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TECHNICAL PAPER

Multi-criteria decision support system for bridge construction system selection utilizing value engineering and TOPSIS

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Abstract

When selecting the appropriate bridge deck construction system, it is essential to consider many criteria such as the span length, geographical location, construction speed, cost, site conditions, resource availability, technology, ease of construction, and service life. The objective of this study is to optimize the decision-making process for selecting a bridge deck construction system in the preliminary design and planning stage. The proposed model allows designers or decision-makers to make an informed choice of an appropriate construction system according to project criteria through a decision support system. The model employs value engineering methodology and a multi-criteria decision-making method and utilizes the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), a multi-criteria decision-making method. To gather modeling data from a focus group consisting of professional bridge engineers, a semi-structured interview and two questionnaires are conducted. When applying the proposed model to two active bridge construction projects in Egypt, it reveals that "Span by Span using launching girder" and "precast post tension girder" are better suited to cases one and two, respectively. The study makes a contribution by presenting a decision support system that combines value engineering methodology and a multi-criteria decision-making method (TOPSIS). This system empowers designers and decision-makers to make project decisions considering specific criteria and constraints.

Keywords Value engineering · Multi-criteria · Decision · Bridge · Construction · TOPSIS · Automation · Decision-support

Introduction

Bridges are a type of infrastructure project characterized by their long-term service life objectives, implementation complexity, and substantial financial investment requirements [1, 2]. Determining the constructability of a bridge is becoming increasingly essential due to new environmental and political requirements as well as construction industry constraints. The construction of a bridge is one of the most challenging projects in the world, necessitating an extensive amount of expertise, machinery, and financial resources [3, 4]. Rapid population growth has created new transportation requirements and increased demand for efficient bridge construction [5].

Several variables, including bridge length, resources availability, project location, and project duration, influence the selection of the bridge construction method and its design [4, 6, 7]. The most appropriate construction method should be chosen after a thorough examination of all available methods using project-specific evaluation criteria. The selection of the appropriate bridge superstructure method is crucial to the success of bridge projects [8]. In bridge design, it is vital to take into account factors such as structural safety, serviceability, economy, constructability, maintainability, and environmental impact in order to determine the appropriate bridge location and structural type [8]. The proposed structural system should then be simplified as much as possible to address various challenges such as

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application difficulties, lack of knowledge, lack of time, and limited resources [9].

The traditional method, Design-Bid-Build, promotes separating design and construction, affecting project quality, especially when no constructability review is mandatory before construction begins. In bridge projects, Field practices have revealed several instances where the contractor changed the primary construction methods to accommodate construction needs that the designer had not anticipated or addressed [10]. The literature indicates that "Design errors made by designers" and "Wrong or improper design" are ranked among the top 10 causes of project time delays and higher costs in both design and construction [10, 11].

Inadequate investigations of alternatives or when the contract terms require the use of a specific construction system are considered factors for inapt selection of the construction system [10, 12]. When there is no a set of specific requirements that clearly make one solution superior to others, evaluating the most appropriate alternative becomes a challenging task [8]. As a result of that, the selection is mostly based on the expertise, skill, knowledge, and judgment of engineers, allowing for subsequent decision-making errors [10].

One of the various tools and techniques that can assist in determining the most practical bridge structure system is value engineering (VE). Even though VE has been known since the middle of the twentieth century, construction practitioners in many developing countries have often been unable to employ it through the design and construction phases due to their limited knowledge and trust in this technique [3]. Incorporating VE methodology into the design process of bridges can help decision-makers choose a better functional method [3]. VE has been successfully adopted in many projects worldwide to eliminate unnecessary costs while maintaining desired quality, safety, and reliability [5].

In a general sense, VE is a relationship between function and cost. VE is described as an organized process that discovers possibilities to cut unnecessary expenses while ensuring that the objective, reliability, performance, and other essential criteria meet or exceed the customer's expectations [13]. Professional duty for the designer is to evaluate all feasible design alternatives that achieve the required and necessary function, for example but is not limited to quality, safety, durability, etc., and make a financial comparison to reach the most valuable alternative. Application of VE during early development stages assists in getting the project off to a good start and saves greater money [12, 14, 15]. Adopting VE methodology could save 10 to 30% reduction in total project construction costs [16].

In the VE methodology, choosing the appropriate construction system necessitates the presence of a decision support tool, as it plays a crucial role in handling the huge amount of knowledge involved in making the decision [17]. A wide range of multi-criteria decision-making methods (MCDM) is utilized to choose a suitable design through different design alternatives [17]. As shown in Table 1, MCDM methods can be classified into different groups according to similar characteristics [18–20]. Choosing a specific method depends on evaluation criteria such as: internal consistency, logical soundness, transparency, ease of use, ability to provide an audit trail, and software availability [21]. The Technique for Order of Preference by Similarity to Ideal Solution, TOPSIS, is based on the concept that the most suitable alternative is the one that simultaneously has the shortest geometric distance from the positive ideal solution

Table 1 MCDM methods description

MCDM Group	MCDM method	Ref.
Scoring methods	Simple additive weighting (SAW)	[25]
	Complex proportional assessment (COPRAS)	[25]
Distance-based methods	Goal programming (GP)	[26]
	Compromise programming (CP)	[27]
	Technique for order of preference by similarity to ideal solution (TOPSIS)	[28]
	Multi-criteria optimization and compromise solution (VIKOR)	[28]
	Data envelopment analysis (DEA)	[29]
Pairwise comparison methods	Analytic hierarchy process (AHP)	[30]
	Analytic network process (ANP)	[30]
	Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH)	[31]
Outranking methods	Preference ranking organization method for enrichment of evaluations (PROMETHEE)	[32]
	Elimination and choice expressing reality (ELECTRE)	[33]
Utility/Valuate methods	Multi-attribute utility theory (MAUT)	[34]
	Multi-attribute value theory (MAVT)	[34]
Other	Quality function development (QFD)	[35]

and the longest geometric distance from the negative ideal solution [22–24].

The purpose of this study is to optimize the decision-making process for selecting a bridge deck construction system during the preliminary design and planning stage. The primary focus is developing an integrated decision support system to include new construction systems and selection criteria, as they emerge over time to help decision-makers select the appropriate alternative [2, 4, 10]. This system could be established through using value engineering methodology and a multi-criteria decision-making method. Including more selection criteria could lead to a more suitable bridge construction system.

Study scope and objectives

The objective of this study is to optimize the decision-making process for selecting a bridge deck construction system during the preliminary design and planning stage. The model allows the designer or decision-maker to select the appropriate construction system by utilizing a decision support system that considers project criteria. This model can be developed by integrating value engineering methodology and a multi-criteria decision-making method. The proposed model utilizes the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), a multi-criteria decision-making method. TOPSIS enables decision-makers to make more informed bridge construction system selection decisions based on project criteria and constraints. Two ongoing bridge construction projects in Egypt were selected to validate the proposed model. The significance of the VE methodology in bridge projects lies in allowing decision-makers to pursue the highest quality and performance without wasting money on unnecessary costs [4, 15].

Research methodology

The proposed study comprises three major phases. Phase one involves conducting a literature review to identify various types of bridge construction systems in Egypt and the evaluation criteria used to select the appropriate construction system for a certain project. The data collected is assessed in semi-structured interviews with bridge construction experts to refine and set a final list of construction systems and criteria for use in the subsequent phases.

Phase two involves conducting two questionnaires to a focus group of professional engineers employed in bridge construction companies. The goal of the first questionnaire is to determine the most important criteria that affect choosing the appropriate construction system. The goal of the second questionnaire aims to apply the structural criteria to each construction system. It also aims to prioritize the subjective criteria for inclusion in the selection process for all bridge construction systems.

Phase three involves the development, implementation, and validation of the value engineering decision support (VEDS) model. Figure 1 illustrates the Research methodology.

Phase one

Several bridge construction systems (BCS) and selection criteria are gathered from the existing literature. Experts from the bridge construction industry in semi-structured interviews to identify any missing system/criteria or eliminate redundant ones then evaluate these collected construction systems and criteria. Phase one results in the creation of two lists: BCSs list and selection criteria of BCS list.

- Identification of BCS

Investigating the construction systems to be used in the study, as identified through semi-structured interview and the literature review [10, 12, 36], a set of 11 construction systems is chosen based on the following measures; (I) construction systems associated with box section, which permanently evolve due to its various construction methods, (II) construction systems newly used in Egypt as a result of the technological advancement in the bridge industry, and III) construction systems commonly used in Egypt. The 11 construction systems included in this study are listed in Table 2.

- Selection criteria of BCS

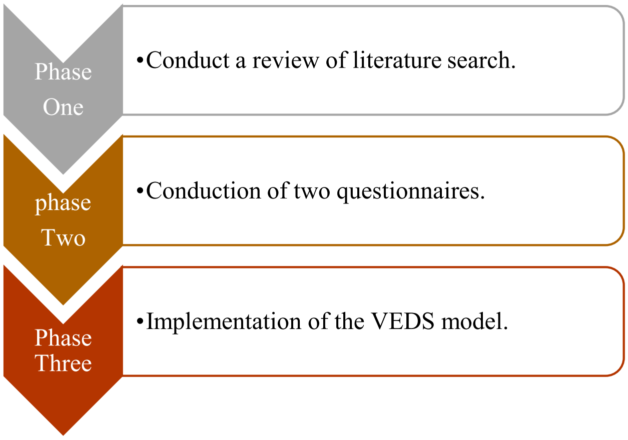


Fig. 1 Research methodology

Table 2 Bridge deck construction systems

Code	Name
BCS1	Precast span by span using launching Girder
BCS2	Full span launching method
BCS3	Free Cantilever precast using lifting frame
BCS4	Balanced Cantilever cast in situ using two travelers
BCS5	Balanced Cantilever precast using lifting frames
BCS6	Precast Incremental launching
BCS7	Cast in Situ segment using formwork supported on ground
BCS8	Reinforced concrete cast in situ girder
BCS9	precast post tension girder
BCS10	cast in situ post tension girder
BCS11	Hollow core slab cast in situ

As shown in Table 3, the literature search has provided 27 criteria that affect the selection of the appropriate construction system by the designer or the decision-maker during the conceptual design phase. Note that 4 out of the 7 references collected in Table 3 have been studied in Egypt to simulate and encompass most of the conditions there. Additionally, during the semi-structured interviews with bridge construction experts in Egypt,7 more criteria are introduced: Construction risk (C28), Use of latest technology (C29), Expandability (C30), Logistics difficulties (C31), Ease Communication among Stakeholders (C32), Payment scheme (C33), and PTO (Provisional Taking Over) difficulty (C34). Consequently, a total of 34 criteria are considered during the subsequent phases of the research study to select the appropriate BCS.

