



Managing risk in tunneling projects: A fuzzy TOPSIS approach for improved decision-making

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Received: 17. April. 2025 Accepted: 18. June. 2025
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Keywords

Risk Assessment
Tunneling Projects
Fuzzy TOPSIS
Multi-Criteria Decision-Making

Abstract

Risk assessment is a critical task in tunneling projects, yet classical methods often fail to adequately manage the inherent uncertainties of expert judgments. This paper presents a comparative risk analysis using two multi-criteria decision-making techniques: Classical TOPSIS and Fuzzy TOPSIS. The study first establishes a baseline risk ranking using the Classical TOPSIS method, which relies on crisp numerical inputs. It then applies the Fuzzy TOPSIS method to the same dataset, leveraging fuzzy set theory to model the linguistic ambiguity and uncertainty in expert evaluations. The methodologies are applied to a case study of a tunnel construction project, assessing 17 distinct risks across 11 criteria. The results demonstrate that while both methods identify similar high-priority risks, the final rankings differ. The Fuzzy TOPSIS model, by incorporating uncertainty, provides a more robust and nuanced prioritization, identifying Owner risks (R10) and Site/Environment risks (R5) as more critical than the classical method did. This study concludes that the Fuzzy TOPSIS approach is a superior and more reliable tool for decision-makers, offering a more realistic framework for managing the complex risks in tunneling projects.

1. INTRODUCTION

Risk assessment is an essential component in the planning and execution of tunneling projects, given the inherent complexities and uncertainties associated with underground construction. Unlike surface projects, tunneling must contend with highly unpredictable geological conditions that can significantly influence safety, cost, schedule, and quality outcomes [1, 2]. For example, historical projects such as the Channel Tunnel have experienced dramatic cost overruns exceeding initial budgets by nearly 80%, due largely to unforeseen geological challenges [3, 4]. Such instances underscore the critical need for a robust risk management framework that not only identifies potential hazards but also prioritizes them in a systematic and reliable manner [5]. Early approaches to risk assessment in tunneling projects predominantly relied on qualitative or semi-quantitative methods. Commonly, tools such as the probability–impact matrix were employed, where risks were categorized into discrete levels (e.g., “Low,” “Medium,” or “High”) based on expert judgment regarding their likelihood and potential impact [6].

Although these methods have the advantage of simplicity and ease of use, they are limited by their reliance on subjective assessments and their tendency to overlook critical aspects of risk such as manageability, proximity, and the inherent uncertainty in the evaluations [7, 8]. Moreover, traditional methods often assume that risk factors are independent and static, which is rarely the case in the dynamic environment of underground construction [9]. In light of these limitations, researchers have sought to develop more sophisticated risk assessment methodologies over the past two decades. Advanced techniques, such as Monte Carlo simulations, enable the generation of probability distributions for various outcomes by simulating numerous “what-if” scenarios. This probabilistic approach provides a more detailed understanding of potential cost overruns and schedule delays, thereby supporting more effective contingency planning [10]. Mathematical modeling in previous studies has also been able to improve project risks, profitability, and safety [11-17]. In parallel, Bayesian networks have been introduced as a means to model the causal relationships among risk factors dynamically, allowing for real-time updating of risk

probabilities as new information becomes available [18]. Another significant advancement is the integration of fuzzy logic into multi-criteria decision-making (MCDM) frameworks. Techniques such as fuzzy TOPSIS extend traditional TOPSIS by incorporating fuzzy set theory to transform imprecise, linguistic expert evaluations into quantitative fuzzy numbers [19, 20]. This method enhances the reliability of risk assessments by accommodating the ambiguity and subjectivity inherent in expert judgments, ultimately resulting in a more coherent and comprehensive risk ranking [21, 22]. Furthermore, these fuzzy MCDM approaches facilitate the simultaneous consideration of multiple risk attributes beyond mere probability and impact, thus addressing a critical shortcoming of earlier qualitative methods [23]. In the recent study, MCDM was used to determine the mine rehabilitation method [24]. Additional contributions to the field have emerged from studies focusing on time and cost estimation under uncertainty [25], which further illustrate the multifaceted nature of tunneling risks. Guidelines and codes of practice, such as those from ITA/AITES [4] and ITIG [26], have also been influential in formalizing risk management practices, even though they often rely on classical methods that do not fully capture the dynamic interplay of risk factors [27]. More recent literature emphasizes the importance of integrating advanced computational tools into risk assessment models. For instance, it has been demonstrated that modern decision-making frameworks can bridge the gap between theoretical models and practical applications by combining fuzzy logic with operational performance measurements [28, 29]. The evolution from traditional qualitative methods to advanced quantitative and hybrid approaches represents a significant progression in tunneling risk assessment. Early models, while foundational, often fell short in accurately reflecting the complex, interdependent nature of risks in underground projects. In contrast, modern methods that incorporate probabilistic simulations, Bayesian networks, and fuzzy MCDM techniques provide a more dynamic and comprehensive framework for risk evaluation [30, 31]. These advancements allow for the continuous updating of risk profiles and better support proactive decision-making, which is crucial for managing the considerable uncertainties that characterize tunneling projects. In summary, the move towards integrating advanced computational techniques with fuzzy logic and multi-criteria decision-making marks a significant enhancement over traditional risk assessment approaches. This new paradigm not only addresses the inherent subjectivity and oversimplification of classical methods but also offers a robust, adaptable, and data-driven framework that can substantially improve project outcomes. As the tunneling industry continues to face challenges associated with unpredictable underground conditions, these advanced methodologies provide the necessary

tools to manage risk more effectively and to ensure the successful delivery of complex tunneling projects [32-36].

