overall scores.

Reinforced concrete structure: 0.924403

Steel structure: 0.789699

Precast structure: 0.741381

Composite structure: 0.72204

The "Reinforced concrete structure" is the best choice. Polat et al. (2018) used AHP method to get the weights of 0.07, 0.15, 0.05, 0.03, 0.04, 0.07, 0.04, 0.04, 0.06, 0.05, 0.03, 0.03, 0.03, 0.02, 0.09, 0.06, 0.09, 0.03, and 0.02 for DS1-DS5, EC1-EC3, PC1-PC6, TC1-TC2, and CP1-CP3 respectively. Using these weights and the VIKOR method, the alternative structural system, in descending order, was suggested as Reinforced concrete structure - Steel structure - Composite structure - Precast structure.

Thus, the AHP-VIKOR method also suggested "Reinforced structure" as the best choice. However, for a fair comparison, if the AHP weights of the sub-criteria as used by Polat et al. (2018) are used in the BHARAT-II method, then the structural systems are arranged in the following order.

BHARAT-II method (with AHP weights):

Reinforced concrete structure: 0.898164

Steel structure: 0.796632

Precast structure: 0.752102

Composite structure: 0.7437

Using the same AHP weights as those used in the VIKOR method of Polat et al. (2018), the BHARAT-II method also suggested a "Reinforced concrete" structure as the best choice. It is to be mentioned here that Polat et al. (2018) made some calculation mistakes and suggested composite structure as the 3rd choice and precast structure as the 4th choice. In fact, the right calculation suggests precast structure as the 3rd choice and composite structure as the 4th choice.

The suggested approach to decision-making entails a straightforward normalization process and the computing of alternative construction methods' total scores in comparison to the computationally demanding VIKOR method. In contrast to the AHP weights employed by Polat et al. (2018), the rank assignment process and the decision-makers subsequent calculations of the selection attribute weights are more straightforward and rational.

4. Conclusions

Two case studies of structural engineering are presented to illustrate the potential of the proposed BHARAT-II methodology. The first case study addressed the issue of choosing the best construction method (out of 04 alternative construction methods involving 07 selection attributes), best structural system (out of 07 alternative structural systems involving 11 selection attributes), and best construction material (out of 04 alternative construction materials involving 04 attributes) for a bridge structure. The final best choice of the first case study is Cantilever construction using a Box structure with Pre- or post-tensioned concrete as the construction material. The second case study addressed the problem of selecting the best structural system for a housing project considering 04 alternative structural systems and 19 sub-criteria. The Reinforced concrete structure is suggested as the best choice for the second case study.

The suggested approach helps determine the overall scores that evaluate the alternatives for the structural engineering problem under consideration. It can incorporate any number of alternatives and quantitative and qualitative selection attributes. Decision-makers might find it easier to provide quantitative values to the qualitative attributes by using the straightforward linear scales that the method suggests. The first case study that is provided clarifies this reality. The suggested approach addresses the selection problem comprehensively, or in its totality, and is simple for decision-makers to implement. The suggested methodology provides a basic process that may be used for a variety of selection issues involving ambiguity, multiple qualities, and alternatives that arise in the civil and structural engineering disciplines. As the BHARAT-II method offers a general decision-making procedure, the method can be used in solving industrial decision-making problems and business-related decision-making problems. It can also be used for solving decision-making problems in any discipline of engineering and sciences.

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