Phase two

In phase two, two questionnaire are conducted to professional engineers working in bridge construction firms. The goal of the first questionnaire is to identify the most important criteria affecting the selection of the appropriate BCS. The goal of the second questionnaire is to prioritize the subjective criteria considered affecting the BCS selection process. The results of both surveys serve as inputs for VEDS model.

Table 3 Criteria collected from published work

Code	Criteria	[36]	[12]	[4]	[2]	[8]	[10]	[14]
C1	Nature of crossing	✓	✓	✓	✓	✓	✓	✓
C2	Surrounding area nature	✓		✓	✓	✓	✓	✓
C3	Accessibility to site	✓					✓	✓
C4	Budget cost	✓	✓			✓	✓	✓
C5	Cost of defected quality	✓				✓		
C6	Life cycle cost			✓				
C7	Service life (durability)		✓	✓			✓	
C8	Contractor experience and capabilities							✓
C9	Diversion cost of Existing utilities			✓	✓			✓
C10	Availability of Equipment		✓		✓			✓
C11	Availability of skilled manpower		✓	✓	✓			✓
C12	Availability of material		✓		✓			✓
C13	Aesthetics of bridge	✓					✓	
C14	Typical span number			✓	✓			✓
C15	Breadth of deck			✓	✓			✓
C16	Bridge height above ground	✓		✓	✓		✓	✓
C17	Soil condition	✓			✓		✓	✓
C18	Horizontal Alignment	✓		✓	✓	✓	✓	✓
C19	Volume of traffic during construction		✓					
C20	Effect of construction on design	✓					✓	✓
C21	Cranes capacity and maneuvering	✓			✓			✓
C22	Climate during construction					✓		
C23	Construction safety requirement	✓		✓		✓	✓	
C24	Ease of maintenance		✓			✓	✓	
C25	Bridge span length	✓		✓	✓		✓	✓
C26	Speed of construction	✓		✓	✓	✓	✓	✓
C27	Land topography	✓						

Sample size

Simple random sampling method is used in the study because the process is easy to follow and viewed as fair as each person can be selected. Additionally, it is a versatile method that can be used for both large and small populations [37]. This study is targeted construction companies specializing in bridge works and large facility works. In Egypt, as of 2021, the Egyptian Engineers Syndicate's records indicate that there are approximately 800,000 registered building and construction engineers. Identifying the proper sample size is important to ensure the survey's reliability and credibility. If the sample size is too small, valuable research insights may be missed, while an excessively large sample can result in unnecessary expenditures of time and resources.

Equation (1) is used to calculate the sample size that best represents the targeted population [38].

$$n = \frac{n'}{1 + \frac{n' - 1}{N}} \tag{1}$$

where: n is the sample size from finite population; N is the total population (800,000 construction engineer) and n' can be calculated using Eq. (2).

$$n' = \frac{z^2 + s^2}{v^2} \tag{2}$$

where: v is standard error of sample population assumed 0.05. S^2 is the standard error variance of population elements which is defined as $S^2 = P\,(1 - P)$ and it is maximum at $P = 0.5$ and Z is the confidence coefficient equals 1.645 at 90% confidence.

Based on Eqs. (1) and (2), a sample size of 271 is required. However, the survey questionnaire received 250 responses through structured interviews, phone calls, or electronic forms out of a total of 300.

Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy

The KMO test is a measure designed to assess the acceptability of data for factor analysis. In other words, it assesses the sample size's adequacy [39]. The KMO statistic has a scale of 0 to 1. scores between 0.8 and 1.0 indicate that the sample is appropriate. For KMO scores in the range of 0.7 to 0.79, it is considered an average result, while values falling between 0.6 and 0.69 are indicative of a suboptimal outcome. KMO values below 0.6 indicate insufficient sampling, necessitating corrective measures. If the value falls below 0.5, it is highly likely that the results of the factor analysis will not be suitable for further data analysis. When the sample size is less than 300, the average communality of the retained items must be tested. For sample size below100, an average value exceeding 0.6 is considered acceptable. For sample sizes between 100 and 200, an average value within the range of 0.5 to 0.6 is acceptable [39–42].

Since the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy equals 0.922, which is greater than 0.5, the current sample size of 250 is suitable for factor analysis.

Figure 2 illustrates the demographic information of the questionnaire respondents. It indicates that 58% of the respondents have more than 10 years of experience, 54% work for consultants, and 52% work as designers.

Questionnaire I

Questionnaire I aims to identify the important criteria that utilizes to choose the appropriate BCS. Respondents rate 34 criteria using 1–5 Likert scale in which 1, 2, 3, 4, and 5 indicate: Extremely not significant, Not significant, Moderate, Significant, and Extremely Significant, respectively [43, 44]. The relative importance index (RII) in Eq. (3) is used to analyze responses and determine the relative importance for each criterion [43, 45].

$$RII = \frac{\sum_1^5 w_i \times x_i}{A \times N} \tag{3}$$

where "w_i" is the five-point Likert scale (1 to 5), "x_i" is the frequency of the Likert scale, "A" is the greatest priority value (5), and "N" is the total number of responses. The RII values are reported at five key levels: High "H" ($0.8 \le RII \le 1$), High–Medium "H–M" ($0.6 \le RII < 0.8$), Medium "M" ($0.4 \le RII < 0.6$), Medium–Low "M–L" ($0.2 \le RII < 0.4$), and Low "L" ($0 \le RII < 0.2$). BCS criteria within the least significance levels "M-L" and "L" are dropped off from further study analysis [46]. This guarantees that the chosen criteria hold sufficient significance according to the perspective of professional bridge experts. As the number of criteria exceeds 16, the effectiveness of the TOPSIS method diminishes, making it more advantageous to have fewer criteria [43]. As a result, 8 criteria that are rated as "L" or "M-L" are removed, namely: C5, C23, C14, C34, C33, C15, C7, and C22. Table 4 presents the list of the 26 BCS criteria that are deemed important.

Questionnaire II

Questionnaire II aims to rank the 26 BCS criteria identified by the RII analysis.

Structural Criteria The selection of the preliminary construction system is mostly influenced by structural criteria, and also influences the preliminary designer choice. Among the 26 criteria, 10 are considered important for the selection of the optimal BCS [2, 4, 8, 36]. In questionnaire II,