2. METHODOLOGY

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a common multi-criteria decision-making tool where the best option is defined as the one that is closest to the positive ideal solution and farthest from the negative ideal solution. In risk assessment applications, expert judgment is often characterized by uncertainty. As a result, fuzzy TOPSIS, which uses triangular fuzzy numbers rather than weightings and represents linguistic evaluations such as "low" and "high", expands the method, while ensuring a typical expert viewpoint, sanity in representation of expert opinions through the use of the center and λ -possibility of the triangle. However, interventions like normalization, weighting, and distance measures, which are often used to produce ranks for decision-making, are done directly on fuzzy values, creating an ordering that is more representative of uncertainty.

A. Classical TOPSIS

A set of m alternatives and n criteria is considered with a normalized weight vector $\omega = \omega_1, \dots, \omega_n$ satisfying $\sum_{j=1}^n \omega_j = 1$. A crisp decision matrix $X = [x_{ij}]_{m \times n}$ is formed, where x_{ij} denotes the performance of alternative i on criterion j . To remove scale effects and ensure unit-invariance, vector (Euclidean) normalization is applied in Eq. (1):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (1)$$

Relative importance is imposed by constructing the weighted normalized matrix $V = [v_{ij}]$ via Eq. (2):

$$v_{ij} = \omega_j r_{ij} \quad (2)$$

Because all criteria are treated as benefit-type in this study, the positive and negative ideal solutions are defined column-wise by the extrema of V in Eq. (3):

$$A^+ = (v_1^+, \dots, v_n^+), v_j^+ = \max_i v_{ij} \quad (3)$$

$$A^- = (v_1^-, \dots, v_n^-), v_j^- = \min_i v_{ij}$$

Proximity to these ideals is quantified by Euclidean separations in Eq. (4):

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (4)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}$$

Ranking is then obtained from the relative closeness coefficient in Eq. (5); larger values indicate higher priority:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (5)$$

B. Fuzzy TOPSIS

Uncertainty in expert judgements is retained by operating directly on triangular fuzzy numbers $\tilde{x}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ with $l_{ij} \leq m_{ij} \leq u_{ij}$. For each criterion j , the upper-bound normalizer $u_j^* = \max_i u_{ij}$ is computed so that all TFNs are mapped to [0,1] while preserving their partial order; fuzzy normalization is performed in Eq. (6):

$$\tilde{r}_{ij} = \frac{\tilde{x}_{ij}}{u_j^*} = \left(\frac{l_{ij}}{u_j^*}, \frac{m_{ij}}{u_j^*}, \frac{u_{ij}}{u_j^*} \right) \quad (6)$$

Because the criterion weights are crisp in this application, fuzzy weighting reduces to scalar multiplication of TFNs as in Eq. (7):

$$\tilde{v}_{ij} = \omega_j \tilde{r}_{ij} = \left(\frac{\omega_j l_{ij}}{u_j^*}, \frac{\omega_j m_{ij}}{u_j^*}, \frac{\omega_j u_{ij}}{u_j^*} \right) \quad (7)$$

Consistent with the benefit-type interpretation, the fuzzy positive and negative ideals are determined component-wise from the column maxima and minima of $\tilde{V} = [\tilde{v}_{ij}]$, as given in Eq. (8):

$$\tilde{v}_j^+ = (\max_i l_{ij}, \max_i m_{ij}, \max_i u_{ij}) \quad (8)$$

$$\tilde{v}_j^- = (\min_i l_{ij}, \min_i m_{ij}, \min_i u_{ij})$$

Distances between TFNs are evaluated by the vertex (Euclidean) metric in R^3 , which is compatible with the normalization in Eq. (6) and avoids arbitrary scale factors; this metric is stated in Eq. (9):

$$d(\tilde{a}, \tilde{b}) = \sqrt{(l_a - l_b)^2 + (m_a - m_b)^2 + (u_a - u_b)^2} \quad (9)$$

Criterion-wise distances to the ideals are then aggregated in quadrature to obtain overall separations in Eq. (10):

$$D_i^+ = \sqrt{\sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^+)^2} \quad (10)$$

$$D_i^- = \sqrt{\sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^-)^2}$$

Finally, a crisp ranking index is produced by the fuzzy closeness coefficient in Eq. (11), which mirrors

the classical definition while carrying uncertainty up to the distance stage:

$$CC_i^{(F)} = \frac{D_i^-}{D_i^+ + D_i^-} \quad (11)$$

3. CASE STUDY DESCRIPTION

The Seymareh dam is being constructed in the southwestern of Iran. The project which lies geographically in latitude 47° 12' and longitude 33° 17' is located in the Zagros range, Eilam province. The main objectives of this project are electricity and irrigation water production. Figure 3 shows a view of the Seymareh project. In this project, two diversion tunnels, one water conveyance tunnel and six horseshoe grouting galleries are excavated in the folded limestones belong to Asmari formation of the Zagros range (Table 2).



Figure 1. A view of the Seymareh dam project

Table 1. Seymareh Tunnels specifications

Tunnel type	Length (m)	Cross section (m ²)
Diversion tunnels	871	63
Conveyance tunnels	1476	94
Grouting galleries	550	15

4. RESULTS AND DISCUSSION

In this paper, the risks were recognized and incorporated based on a risk breakdown structure [37]. As can be seen from Table 1, the risks involved in tunneling projects are broadly divided into two categories: internal and external. As a matter of fact, only internal risks that are intrinsic to each project can be controlled by the management. But external risks that originated from sources other than the project conditions cannot be organized by the managers.