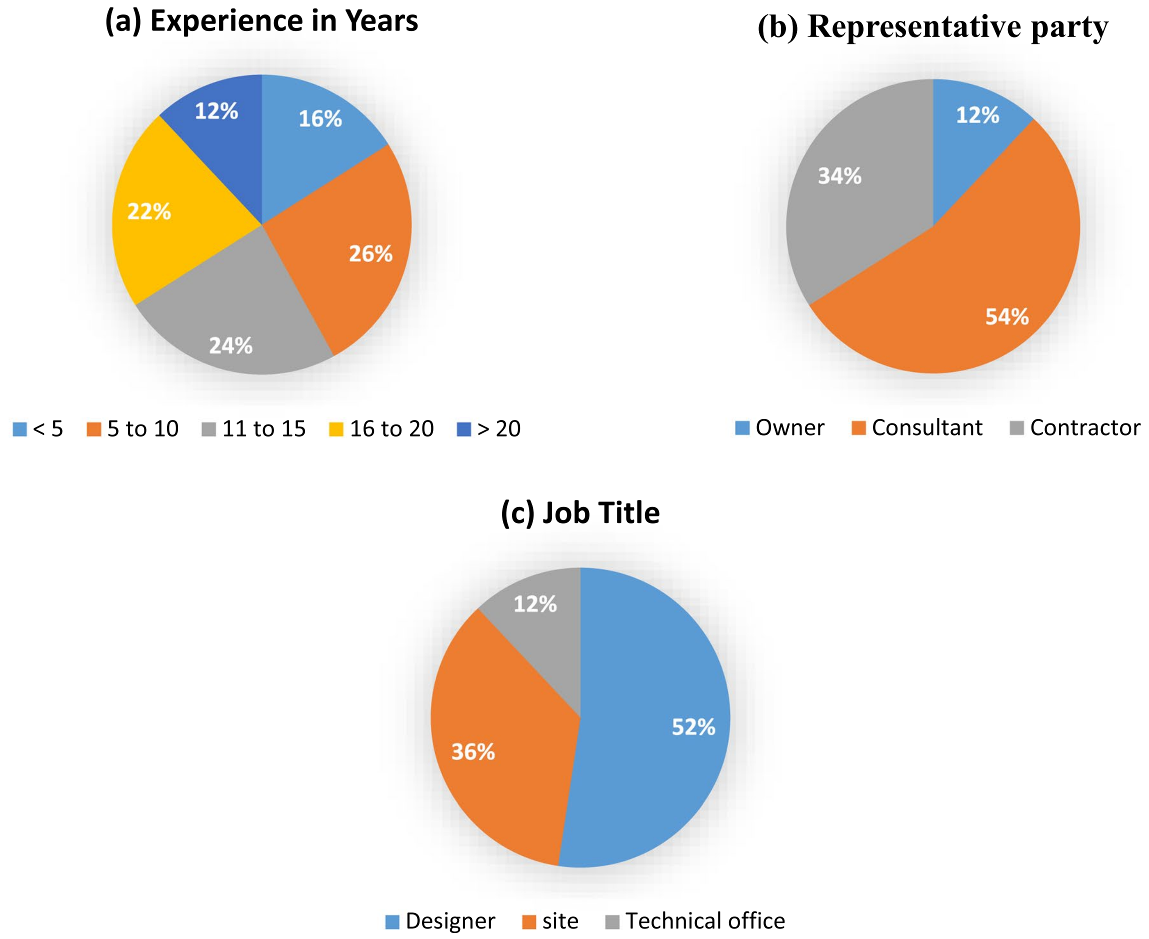


Fig. 2 Survey demographic data

respondents are asked to rate each structural criterion with respect to each construction system as 0 or 1. A rating of (0) indicates that the criterion does not apply to the construction system, whereas a rating of (1) indicates that the criterion is applicable to the construction system. This allowed the authors to determine the criteria that apply to each construction system. Table 5 introduces the results for all respondents, where (1) meaning that more than half of the respondents select (1), and (0) meaning that more than half of the respondents select (0).

Subjective criteria Subjective criteria are used to arrange the only applicable BCS and finally get the appropriate one. Where, the applicable BCS are derived from the allocation of the structural criteria to a project, as demonstrated in the VEDS model presented below. In questionnaire II, the respondents are required to rate the remaining important criteria which is 16, in relation to each bridge deck construction system. Respondents are asked to use a Likert scale ranging from of 1 to 9, where 1 and 9 represents the least degree of correspondence and the highest degree of correspondence, respectively [36, 43, 44].

Table 6 illustrates the collective average score for subjective criteria. For the criteria "Speed of Construction," the "Full span launching method" is rated the highest rating of (8.50). This rating indicates that, in terms of "Speed of Construction," the "Full span launching method" is considered the most preferred BCS among the methods examined in this study. Similarly, for the criteria "Availability of Equipment," the "Full span launching method" is rated the lowest rating of (3.50). This rating indicates that, in terms of "Availability of Equipment," the "Full span launching method" is comparatively more challenging compared to the other methods examined in this study.

Table 4 Ranking the criteria using the RII

No	Criteria		RII	Importance
1	C1	Nature of crossing	1	H
2	C25	Bridge span length	1	H
3	C26	Speed of construction	0.98	H
4	C20	Effect of construction on design	0.94	H
5	C21	Cranes capacity and maneuvering	0.94	H
6	C4	Budget cost	0.94	H
7	C12	Availability of material	0.9	H
8	C2	Surrounding area nature	0.88	H
9	C10	Availability of equipment	0.88	H
10	C3	Accessibility to site	0.88	H
11	C29	Use of latest technology	0.86	H
12	C27	Land topography	0.86	H
13	C28	Construction risk	0.86	H
14	C16	Bridge height above ground	0.86	H
15	C11	Availability of skilled manpower	0.84	H
16	C6	Life cycle cost	0.84	H
17	C24	Ease of Maintenance	0.82	H
18	C8	Contractor experience and capabilities	0.82	H
19	C19	Volume of traffic during construction	0.78	M-H
20	C9	Diversion cost of existing utilities	0.78	M-H
21	C30	Expandability	0.74	M-H
22	C17	Soil condition	0.72	M-H
23	C13	Aesthetics of bridge	0.68	M-H
24	C31	logistics difficulties	0.64	M-H
25	C18	Horizontal Alignment	0.62	M-H
26	C32	Ease communication among Stakeholders	0.52	M-H
27	C5	Cost of defected quality	0.38	M-L
28	C23	Construction safety requirement	0.36	M-L
29	C14	Typical span number	0.35	M-L
30	C34	PTO difficulty	0.33	M-L
31	C33	Payment scheme method	0.32	M-L
32	C15	Breadth of deck	0.28	M-L
33	C7	Service life (durability)	0.26	M-L
34	C22	Climate during construction	0.24	M-L

Phase three

Value engineering decision support (VEDS) model

The VEDS model aims to implement the VE methodology, which is integrated with multi-criteria decision-making for BCS. The value engineering methodology progresses through the following phases: Information, Creativity, Analytical, Development, and presentation. The VEDS model is transformed into a VEDS software, developed as a Java program, using TOPSIS as a Multi-Criteria decision-making engine, MySQL as a database engine, and Spring Boot as a framework. The flow chart of the VEDS software is shown in Fig. 3.

The Goals of the VEDS model are:

1. The software guides the user through all phases of the Value Engineering task plan in a logical order.
2. In terms of the amount of paperwork needed, the model creation would save a lot of space while also ensuring quick retrieval of the many pieces of information.
3. The model handles the entire work, ensuring precise and exact unbiased outcomes.
4. The model serves as a decision support system by assisting the user in selecting the appropriate bridge construction system.
5. The model assists in applying the Value Engineering methodology in an organized manner to save time and effort.

Multi-criteria decision-making (MCDM)

Multi-Criteria Decision-Making (MCDM) encompasses various methods designed to provide an overall ranking of alternatives, arranged from most to least desired. There may be differences in the extent to which the alternatives satisfy certain criteria, and no one alternative is certainly the greatest at fulfilling all requirements. The alternatives in the current study are 11 BCS and 26 criteria.

Among the different methods of MCDM, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is chosen in the analytical phase to prioritize the different alternatives based on a set of criteria and select the appropriate BCS. The TOPSIS method aids in the ranking of alternatives based on their proximity to the optimal ideal solution and obtaining the highest possible level from available alternatives [47]. The TOPSIS method is chosen out of the other methods of MCDM for its simplicity, rationality, comprehensibility, good computational efficiency, and ease of computation [21, 48]. The TOPSIS method is suitable to use in the field of bridge construction [49]. The TOPSIS method is simpler for use and robust in assessing more criteria. Also, this method results in an indisputable order of preference [24, 50].

The steps for the analysis using TOPSIS are as follows: [21, 51].

Step 1: Construct the decision matrix.

$$\mathrm{DM} = \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_p \end{array} \begin{bmatrix} R_1 & R_2 & \cdots & R_q \\ C_{11} & C_{12} & \cdots & C_{1q} \\ C_{21} & C_{22} & \cdots & C_{2q} \\ \vdots & \vdots & \ddots & \vdots \\ C_{p1} & C_{p2} & \cdots & C_{pq} \end{bmatrix} \tag{4}$$

Table 5 Structural criteria results with respect to each construction system

Structural criteria		Bridge deck construction systems										
		BCS1	BCS2	BCS3	BCS4	BCS5	BCS6	BCS7	BCS8	BCS9	BCS10	BCS11
C1	Highway	1	1	1	1	1	1	1	1	1	1	1
	Railway	1	1	0	0	1	1	0	0	0	0	0
	Waterway	1	1	0	1	1	1	0	0	1	0	0
C2	Downtown	1	1	1	1	1	1	1	1	1	1	1
	Desert	1	1	1	1	1	1	1	1	1	1	1
	Agrarian	1	1	1	1	1	1	1	1	1	1	1
C3	Ease access	1	1	1	1	1	1	1	1	1	1	1
	non-ease access	1	1	0	1	1	1	1	1	0	1	1
C17	Strong	1	1	1	1	1	1	1	1	1	1	1
	Medium	1	1	1	1	1	1	1	1	1	1	1
	Weak	1	0	0	1	1	1	1	0	1	1	0
C19	Moderate	1	1	1	1	1	1	1	1	1	1	1
	Height	1	1	0	1	1	1	0	0	1	0	0
C27	0–100 cm	1	1	1	1	1	1	1	1	1	1	1
	100–200 cm	1	1	1	1	1	1	0	0	1	0	0
	> 200 cm	1	1	0	1	1	1	0	0	0	0	0
C16	0–7 m	1	1	1	1	1	1	1	1	1	1	1
	7–20 m	1	1	1	1	1	1	1	1	1	1	1
	> 20 m	1	1	0	1	1	1	0	0	1	0	0
C18	Small to medium	1	1	1	1	1	1	1	1	1	1	1
	medium to high	0	0	1	1	1	0	1	1	0	0	1
C25	0–20 m	0	0	0	0	0	0	0	1	1	1	1
	20–50 m	1	1	0	0	0	1	1	1	1	1	1
	50–200 m	0	0	1	1	1	0	1	0	0	0	0
	> 200 m	0	0	0	1	1	0	0	0	0	0	0
C21	Area for maneuvering	1	1	1	1	1	1	1	1	1	1	1
	No area for maneuvering	1	1	0	1	1	1	0	0	0	0	0

Table 6 Collective subjective criteria scores

Subjective criteria	Bridge deck construction systems										
	BCS1	BCS2	BCS3	BCS4	BCS5	BCS6	BCS7	BCS8	BCS9	BCS10	BCS11
C11	5	5	4	4	4	3	7.5	8	6.5	6.5	6.5
C12	5.25	5.25	5.25	5.25	5.25	5.25	8.25	8.25	7.25	7.25	7.25
C13	6.5	6.5	6.5	6.5	6.5	6.5	6.5	4.5	4.5	4.5	5
C10	5	3.5	6	6	6	4	8.5	8.5	8.5	8.5	7.5
C26	7.5	8.5	6	5.5	5.5	5.5	4.5	4	6.5	5.5	4.5
C8	7.5	8	7.25	7.25	7.25	8.25	5.25	3	5.5	4.25	5.5
C24	6	6	6	6	6	6	8	8	8	8	6
C30	4	4	4	4	4	4	7	6	6	6	6
C29	7	8	5	5	5	8	4	3	3	3	3
C20	5	7	8	8	8	6	4	4	4	4	3.5
C6	7.5	8.5	6.5	6.5	7	7.5	4	4	4.5	4.5	4.5
C9	5	5	4	4	4	4	5	6	6	6	6
C4	7.5	8.5	6.5	6.5	7	7.5	4	4	4.5	4.5	4.5
C32	8	8	7	6.5	7	8	4.5	4.5	5.5	5.5	5.5
C28	6	6.5	6	6	6	3.5	2.5	2.5	3	3	3
C31	7	7	5	4.5	5	6.5	4	4	5	4	4

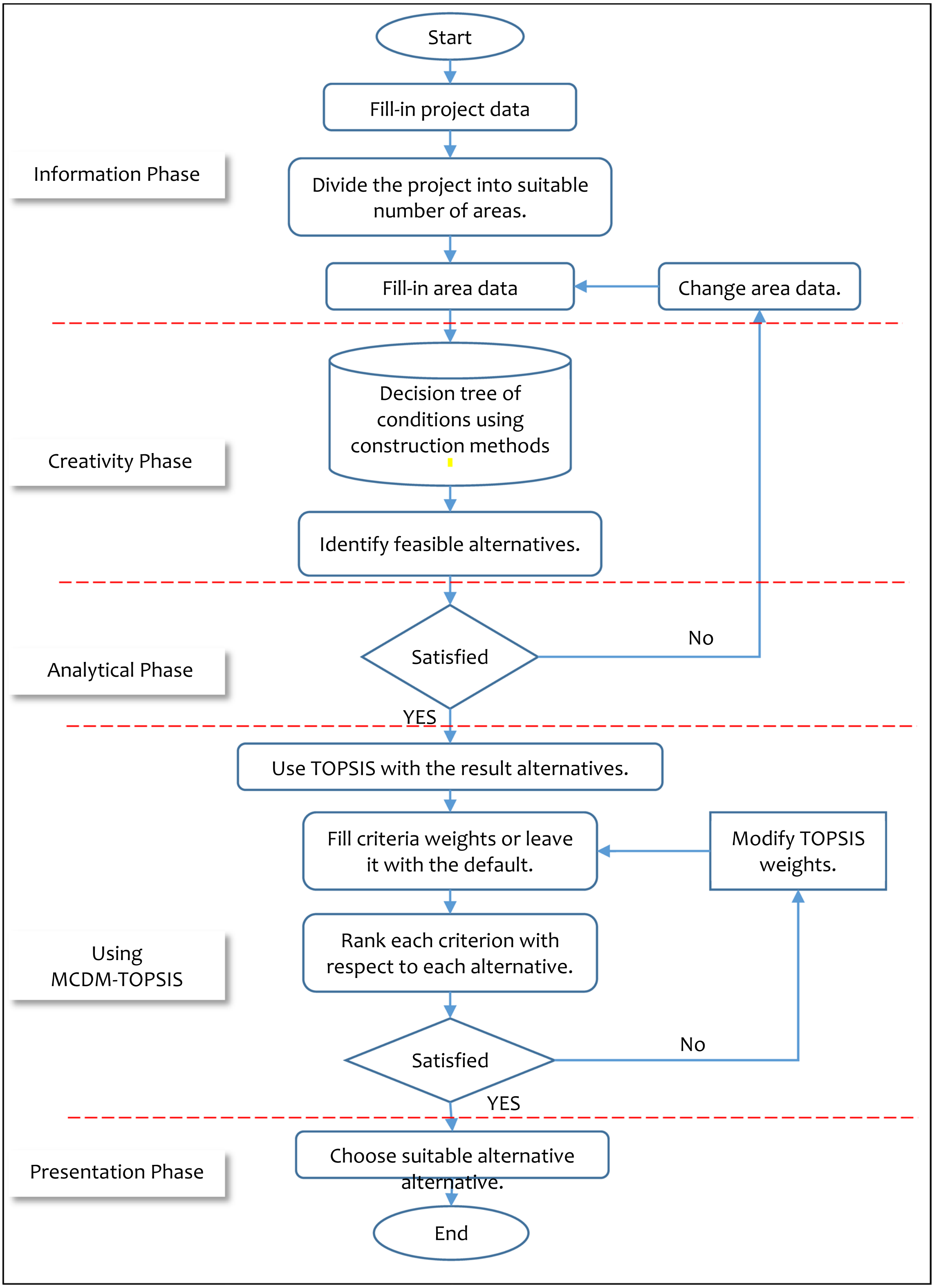


Fig. 3 Flowchart of the VEDS software

where DM is the decision matrix, (A_1, A_2, …., $A_{p)}$ defining the alternatives, ($R_{1,}$ R_2..., $R_{q)}$ defining the criteria, and C_{pq} is rating of alternative A_p with respect to Criteria C_q.

Step 2: Calculate the Normalized Decision Matrix

$$\overline{X_{ij}} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}} \tag{5}$$

where i determines the alternative index ($i=1, 2, \ldots, \mathrm{n}$), j determines the criteria index ($j=1, 2, \ldots, m$).

Step 3: Calculate weighted Normalized Decision Matrix

$$V_{ij} = \overline{X}_{ij} \times W_j \tag{6}$$

where W_j is the weight of the criteria for all j.

Step 4: Calculate the ideal best and ideal worst value (Max $V+$ & Min $V-$).

Step 5: Calculate the Euclidean distance from the ideal best

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right]^{0.5} \tag{7}$$

where $i=1, 2, \ldots, q$

Step 6: Calculate the Euclidean distance from the ideal Worst

$$S_i^- = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2\right]^{0.5} \tag{8}$$

where $i=1, 2, \ldots, q$

Step 7: Calculate Performance Score

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{9}$$

where $0 \le P_i \le 1$.

Step 8: Rank the performance score.

Step 9: Select the alternative with the highest performance score in order to be the suitable construction system.

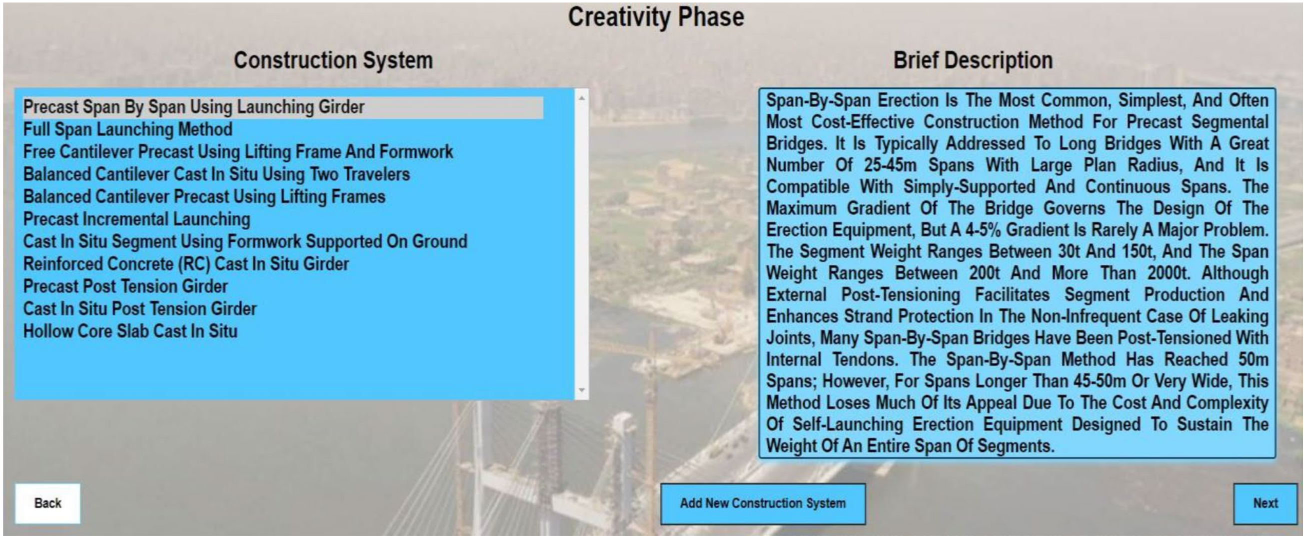
VEDS software

Information phase The VEDS software starts by asking the user to provide general project information such as the project's name, country, starting date, location, project description, and project regions. As showed in Fig. 4**,** the user then specifies the characteristics of the structural criteria for each project region before moving to the creativity phase.

Creativity phase The VEDS software includes all 11 BCS discussed in phase one of the study methodology. The VEDS software provides the user with a brief description of each of these selected BCS. Subsequently, the software presents the user with the 26 subjective criteria required for determining the appropriate BCS. These 26 criteria were identified in phase two of the study methodology. Finally, the software allows users to add "construction systems" and incorporate "new criteria" as needed. The creativity phase, as its name implies, is established for brainstorming, thinking, and adding new creative alternatives and solutions to avoid any limitations. Figures 5 and 6 illustrate the creativity phase.