Table 2. Involved risks in the tunneling projects risk assessment

External	Internal
Political risks (R ₁)	Loss or damages risks (R ₇)
Social risks (R ₂)	Contracting risks (R ₈)
Economic risks (R ₃)	Financial risks (R ₉)
Legal and regulatory risks (R ₄)	Owner risks (R ₁₀)
Site or environment risks (R ₅)	Management risks (R ₁₁)
Acts of God (R ₆)	Planning risks (R ₁₂)
	Technical risks (R ₁₃)
	Material and Equipment risks (R ₁₄)
	Schedule risks (R ₁₅)
	Guarantees risks (R ₁₆)
	Labor risks (R ₁₇)

After identification of the risks, required criteria have to be determined (Table 4). As it can be seen from Table 2, to achieve a more coherent assessment, various criteria have been incorporated the case which is not possible for the conventional method. The

criterion C₁ directly comes from the classical method but the risk impact of the classical method is broken into four major project objectives; cost, schedule, quality and scope (C₂ to C₅). Also, six other complementary criteria have been considered.

Table 3. Criteria of risk assessment

symbol	Criteria	symbol	Criteria
C ₁	Occurrence probability	C ₆	Manageability
C ₂	Impact of the risks on the projects' cost	C ₇	Uncertainty level
C ₃	Impact of the risks on the projects' schedule	C ₈	Proximity of risk
C ₄	Impact of the risks on the projects' quality	C ₉	Risk exposure
C ₅	Impact of the risks on the projects' scope	C ₁₀	Environmental effect
		C ₁₁	Socio economics effect

Collection of expert judgments regarding criteria evaluation for each individual alternative was on the basis of group decision-making method [38]. Evaluation of the criteria occurrence probability and extended impacts was performed using Table 5 [2]. For obtaining the fuzzy-decision matrix D, a

questionnaire was designed and distributed to 30 experts grouped into six different panels. The experts' qualitative linguistic expressions were converted into quantitative triangular fuzzy numbers using the Likert scale [36].

Table 4. Evaluating the impact of risks and occurrence probability

Probability of occurrence	Impacts of risks																			
	Overall Project Schedule Slippage				Cost increase				Quality				Scope							
< 5 %	Insignificant	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Insignificant	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Quality Degradation Barely Noticeable	Only very demanding Application Are Affected	Quality Reduction Requires Client Approval	Quality Reduction Unacceptable to the Client	Project End Item is Effectively Unusable	Scope Decrease Barely Noticeable	Minor Area of Scope Are Affected	Major Area of Scope Are Affected	Scope Reduction Unacceptable to the Client	Project End Item is Effectively Unusable
6 - 25 %	> 71%	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Insignificant	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Quality Degradation Barely Noticeable	Only very demanding Application Are Affected	Quality Reduction Requires Client Approval	Quality Reduction Unacceptable to the Client	Project End Item is Effectively Unusable	Scope Decrease Barely Noticeable	Minor Area of Scope Are Affected	Major Area of Scope Are Affected	Scope Reduction Unacceptable to the Client	Project End Item is Effectively Unusable
26 - 50 %	51 - 70 %	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Insignificant	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Quality Degradation Barely Noticeable	Only very demanding Application Are Affected	Quality Reduction Requires Client Approval	Quality Reduction Unacceptable to the Client	Project End Item is Effectively Unusable	Scope Decrease Barely Noticeable	Minor Area of Scope Are Affected	Major Area of Scope Are Affected	Scope Reduction Unacceptable to the Client	Project End Item is Effectively Unusable
51 - 70 %	> 71%	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Insignificant	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Quality Degradation Barely Noticeable	Only very demanding Application Are Affected	Quality Reduction Requires Client Approval	Quality Reduction Unacceptable to the Client	Project End Item is Effectively Unusable	Scope Decrease Barely Noticeable	Minor Area of Scope Are Affected	Major Area of Scope Are Affected	Scope Reduction Unacceptable to the Client	Project End Item is Effectively Unusable
6 - 25 %	> 71%	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Insignificant	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Quality Degradation Barely Noticeable	Only very demanding Application Are Affected	Quality Reduction Requires Client Approval	Quality Reduction Unacceptable to the Client	Project End Item is Effectively Unusable	Scope Decrease Barely Noticeable	Minor Area of Scope Are Affected	Major Area of Scope Are Affected	Scope Reduction Unacceptable to the Client	Project End Item is Effectively Unusable
< 5 %	Insignificant	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Insignificant	< 5 %	5 - 10 %	10 - 20 %	> 20 %	Quality Degradation Barely Noticeable	Only very demanding Application Are Affected	Quality Reduction Requires Client Approval	Quality Reduction Unacceptable to the Client	Project End Item is Effectively Unusable	Scope Decrease Barely Noticeable	Minor Area of Scope Are Affected	Major Area of Scope Are Affected	Scope Reduction Unacceptable to the Client	Project End Item is Effectively Unusable

Table 6 shows details of conversion linguistic terms into triangular fuzzy numbers [36]. Aggregation of the expert opinions was fulfilled using weighted average technique.

Table 5. Linguistic variables for the ratings

Linguistic variable	Triangle fuzzy numbers
Very High (VH)	(0.7,0.9,1)
High (H)	(0.5,0.7,0.9)
Medium (M)	(0.3,0.5,0.7)
Low (L)	(0.1,0.3,0.5)
Very Low (VL)	(0,0.1,0.3)

Finally, the obtained fuzzy ratings were set into the fuzzy decision matrix D (Table 5). In the next step, a normalized fuzzy decision matrix (R) was produced (Table 6). Also, the criteria weights were extracted from experts' opinions (Table 7), after which a weighted normalized fuzzy decision matrix (V) was computed (Table 8). In the final step, relative closeness (C_j) has to be determined. For this, firstly separations of each alternative from the positive and negative ideal solutions (S_j^+, S_j^-) were calculated, and then the relative closeness of each risk was computed (Table 9), by which the risks were ordered according to the obtained closeness.

Table 6. Fuzzy decision matrix

	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁
R ₁	(0.070, 0.240, 0.440)	(0.030, 0.160, 0.360)	(0.673, 0.873, 0.987)	(0.673, 0.873, 0.973)	(0.013, 0.127, 0.327)	(0.127, 0.327, 0.527)	(0.267, 0.467, 0.667)	(0.667, 0.867, 0.983)	(0.640, 0.840, 0.970)	(0.013, 0.127, 0.327)	(0.273, 0.473, 0.673)
R ₂	(0.640, 0.840, 0.970)	(0.017, 0.133, 0.333)	(0.647, 0.847, 0.973)	(0.473, 0.673, 0.873)	(0.000, 0.100, 0.300)	(0.673, 0.873, 0.987)	(0.533, 0.733, 0.917)	(0.667, 0.867, 0.983)	(0.673, 0.873, 0.987)	(0.013, 0.127, 0.327)	(0.273, 0.473, 0.673)
R ₃	(0.647, 0.847, 0.973)	(0.273, 0.473, 0.673)	(0.640, 0.840, 0.970)	(0.333, 0.533, 0.700)	(0.017, 0.133, 0.333)	(0.667, 0.867, 0.983)	(0.273, 0.473, 0.673)	(0.673, 0.873, 0.987)	(0.700, 0.900, 1.000)	(0.083, 0.267, 0.467)	(0.267, 0.467, 0.667)
R ₄	(0.017, 0.133, 0.333)	(0.013, 0.127, 0.327)	(0.097, 0.227, 0.427)	(0.013, 0.127, 0.353)	(0.013, 0.127, 0.327)	(0.127, 0.327, 0.527)	(0.333, 0.533, 0.733)	(0.017, 0.133, 0.333)	(0.013, 0.127, 0.327)	(0.013, 0.127, 0.327)	(0.013, 0.127, 0.327)
R ₅	(0.000, 0.100, 0.300)	(0.673, 0.873, 0.987)	(0.673, 0.873, 0.987)	(0.673, 0.873, 0.987)	(0.000, 0.100, 0.300)	(0.673, 0.873, 0.987)	(0.133, 0.333, 0.533)	(0.333, 0.533, 0.733)	(0.473, 0.673, 0.873)	(0.000, 0.100, 0.300)	(0.267, 0.467, 0.667)
R ₆	(0.273, 0.473, 0.673)	(0.667, 0.867, 0.983)	(0.133, 0.333, 0.533)	(0.133, 0.333, 0.500)	(0.087, 0.273, 0.467)	(0.473, 0.673, 0.873)	(0.273, 0.473, 0.673)	(0.127, 0.327, 0.527)	(0.127, 0.327, 0.527)	(0.017, 0.133, 0.333)	(0.267, 0.467, 0.667)
R ₇	(0.473, 0.673, 0.873)	(0.273, 0.473, 0.673)	(0.667, 0.867, 0.983)	(0.667, 0.867, 0.983)	(0.000, 0.100, 0.300)	(0.640, 0.840, 0.970)	(0.527, 0.727, 0.913)	(0.013, 0.127, 0.327)	(0.000, 0.100, 0.300)	(0.000, 0.100, 0.300)	(0.000, 0.100, 0.300)