Area Name	From Axis 1 To 100
Nature Of Crossing	Highway
Surrounding Area Nature	Downtown
Accessability To Site	Ease Access
Soil Condition	Strong
Volume Of Traffic During Construction	Moderate
Land Tepography Range	0 - 200 Cm
Bridge Hight Above Ground	0- 7 M
Horizontal Alignment	Small To Medium Curvature
Bridge Span Length	0-20 M
Cranes Capacity And Maneuvering	Require Area For Maneuvering

Fig. 4 Information Phase–Determine Region's Criteria



Creativity Phase

Construction System

Precast Span By Span Using Launching Girder
Full Span Launching Method
Free Cantilever Precast Using Lifting Frame And Formwork
Balanced Cantilever Cast In Situ Using Two Travelers
Balanced Cantilever Precast Using Lifting Frames
Precast Incremental Launching
Cast In Situ Segment Using Formwork Supported On Ground
Reinforced Concrete (RC) Cast In Situ Girder
Precast Post Tension Girder
Cast In Situ Post Tension Girder
Hollow Core Slab Cast In Situ

Brief Description

Span-By-Span Erection Is The Most Common, Simplest, And Often Most Cost-Effective Construction Method For Precast Segmental Bridges. It Is Typically Addressed To Long Bridges With A Great Number Of 25-45m Spans With Large Plan Radius, And It Is Compatible With Simply-Supported And Continuous Spans. The Maximum Gradient Of The Bridge Governs The Design Of The Erection Equipment, But A 4-5% Gradient Is Rarely A Major Problem. The Segment Weight Ranges Between 30t And 150t, And The Span Weight Ranges Between 200t And More Than 2000t. Although External Post-Tensioning Facilitates Segment Production And Enhances Strand Protection In The Non-Infrequent Case Of Leaking Joints, Many Span-By-Span Bridges Have Been Post-Tensioned With Internal Tendons. The Span-By-Span Method Has Reached 50m Spans; However, For Spans Longer Than 45-50m Or Very Wide, This Method Loses Much Of Its Appeal Due To The Cost And Complexity Of Self-Launching Erection Equipment Designed To Sustain The Weight Of An Entire Span Of Segments.

Fig. 5 Creativity Phase–Bridge Construction Systems

Creativity Phase Con't

Surrounding Environment
Nature Of Crossing
Surrounding Area Nature
Accessibility To Site
Diversion Cost Of Existing Utilities
Soil Condition
Volume Of Traffic During Construction
Climate During Construction
Land Topography
Bridge Physical Characteristics
No. Of Bridge Span
Bridge Height Above Ground
Breadth Of Deck
Horizontal Alignment
Bridge Span Length
Construction Method Characteristics
Availability Of Skilled Manpower
Availability Of Material
Aesthetics Of Bridge
Effect Of Construction On Design
Cranes Capacity And Maneuvering
Safety Requirement During Construction
Cost Of Defected Quality During Construction
Availability Of Equipment

Bridges Span Barriers Such As Railway, Highway, Waterway, Utilities, Valleys, Etc

Fig. 6 Creativity Phase–Selection Criteria

Analytical phase Analytical phase begins with acquiring all possible BCS as illustrated in Fig. 7. Next, the user proceeds to assign weighs to the subjective criteria. It is worth noting that the default weights used within the VEDS software are the ones determined during the second phase of the study methodology, the weights can be modified as per the user's needs as shown in Fig. 8**.**

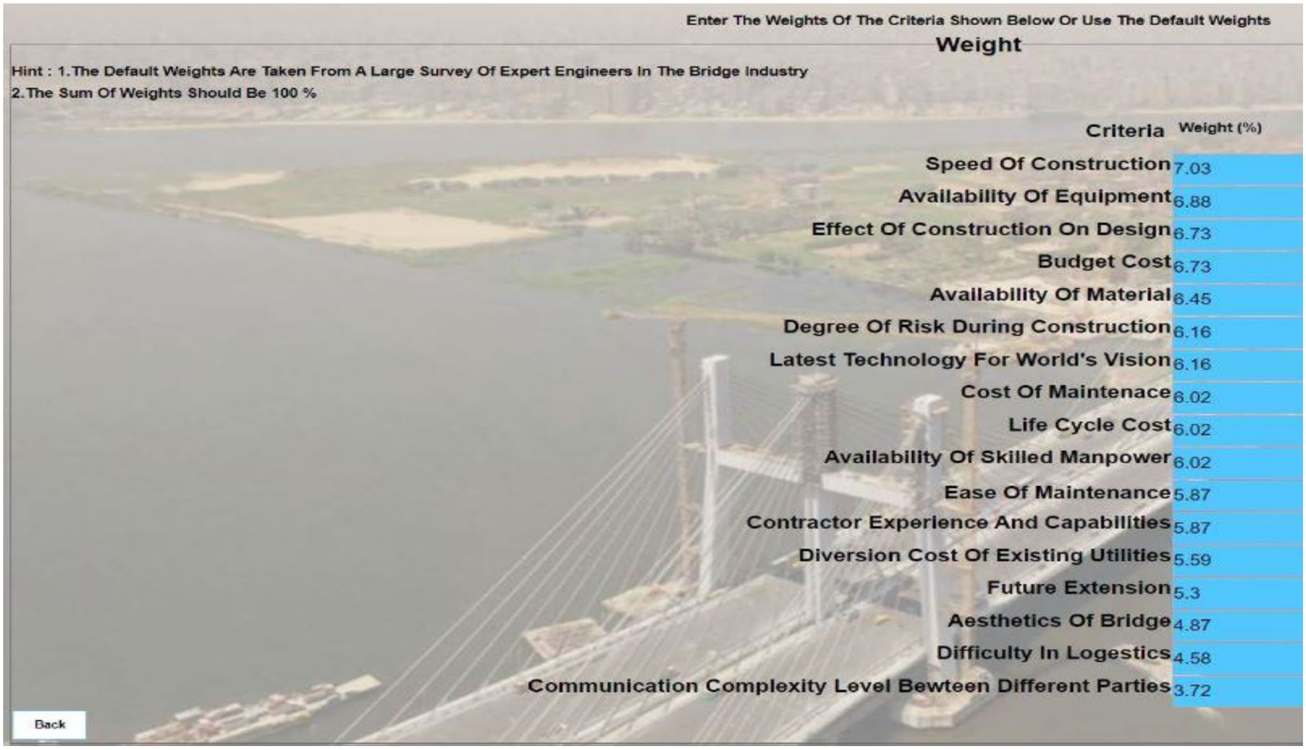
The next step in this process involves evaluating the subjective criteria for each construction system on a scale of 1 to 9. The performance score for each BCS is then calculated using TOPSIS, based on the user's ranking criteria in the previous step. Figure 9 illustrates the Analytical Phase–performance score table.

Development and presentation phase Based on the input data, the VEDS model recommends a suggestion for the appropriate BCS. The user has the option to receive a presentation regarding the recommended system, which comprises

Analytical Phase

Nature Of Crossing	Surrounding Area Nature	Accessability To Site	Soil Condition	Volume Of Traffic During Construction	Land Tepography Range	Bridge Hight Above Ground	Horizontal Alignment	Bridge Span Length	Cranes Capacity And Maneuvering
Highway	Downtown	Ease Access	Strong	Moderate	0 - 200 Cm	0 - 7 M	Small To Medium Curvature	0-20 M	Require Area For Maneuvering

Fig. 7 Analytical phase–construction systems



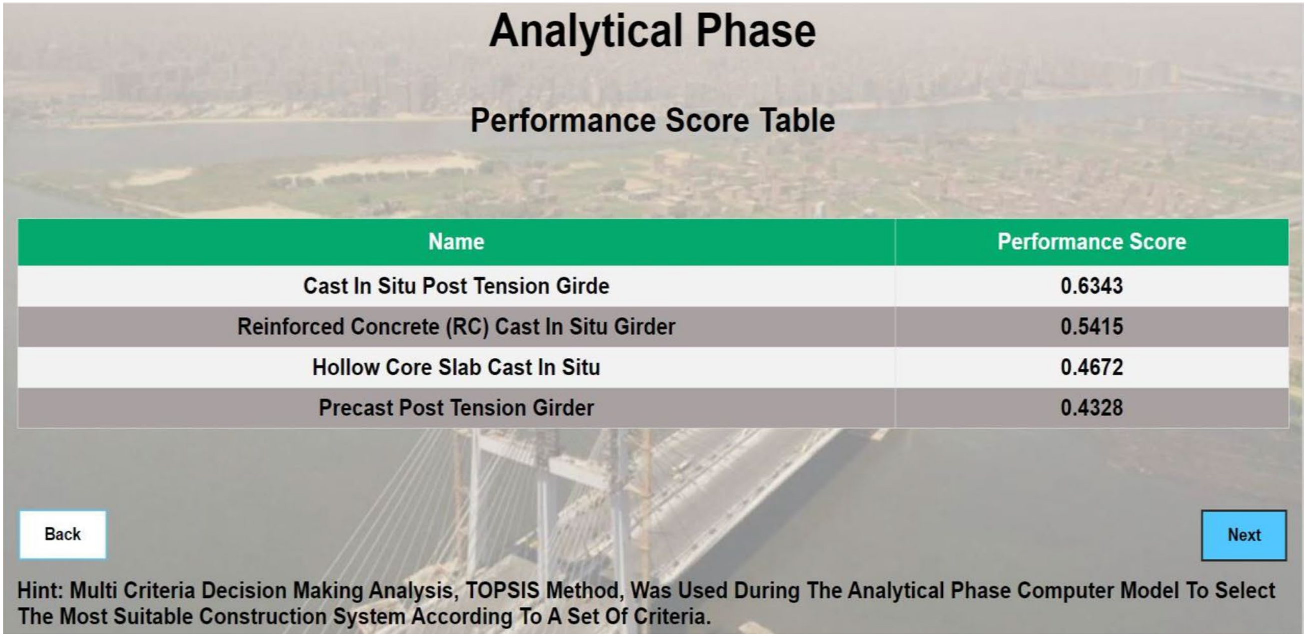
Enter The Weights Of The Criteria Shown Below Or Use The Default Weights

Weight

Hint : 1.The Default Weights Are Taken From A Large Survey Of Expert Engineers In The Bridge Industry
2.The Sum Of Weights Should Be 100 %

Criteria	Weight (%)
Speed Of Construction	7.03
Availability Of Equipment	6.88
Effect Of Construction On Design	6.73
Budget Cost	6.73
Availability Of Material	6.45
Degree Of Risk During Construction	6.16
Latest Technology For World's Vision	6.16
Cost Of Maintenace	6.02
Life Cycle Cost	6.02
Availability Of Skilled Manpower	6.02
Ease Of Maintenance	5.87
Contractor Experience And Capabilities	5.87
Diversion Cost Of Existing Utilities	5.59
Future Extension	5.3
Aesthetics Of Bridge	4.87
Difficulty In Logestics	4.58
Communication Complexity Level Bewteen Different Parties	3.72

Fig. 8 Analytical phase–Weighting the subjective criteria



Analytical Phase

Performance Score Table

Name	Performance Score
Cast In Situ Post Tension Girde	0.6343
Reinforced Concrete (RC) Cast In Situ Girder	0.5415
Hollow Core Slab Cast In Situ	0.4672
Precast Post Tension Girder	0.4328

Hint: Multi Criteria Decision Making Analysis, TOPSIS Method, Was Used During The Analytical Phase Computer Model To Select The Most Suitable Construction System According To A Set Of Criteria.