R ₈	(0.267, 0.467, 0.667)	(0.017, 0.133, 0.333)	(0.133, 0.333, 0.533)	(0.017, 0.133, 0.300)	(0.273, 0.473, 0.667)	(0.327, 0.527, 0.727)	(0.527, 0.727, 0.913)	(0.273, 0.473, 0.673)	(0.673, 0.873, 0.987)	(0.000, 0.100, 0.300)	(0.267, 0.467, 0.667)
R ₉	(0.500, 0.700, 0.900)	(0.087, 0.273, 0.473)	(0.673, 0.873, 0.987)	(0.533, 0.733, 0.917)	(0.000, 0.100, 0.300)	(0.640, 0.840, 0.970)	(0.360, 0.560, 0.760)	(0.667, 0.867, 0.983)	(0.700, 0.900, 1.000)	(0.000, 0.100, 0.300)	(0.247, 0.447, 0.647)
R ₁₀	(0.647, 0.847, 0.973)	(0.273, 0.473, 0.673)	(0.640, 0.840, 0.970)	(0.667, 0.867, 1.000)	(0.013, 0.127, 0.353)	(0.673, 0.873, 0.987)	(0.017, 0.133, 0.333)	(0.700, 0.900, 1.000)	(0.667, 0.867, 0.983)	(0.000, 0.100, 0.300)	(0.327, 0.527, 0.727)
R ₁₁	(0.473, 0.673, 0.873)	(0.087, 0.273, 0.473)	(0.700, 0.900, 1.000)	(0.533, 0.733, 0.900)	(0.000, 0.100, 0.300)	(0.473, 0.673, 0.873)	(0.673, 0.873, 0.987)	(0.527, 0.727, 0.913)	(0.473, 0.673, 0.873)	(0.273, 0.473, 0.673)	(0.267, 0.467, 0.667)
R ₁₂	(0.433, 0.633, 0.833)	(0.527, 0.727, 0.913)	(0.133, 0.333, 0.533)	(0.127, 0.327, 0.533)	(0.127, 0.327, 0.553)	(0.333, 0.533, 0.733)	(0.667, 0.867, 0.983)	(0.700, 0.900, 1.000)	(0.667, 0.867, 0.983)	(0.300, 0.500, 0.700)	(0.300, 0.500, 0.700)
R ₁₃	(0.667, 0.867, 0.983)	(0.513, 0.713, 0.853)	(0.533, 0.733, 0.917)	(0.473, 0.673, 0.873)	(0.000, 0.100, 0.300)	(0.527, 0.727, 0.913)	(0.673, 0.873, 0.987)	(0.673, 0.873, 0.987)	(0.667, 0.867, 0.983)	(0.267, 0.467, 0.667)	(0.273, 0.473, 0.673)
R ₁₄	(0.467, 0.667, 0.867)	(0.013, 0.127, 0.327)	(0.267, 0.467, 0.667)	(0.267, 0.467, 0.667)	(0.087, 0.273, 0.447)	(0.273, 0.473, 0.673)	(0.273, 0.473, 0.673)	(0.000, 0.100, 0.300)	(0.083, 0.267, 0.467)	(0.273, 0.473, 0.673)	(0.273, 0.473, 0.673)
R ₁₅	(0.613, 0.813, 0.943)	(0.230, 0.400, 0.573)	(0.447, 0.647, 0.847)	(0.440, 0.640, 0.873)	(0.117, 0.300, 0.467)	(0.440, 0.640, 0.840)	(0.440, 0.640, 0.840)	(0.647, 0.847, 0.973)	(0.647, 0.847, 0.973)	(0.013, 0.127, 0.327)	(0.247, 0.447, 0.647)
R ₁₆	(0.233, 0.433, 0.633)	(0.070, 0.240, 0.440)	(0.247, 0.447, 0.647)	(0.447, 0.647, 0.820)	(0.240, 0.440, 0.633)	(0.240, 0.440, 0.640)	(0.447, 0.647, 0.847)	(0.087, 0.273, 0.473)	(0.083, 0.267, 0.467)	(0.000, 0.100, 0.300)	(0.247, 0.447, 0.647)
R ₁₇	(0.640, 0.840, 0.970)	(0.013, 0.127, 0.327)	(0.420, 0.620, 0.820)	(0.433, 0.633, 0.867)	(0.013, 0.127, 0.327)	(0.473, 0.673, 0.873)	(0.440, 0.640, 0.840)	(0.167, 0.353, 0.540)	(0.113, 0.300, 0.500)	(0.087, 0.273, 0.473)	(0.070, 0.240, 0.440)

Table 7. Normalized fuzzy decision matrix

C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁
(0.018, 0.063, 0.113)	(0.010, 0.059, 0.124)	(0.168, 0.218, 0.247)	(0.177, 0.236, 0.256)	(0.008, 0.097, 0.192)	(0.032, 0.082, 0.132)	(0.070, 0.126, 0.175)	(0.171, 0.222, 0.252)	(0.160, 0.210, 0.243)	(0.007, 0.079, 0.172)	(0.098, 0.189, 0.240)
(0.164, 0.221, 0.249)	(0.006, 0.049, 0.115)	(0.162, 0.212, 0.243)	(0.125, 0.182, 0.230)	(0.000, 0.077, 0.176)	(0.168, 0.218, 0.247)	(0.140, 0.198, 0.241)	(0.171, 0.222, 0.252)	(0.168, 0.218, 0.247)	(0.007, 0.079, 0.172)	(0.098, 0.189, 0.240)
(0.166, 0.223, 0.250)	(0.094, 0.175, 0.232)	(0.160, 0.210, 0.243)	(0.088, 0.144, 0.184)	(0.010, 0.103, 0.196)	(0.167, 0.217, 0.246)	(0.072, 0.128, 0.177)	(0.173, 0.224, 0.253)	(0.175, 0.225, 0.250)	(0.044, 0.167, 0.246)	(0.095, 0.187, 0.238)
(0.004, 0.035, 0.085)	(0.005, 0.047, 0.113)	(0.024, 0.057, 0.107)	(0.004, 0.034, 0.093)	(0.008, 0.097, 0.192)	(0.032, 0.082, 0.132)	(0.088, 0.144, 0.193)	(0.004, 0.034, 0.085)	(0.003, 0.032, 0.082)	(0.007, 0.079, 0.172)	(0.005, 0.051, 0.117)
(0.000, 0.026, 0.077)	(0.232, 0.323, 0.340)	(0.168, 0.218, 0.247)	(0.177, 0.236, 0.260)	(0.000, 0.077, 0.176)	(0.168, 0.218, 0.247)	(0.035, 0.090, 0.140)	(0.085, 0.137, 0.188)	(0.118, 0.168, 0.218)	(0.000, 0.063, 0.158)	(0.095, 0.187, 0.238)
(0.070, 0.125, 0.173)	(0.230, 0.321, 0.339)	(0.033, 0.083, 0.133)	(0.035, 0.090, 0.132)	(0.051, 0.210, 0.275)	(0.118, 0.168, 0.218)	(0.072, 0.128, 0.177)	(0.032, 0.084, 0.135)	(0.032, 0.082, 0.132)	(0.009, 0.083, 0.175)	(0.095, 0.187, 0.238)
(0.121, 0.177, 0.224)	(0.094, 0.175, 0.232)	(0.167, 0.217, 0.246)	(0.175, 0.234, 0.259)	(0.000, 0.077, 0.176)	(0.160, 0.210, 0.243)	(0.139, 0.196, 0.240)	(0.003, 0.032, 0.084)	(0.000, 0.025, 0.075)	(0.000, 0.063, 0.158)	(0.000, 0.040, 0.107)
(0.068, 0.123, 0.171)	(0.006, 0.049, 0.115)	(0.033, 0.083, 0.133)	(0.004, 0.036, 0.079)	(0.161, 0.364, 0.392)	(0.082, 0.132, 0.182)	(0.139, 0.196, 0.240)	(0.070, 0.121, 0.173)	(0.168, 0.218, 0.247)	(0.000, 0.063, 0.158)	(0.095, 0.187, 0.238)
(0.128, 0.184, 0.231)	(0.030, 0.101, 0.163)	(0.168, 0.218, 0.247)	(0.140, 0.198, 0.241)	(0.000, 0.077, 0.176)	(0.160, 0.210, 0.243)	(0.095, 0.151, 0.200)	(0.171, 0.222, 0.252)	(0.175, 0.225, 0.250)	(0.000, 0.063, 0.158)	(0.088, 0.179, 0.231)
(0.166, 0.223, 0.250)	(0.094, 0.175, 0.232)	(0.160, 0.210, 0.243)	(0.175, 0.234, 0.263)	(0.008, 0.097, 0.208)	(0.168, 0.218, 0.247)	(0.004, 0.036, 0.088)	(0.179, 0.231, 0.256)	(0.167, 0.217, 0.246)	(0.000, 0.063, 0.158)	(0.117, 0.211, 0.260)
(0.121, 0.177, 0.224)	(0.030, 0.101, 0.163)	(0.175, 0.225, 0.250)	(0.140, 0.198, 0.237)	(0.000, 0.077, 0.176)	(0.118, 0.168, 0.218)	(0.177, 0.236, 0.260)	(0.135, 0.186, 0.234)	(0.118, 0.168, 0.218)	(0.144, 0.296, 0.354)	(0.095, 0.187, 0.238)
(0.111, 0.167, 0.214)	(0.182, 0.269, 0.315)	(0.033, 0.083, 0.133)	(0.033, 0.088, 0.140)	(0.075, 0.251, 0.325)	(0.083, 0.133, 0.183)	(0.175, 0.234, 0.259)	(0.179, 0.231, 0.256)	(0.167, 0.217, 0.246)	(0.158, 0.313, 0.368)	(0.107, 0.200, 0.250)
(0.171, 0.228, 0.252)	(0.177, 0.264, 0.294)	(0.133, 0.183, 0.229)	(0.125, 0.182, 0.230)	(0.000, 0.077, 0.176)	(0.132, 0.182, 0.228)	(0.177, 0.236, 0.260)	(0.173, 0.224, 0.253)	(0.167, 0.217, 0.246)	(0.140, 0.292, 0.351)	(0.098, 0.189, 0.240)
(0.120, 0.175, 0.222)	(0.005, 0.047, 0.113)	(0.067, 0.117, 0.167)	(0.070, 0.126, 0.175)	(0.051, 0.210, 0.263)	(0.068, 0.118, 0.168)	(0.072, 0.128, 0.177)	(0.000, 0.026, 0.077)	(0.021, 0.067, 0.117)	(0.144, 0.296, 0.354)	(0.098, 0.189, 0.240)
(0.157, 0.214, 0.242)	(0.079, 0.148, 0.198)	(0.112, 0.162, 0.212)	(0.116, 0.173, 0.230)	(0.069, 0.231, 0.275)	(0.110, 0.160, 0.210)	(0.116, 0.173, 0.221)	(0.166, 0.217, 0.250)	(0.162, 0.212, 0.243)	(0.007, 0.079, 0.172)	(0.088, 0.179, 0.231)
(0.060, 0.114, 0.162)	(0.024, 0.089, 0.152)	(0.062, 0.112, 0.162)	(0.118, 0.175, 0.216)	(0.141, 0.338, 0.373)	(0.060, 0.110, 0.160)	(0.118, 0.175, 0.223)	(0.022, 0.070, 0.121)	(0.021, 0.067, 0.117)	(0.000, 0.063, 0.158)	(0.088, 0.179, 0.231)
(0.164, 0.221, 0.249)	(0.005, 0.047, 0.113)	(0.105, 0.155, 0.205)	(0.114, 0.171, 0.228)	(0.008, 0.097, 0.192)	(0.118, 0.168, 0.218)	(0.116, 0.173, 0.221)	(0.043, 0.091, 0.138)	(0.028, 0.075, 0.125)	(0.046, 0.171, 0.249)	(0.025, 0.096, 0.157)

Table 8I. Weights of criteria

	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁
w	0.05	0.06	0.09	0.09	0.10	0.11	0.09	0.10	0.11	0.08	0.07
	8	5	4	4	8	6	4	1	1	7	2