Fig. 9 Illustrates Analytical phase–Performance score table

an overview of the recommended system and its relevant construction procedure.

Model implementation and validation

The VEDS model has been implemented on two case study projects in Egypt: The Cairo metro and the New 26th July axis.

Case one: Cairo metro

Cairo metro Line 3-Phase 3B spans approximately 6.3 km and includes a total of 5 stations. This phase encompasses four elevated stations and one at-grade station. The owner is the National Authority for Tunnels, and the consultant is a joint venture consisting of Systra (France), EHAF (Egypt), ACCE (Egypt), and AGIS (Egypt). The contractor is a joint venture consisting of Vinci (France), Bouygues group (France), Orascom (Egypt), and Arab Contractors (Egypt). The selected case study is a 124-span bridge with a total length of 4000 m.

The structural criteria for case study one in Table 7 are entered into the VEDS Software. The results obtained from applying the VEDS model revealed that "Span by Span using a launching girder" method is the preferred choice. Screens illustrating the VEDS model steps are displayed in Figs. 10, 11, 12, 13, 14.

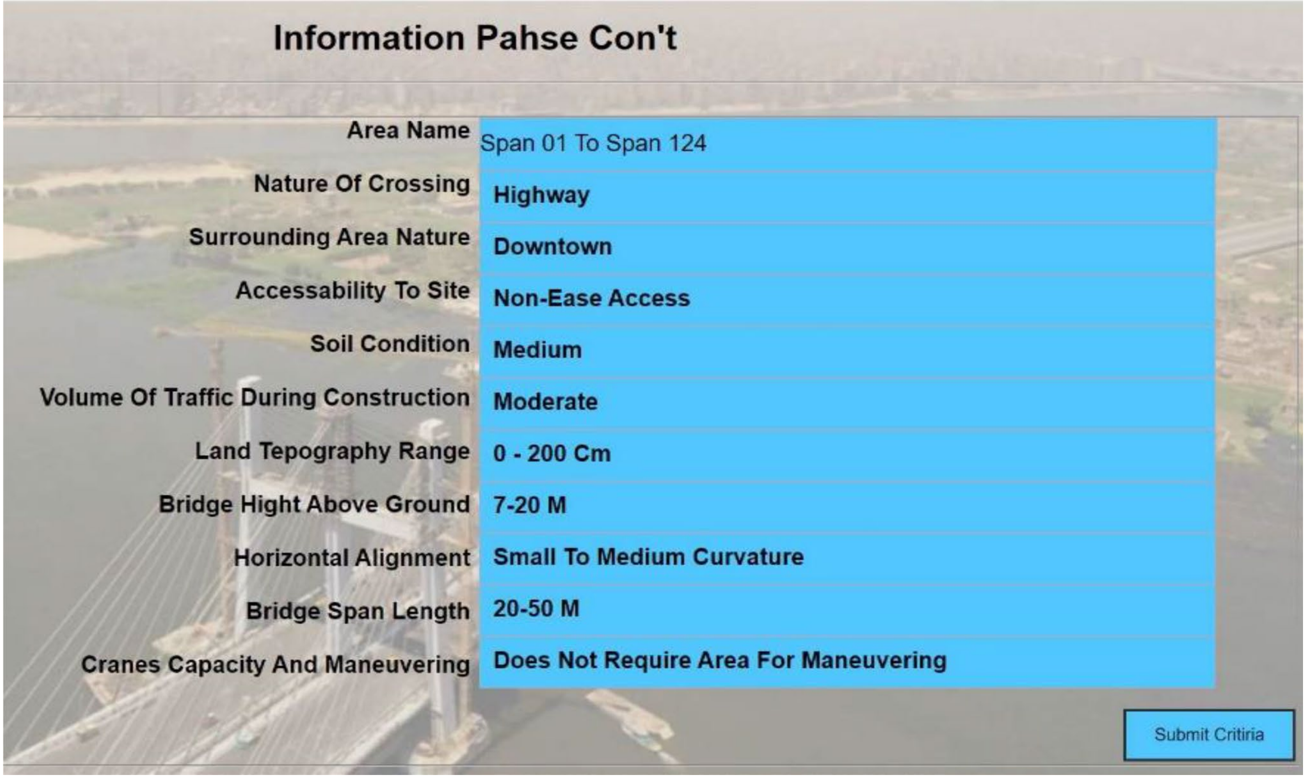
Table 7 Case study one structural criteria

Main structural criteria	Cairo metro–Phase 3B
Nature of crossing	Highways, railway and roads
Surrounding area nature	Down town and Agrarian
Accessibility to site	Non-ease access
Soil condition	Medium
Volume of traffic during construction	Moderate
Land topography	0-50 cm
Bridge high above ground	15 m
Horizontal Alignment	Small to medium curvature.
Bridge span length	Standard span: 33 m & longest span: 47 m
Cranes Capacity and maneuvering	No area for maneuvering
Construction system used	Precast Span by Span Using Launching Girder

Information Phase

Project Id	1
Project Name	Line 3-Phase 3B Cairo Metro
Project Owner	National Authority For Tunnels
Country	Egypt
City	Cairo
Project Address	Imbaba Zone
Date	18-2-2018
Project Description	Phase 3B Comprises Of Four Elevated Stations, And One At Grade Station, In Addition To The Workshop.

Fig. 10 Illustrates Information Phase–Entering project information



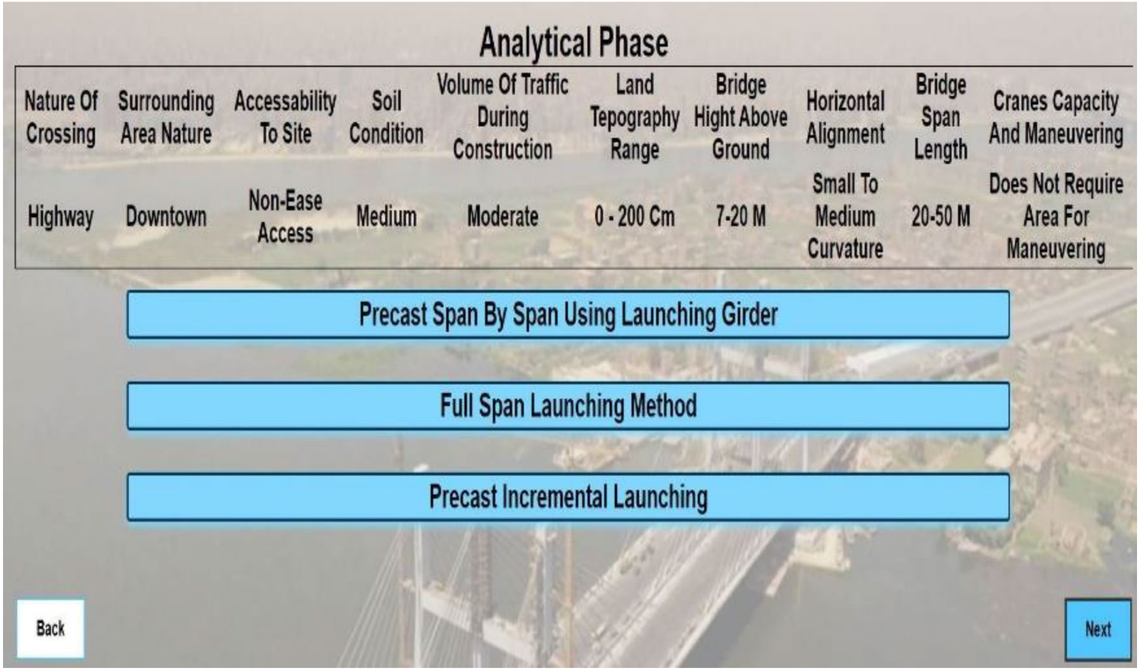
Information Pahse Con't

Area Name	Span 01 To Span 124
Nature Of Crossing	Highway
Surrounding Area Nature	Downtown
Accessability To Site	Non-Ease Access
Soil Condition	Medium
Volume Of Traffic During Construction	Moderate
Land Tepography Range	0 - 200 Cm
Bridge Hight Above Ground	7-20 M
Horizontal Alignment	Small To Medium Curvature
Bridge Span Length	20-50 M
Cranes Capacity And Maneuvering	Does Not Require Area For Maneuvering

Fig. 11 Illustrates Information phase–Determine region's criteria

Case two: new 26th July axis

The new 26th of July axis project aims to alleviate traffic congestion on the existing 26th of July axis while improving access to the cities of 6th of October and Sheikh Zayed. The owner is the Armed Forces Engineering Authority, and the consultant is a joint venture consisting of El-Raeid Engineering Consultants, and SICE office. The contractor is Hassan Allam Roads & Bridges. The selected case study is a 30-span bridge with a total length of 1200 m.