Table 9. Weighted normalized fuzzy decision matrix

	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁
R ₁	(0.001, 0.004, 0.007)	(0.001, 0.004, 0.008)	(0.016, 0.021, 0.023)	(0.017, 0.022, 0.024)	(0.001, 0.011, 0.021)	(0.004, 0.009, 0.015)	(0.007, 0.012, 0.016)	(0.017, 0.022, 0.026)	(0.018, 0.023, 0.027)	(0.001, 0.007, 0.015)	(0.007, 0.014, 0.017)
R ₂	(0.009, 0.013, 0.014)	(0.000, 0.003, 0.007)	(0.015, 0.020, 0.023)	(0.012, 0.017, 0.022)	(0.000, 0.008, 0.019)	(0.019, 0.025, 0.029)	(0.013, 0.019, 0.023)	(0.017, 0.022, 0.026)	(0.019, 0.024, 0.027)	(0.001, 0.007, 0.015)	(0.007, 0.014, 0.017)
R ₃	(0.010, 0.013, 0.014)	(0.006, 0.011, 0.015)	(0.015, 0.020, 0.023)	(0.008, 0.014, 0.017)	(0.001, 0.011, 0.021)	(0.019, 0.025, 0.028)	(0.007, 0.012, 0.017)	(0.017, 0.023, 0.026)	(0.019, 0.025, 0.028)	(0.004, 0.014, 0.021)	(0.007, 0.013, 0.017)
R ₄	(0.000, 0.002, 0.005)	(0.000, 0.003, 0.007)	(0.002, 0.005, 0.010)	(0.000, 0.003, 0.009)	(0.001, 0.011, 0.021)	(0.004, 0.009, 0.015)	(0.008, 0.014, 0.018)	(0.000, 0.003, 0.009)	(0.000, 0.004, 0.009)	(0.001, 0.007, 0.015)	(0.000, 0.004, 0.008)
R ₅	(0.000, 0.002, 0.004)	(0.015, 0.021, 0.022)	(0.016, 0.021, 0.023)	(0.017, 0.022, 0.024)	(0.000, 0.008, 0.019)	(0.019, 0.025, 0.029)	(0.003, 0.008, 0.013)	(0.009, 0.014, 0.019)	(0.013, 0.019, 0.024)	(0.000, 0.005, 0.014)	(0.007, 0.013, 0.017)
R ₆	(0.004, 0.007, 0.010)	(0.015, 0.021, 0.022)	(0.003, 0.008, 0.013)	(0.003, 0.008, 0.012)	(0.006, 0.023, 0.030)	(0.014, 0.019, 0.025)	(0.007, 0.012, 0.017)	(0.003, 0.008, 0.014)	(0.004, 0.009, 0.015)	(0.001, 0.007, 0.015)	(0.007, 0.013, 0.017)
R ₇	(0.007, 0.010, 0.013)	(0.006, 0.011, 0.015)	(0.016, 0.020, 0.023)	(0.016, 0.022, 0.024)	(0.000, 0.008, 0.019)	(0.018, 0.024, 0.028)	(0.013, 0.018, 0.023)	(0.000, 0.003, 0.008)	(0.000, 0.003, 0.008)	(0.000, 0.005, 0.014)	(0.000, 0.003, 0.008)
R ₈	(0.004, 0.007, 0.010)	(0.000, 0.003, 0.007)	(0.003, 0.008, 0.013)	(0.000, 0.003, 0.007)	(0.017, 0.039, 0.043)	(0.009, 0.015, 0.021)	(0.013, 0.018, 0.023)	(0.007, 0.012, 0.017)	(0.019, 0.024, 0.027)	(0.000, 0.005, 0.014)	(0.007, 0.013, 0.017)
R ₉	(0.007, 0.011, 0.013)	(0.002, 0.007, 0.011)	(0.016, 0.021, 0.023)	(0.013, 0.019, 0.023)	(0.000, 0.008, 0.019)	(0.018, 0.024, 0.028)	(0.009, 0.014, 0.019)	(0.017, 0.022, 0.026)	(0.019, 0.025, 0.028)	(0.000, 0.005, 0.014)	(0.006, 0.013, 0.017)
R ₁₀	(0.010, 0.013, 0.014)	(0.006, 0.011, 0.015)	(0.015, 0.020, 0.023)	(0.016, 0.022, 0.025)	(0.001, 0.011, 0.023)	(0.019, 0.025, 0.029)	(0.000, 0.003, 0.008)	(0.018, 0.023, 0.026)	(0.019, 0.024, 0.027)	(0.000, 0.005, 0.014)	(0.008, 0.015, 0.019)
R ₁₁	(0.007, 0.010, 0.013)	(0.002, 0.007, 0.011)	(0.016, 0.021, 0.023)	(0.013, 0.019, 0.022)	(0.000, 0.008, 0.019)	(0.014, 0.019, 0.025)	(0.017, 0.022, 0.024)	(0.014, 0.019, 0.024)	(0.013, 0.019, 0.024)	(0.012, 0.026, 0.031)	(0.007, 0.013, 0.017)
R ₁₂	(0.006, 0.010, 0.012)	(0.012, 0.018, 0.020)	(0.003, 0.008, 0.013)	(0.003, 0.008, 0.013)	(0.008, 0.027, 0.035)	(0.010, 0.015, 0.021)	(0.016, 0.022, 0.024)	(0.018, 0.023, 0.026)	(0.019, 0.024, 0.027)	(0.014, 0.027, 0.032)	(0.008, 0.014, 0.018)
R ₁₃	(0.010, 0.013, 0.015)	(0.012, 0.017, 0.019)	(0.013, 0.017, 0.022)	(0.012, 0.017, 0.022)	(0.000, 0.008, 0.019)	(0.015, 0.021, 0.026)	(0.017, 0.022, 0.024)	(0.017, 0.023, 0.026)	(0.019, 0.024, 0.027)	(0.012, 0.025, 0.030)	(0.007, 0.014, 0.017)
R ₁₄	(0.007, 0.010, 0.013)	(0.000, 0.003, 0.007)	(0.006, 0.011, 0.016)	(0.007, 0.012, 0.016)	(0.006, 0.023, 0.028)	(0.008, 0.014, 0.019)	(0.007, 0.012, 0.017)	(0.000, 0.003, 0.008)	(0.002, 0.007, 0.013)	(0.012, 0.026, 0.031)	(0.007, 0.014, 0.017)
R ₁₅	(0.009, 0.012, 0.014)	(0.005, 0.010, 0.013)	(0.010, 0.015, 0.020)	(0.011, 0.016, 0.022)	(0.007, 0.025, 0.030)	(0.013, 0.018, 0.024)	(0.011, 0.016, 0.021)	(0.017, 0.022, 0.025)	(0.018, 0.024, 0.027)	(0.001, 0.007, 0.015)	(0.006, 0.013, 0.017)
R ₁₆	(0.003, 0.007, 0.009)	(0.002, 0.006, 0.010)	(0.006, 0.010, 0.015)	(0.011, 0.016, 0.020)	(0.015, 0.037, 0.040)	(0.007, 0.013, 0.018)	(0.011, 0.016, 0.021)	(0.002, 0.007, 0.012)	(0.002, 0.007, 0.013)	(0.000, 0.005, 0.014)	(0.006, 0.013, 0.017)
R ₁₇	(0.009, 0.013, 0.014)	(0.000, 0.003, 0.007)	(0.010, 0.015, 0.019)	(0.011, 0.016, 0.021)	(0.001, 0.011, 0.021)	(0.014, 0.019, 0.025)	(0.011, 0.016, 0.021)	(0.004, 0.009, 0.014)	(0.003, 0.008, 0.014)	(0.004, 0.015, 0.022)	(0.002, 0.007, 0.011)