Analytical Phase

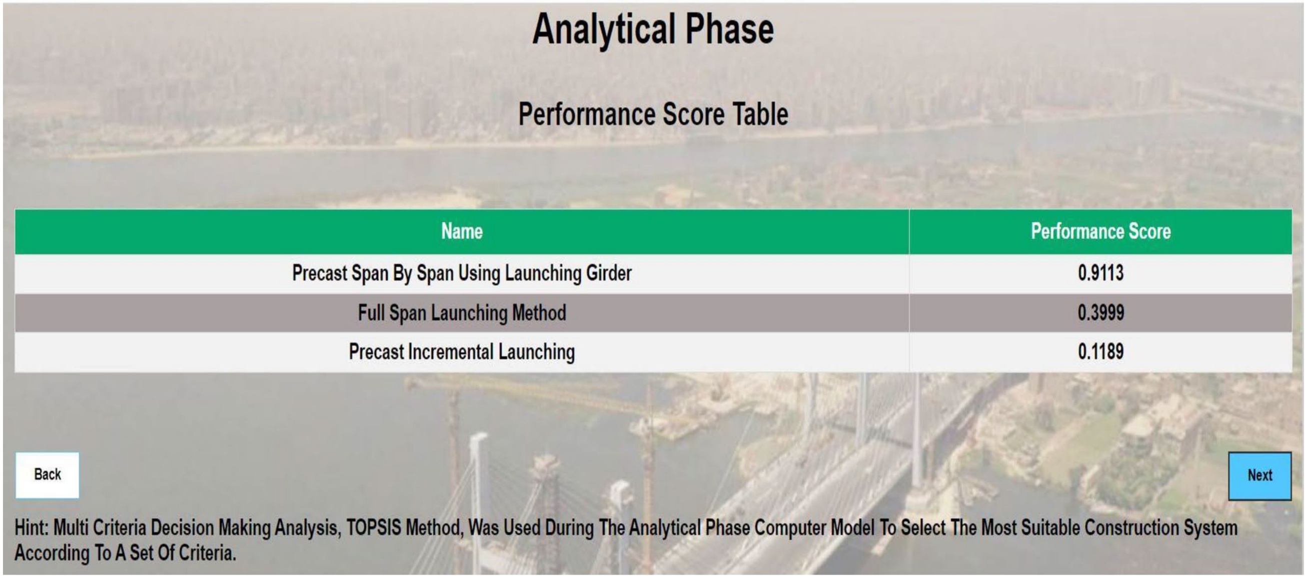
Nature Of Crossing	Surrounding Area Nature	Accessability To Site	Soil Condition	Volume Of Traffic During Construction	Land Tepography Range	Bridge Hight Above Ground	Horizontal Alignment	Bridge Span Length	Cranes Capacity And Maneuvering
Highway	Downtown	Non-Ease Access	Medium	Moderate	0 - 200 Cm	7-20 M	Small To Medium Curvature	20-50 M	Does Not Require Area For Maneuvering

Precast Span By Span Using Launching Girder

Full Span Launching Method

Precast Incremental Launching

Fig. 12 Illustrates Analytical phase–Construction systems recommended



Analytical Phase

Performance Score Table

Name	Performance Score
Precast Span By Span Using Launching Girder	0.9113
Full Span Launching Method	0.3999
Precast Incremental Launching	0.1189

Hint: Multi Criteria Decision Making Analysis, TOPSIS Method, Was Used During The Analytical Phase Computer Model To Select The Most Suitable Construction System According To A Set Of Criteria.

Fig. 13 Illustrates Analytical phase–Performance score table

The structural criteria for case study two in Table 8 are entered into the VEDS Software. The results obtained from applying the VEDS model revealed that the "precast post tension girder" method is the preferred choice. Screens illustrating the VEDS model steps are displayed in Figs. 15, 16, 17, 18, 19.

Discussion of results

Based on the results presented in case study 1, as illustrated in Figs. 13 and 14, it is evident that the performance score for the "span by span using launching girder" is 0.9113, which is less than the ideal score of 1. This result means that the executed construction system, within a set of project criteria, could be the preferred choice. The result is affected

Fig. 14 Illustrates Development & presentation phase–The chosen system

Table 8 Case study two structural criteria

Main structural criteria	New 26th July axis
Nature of crossing	Roads
Surrounding area nature	Down town
Accessibility to site	Ease access to the site
Soil condition	Medium
Volume of traffic during construction	High
Land topography	0–50 cm
Bridge high above ground	17 m
Horizontal Alignment	Small to medium curvature
Bridge span length	Span length: 40 m
Cranes Capacity and maneuvering	Have area for maneuvering
Construction system used	Precast post tension girder

by the subjective criteria rates provided for each recommended construction system during the analytical phase on a Likert scale from 1 to 9, highly meets the first alternative conditions.

The same is true for case study 2, as illustrated in Figs. 18 and 19, it is evident that the performance score for the "Precast Post Tension Girder" is 0.7969. This result means that the executed construction system, within a set of project criteria, could be the preferred choice. This result is affected by the subjective criteria rates provided for each recommended construction system during the analytical phase on a Likert scale from 1 to 9, highly meets the first alternative conditions. These rates are entered based on the project participant’s requirements, project conditions, and the market's current status. For improved results, the project participant’s requirements and project conditions must be modified. For example, but not limited to, budget cost, speed of construction, contractor experience, and capabilities. Similarly, the market status should be enhanced. For example, but not limited to, the availability of material, equipment, and skilled manpower.

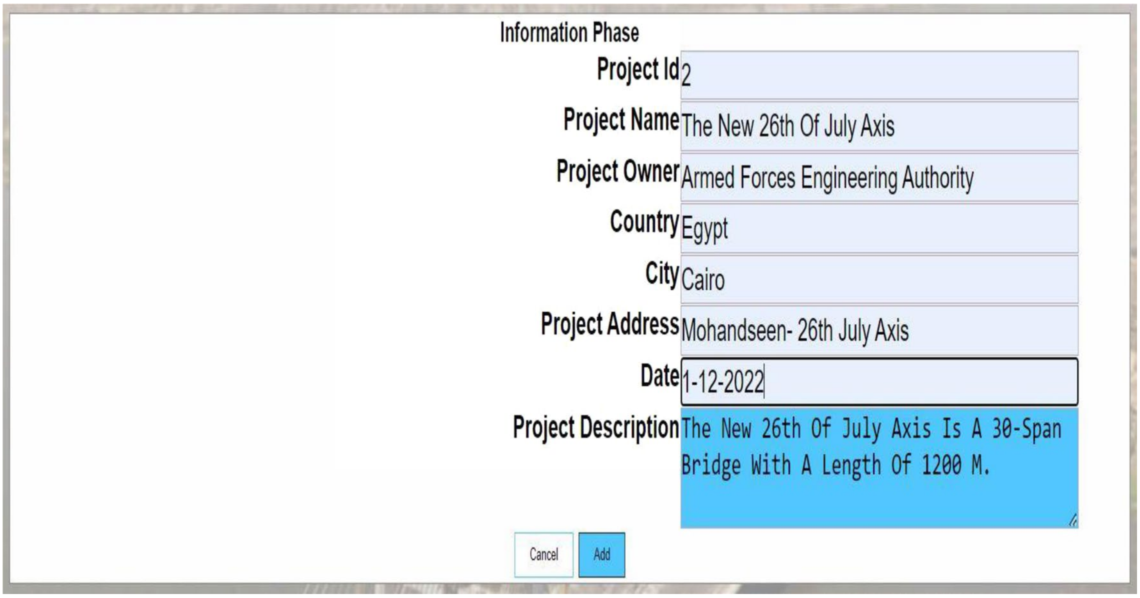
Validation results

A semi-structured interview is carried out with a total of 6 bridge engineers, with 3 engineers from each project, to check the validation and accuracy of the VEDS software in selecting the two construction systems mentioned above.

For case study one, all three experts report that "precast span by span using a launching girder" is the most preferred construction system to be used. This feedback complies with the results produced by the VEDS software. For case study two, all three experts report that the "precast post tension girder" is the most preferred construction system to be used. This feedback complies with the results produced by the VEDS software. Additionally, the interviewees report that the current selection criteria adequately suit the project's circumstances in Egypt and recommend the inclusion of additional construction systems in the model.

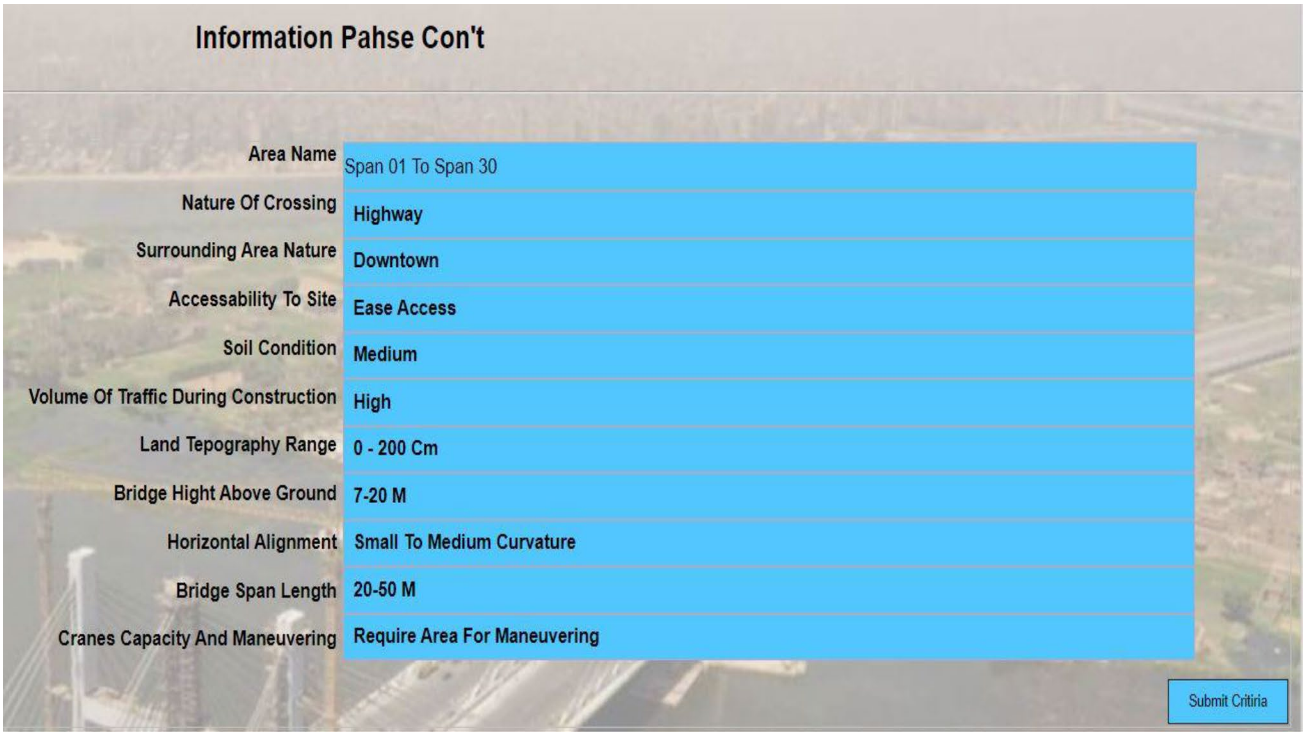
Study limitations

While the proposed model has proven successful in both case studies, it is important to acknowledge that this research



Project Id	2
Project Name	The New 26th Of July Axis
Project Owner	Armed Forces Engineering Authority
Country	Egypt
City	Cairo
Project Address	Mohandseen- 26th July Axis
Date	1-12-2022
Project Description	The New 26th Of July Axis Is A 30-Span Bridge With A Length Of 1200 M.

Fig. 15 Illustrates Information phase–Entering project data



Area Name	Span 01 To Span 30
Nature Of Crossing	Highway
Surrounding Area Nature	Downtown
Accessability To Site	Ease Access
Soil Condition	Medium
Volume Of Traffic During Construction	High
Land Tepography Range	0 - 200 Cm
Bridge Hight Above Ground	7-20 M
Horizontal Alignment	Small To Medium Curvature
Bridge Span Length	20-50 M
Cranes Capacity And Maneuvering	Require Area For Maneuvering

Fig. 16 Illustrates information phase–Determine region's criteria

still has some limitations that should be addressed in future studies. First, the proposed VEDS model is constrained by a specific number of construction systems. Such construction systems limitations may prevent the generalization for applying this model for a broader range during the preliminary design. Secondly, certain structural criteria have limited

Analytical Phase

Nature Of Crossing	Surrounding Area Nature	Accessability To Site	Soil Condition	Volume Of Traffic During Construction	Land Tepography Range	Bridge Hight Above Ground	Horizontal Alignment	Bridge Span Length	Cranes Capacity And Maneuvering
Highway	Downtown	Ease Access	Medium	High	0 - 200 Cm	7-20 M	Small To Medium Curvature	20-50 M	Require Area For Maneuvering

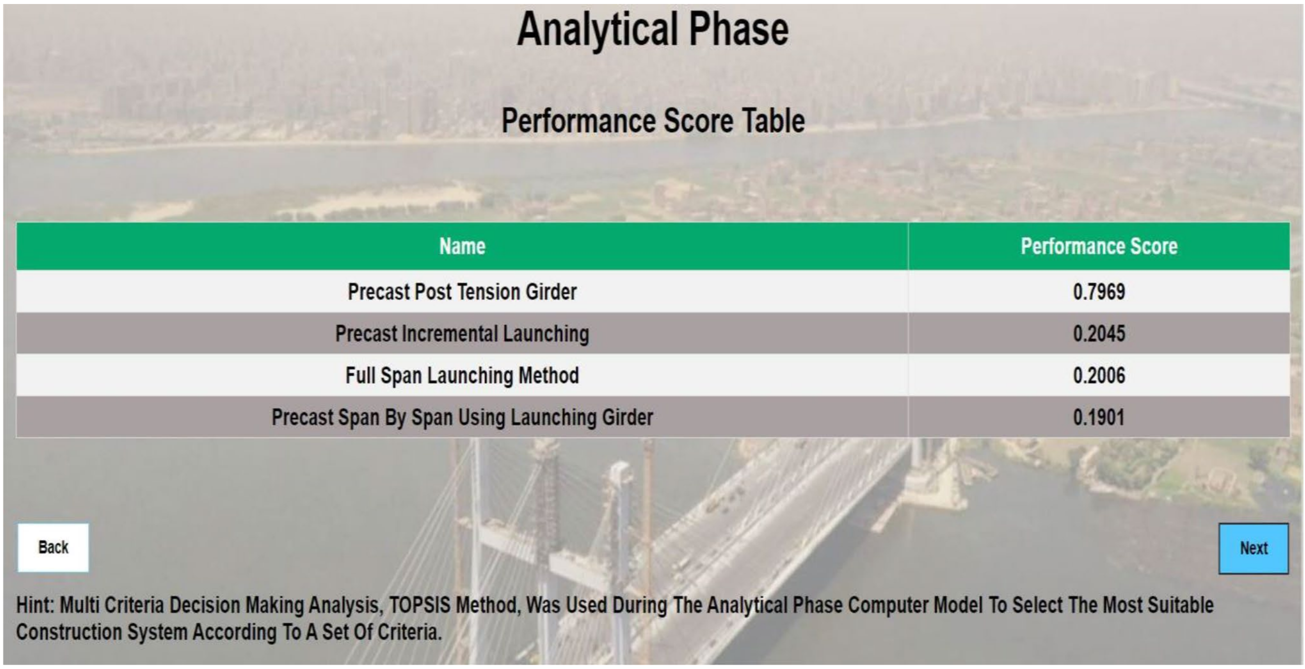
Precast Span By Span Using Launching Girder

Full Span Launching Method

Precast Incremental Launching

Precast Post Tension Girder

Fig. 17 Illustrates Analytical phase–Construction systems recommended



Analytical Phase

Performance Score Table

Name	Performance Score
Precast Post Tension Girder	0.7969
Precast Incremental Launching	0.2045
Full Span Launching Method	0.2006
Precast Span By Span Using Launching Girder	0.1901

Hint: Multi Criteria Decision Making Analysis, TOPSIS Method, Was Used During The Analytical Phase Computer Model To Select The Most Suitable Construction System According To A Set Of Criteria.

Fig. 18 Illustrates Analytical phase–Performance score table

to specific characteristics, such as land topography, bridge high from ground, etc. These limitations prevent the model from being applied on all the construction bridge projects. Lastly, the VEDS model is applied on bridge projects in Egypt based on the methodology for choosing construction

The Best Model Is : Precast Post Tension Girder

Fig. 19 Illustrates development & presentation phase–The chosen system

systems and criteria. However, in order to use the model internationally, it could be need to review the selection of criteria and the construction systems used into the model.

Summary and conclusions

Clients and consultants aim to choose the appropriate bridge construction system during the conceptual design phase. The primary goal of this research is to provide a decision support tool that recommends the appropriate construction system, considering project-specific criteria. The research went through three major phases to attain the previously mentioned goal.

The first phase included conducting literature review to identify and collect various types of bridge construction systems and criteria for evaluating and selecting the appropriate construction system for a certain project. The collected data are reviewed in semi-structured interviews with experts from the bridge construction industry. This process aims to add or remove any construction system or criteria, resulting in a final list of construction systems and criteria to be used in the subsequent phases.

The second phase is conducted using two questionnaires that are directed at a specific focus group consisting of professional engineers employed in bridge construction companies. The goal of the first questionnaire is to determine the most important criteria influencing the selection of the appropriate construction system. The goal of the second questionnaire is to apply the structural criteria for each bridge construction system. Additionally, it prioritizes the subjective criteria to be considered throughout the selection process for all bridge construction systems.

Lastly, the third phase of this study involves the creation and implementation of the VEDS software, designed to compare various bridge deck construction systems. The model, which is intended to assist in the selection of the appropriate bridge deck construction system, is introduced during this phase.

To validate the computer model and assist the decision-maker in choosing the appropriate construction system, two case studies are used. The VEDS model performed well in the results, with the experts surveyed recommending the same construction system as suggested by the VEDS model.

The contribution of this research lies in presenting a value engineering decision support system that utilizes a multi-criteria decision making method, using the TOPSIS method. This system helps designers or decision-makers in choosing the appropriate bridge system based on a range of structural and subjective criteria.

In addition to the efforts outlined in this paper, it has become evident that additional efforts are required to bridge the gap in the following areas: (1) Improve the proposed model to include new construction systems. (2) Add more characteristics of structural criteria, such as span lengths ranging from 500 to 1000, to enhance the precision of the selection of the appropriate construction system. (3) Introduce additional subjective criteria to further enhance the model's accuracy. (4) Upgrade the model by incorporating substructure elements, such as foundations, piers, and bearings, which will contribute to the determination of the appropriate construction system.

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Data and material availability Datasets are available upon reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

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