Table 10. Closeness coefficients and the ranking of risks

Risk number	S_j^+	S_j^-	C_j	Rank
R ₁	4.92	2.09	0.2978	8
R ₂	4.90	2.11	0.3009	6
R ₃	4.89	2.12	0.3027	3
R ₄	5.00	2.01	0.2865	17
R ₅	4.89	2.12	0.3030	2
R ₆	4.95	2.06	0.2933	12
R ₇	4.93	2.08	0.2963	10
R ₈	5.00	2.01	0.2869	16
R ₉	4.89	2.12	0.3021	4
R ₁₀	4.87	2.14	0.3058	1
R ₁₁	4.92	2.09	0.2987	7
R ₁₂	4.96	2.06	0.2931	13
R ₁₃	4.89	2.11	0.3017	5
R ₁₄	4.97	2.04	0.2906	14
R ₁₅	4.92	2.09	0.2978	9
R ₁₆	4.99	2.02	0.2886	15
R ₁₇	4.95	2.06	0.2943	11

One of the standard approaches for prioritizing risks in complex projects is the use of the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) multi-criteria decision-making technique. This method is widely used due to its simplicity and power in ranking alternatives based on multiple criteria. The general process involves converting qualitative expert assessments into a numerical matrix, normalizing and weighting the data, and finally, ranking the risks based on their distance from an ideal solution (the worst possible case) and a negative-ideal solution (the best possible case).

To begin the analysis, qualitative expert assessments are converted into crisp (single) numbers. In this analysis, the middle value of the triangular fuzzy numbers presented in the original paper was used to create this matrix in Table 10.

Table 11. Crisp Decision Matrix

Risk	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
R1	0.240	0.160	0.873	0.873	0.127	0.327	0.467	0.867	0.840	0.127	0.473
R2	0.840	0.133	0.847	0.673	0.100	0.873	0.733	0.867	0.873	0.127	0.473
R3	0.847	0.473	0.840	0.533	0.133	0.867	0.473	0.873	0.900	0.267	0.467
R4	0.133	0.127	0.227	0.127	0.127	0.327	0.533	0.133	0.127	0.127	0.127
R5	0.100	0.873	0.873	0.873	0.100	0.873	0.333	0.533	0.673	0.100	0.467
R6	0.473	0.867	0.333	0.333	0.273	0.673	0.473	0.327	0.327	0.133	0.467
R7	0.673	0.473	0.867	0.867	0.100	0.840	0.727	0.127	0.100	0.100	0.100
R8	0.467	0.133	0.333	0.133	0.473	0.527	0.727	0.473	0.873	0.100	0.467
R9	0.700	0.273	0.873	0.733	0.100	0.840	0.560	0.867	0.900	0.100	0.447
R10	0.847	0.473	0.840	0.867	0.127	0.873	0.133	0.900	0.867	0.100	0.527
R11	0.673	0.273	0.900	0.733	0.100	0.673	0.873	0.727	0.673	0.473	0.467
R12	0.633	0.727	0.333	0.327	0.327	0.533	0.867	0.900	0.867	0.500	0.500
R13	0.867	0.713	0.733	0.673	0.100	0.727	0.873	0.873	0.867	0.467	0.473
R14	0.667	0.127	0.467	0.467	0.273	0.473	0.473	0.100	0.267	0.473	0.473
R15	0.813	0.400	0.647	0.640	0.300	0.640	0.640	0.847	0.847	0.127	0.447
R16	0.433	0.240	0.447	0.647	0.440	0.440	0.647	0.273	0.267	0.100	0.447
R17	0.840	0.127	0.620	0.633	0.127	0.673	0.640	0.353	0.300	0.273	0.240

To make the criteria values comparable, the decision matrix is scaled using the vector normalization method in Table 11.

Table 12. Normalized Decision Matrix

Risk	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
R1	0.096	0.076	0.341	0.36	0.135	0.119	0.184	0.33	0.317	0.095	0.252
R2	0.337	0.063	0.331	0.278	0.106	0.318	0.288	0.33	0.329	0.095	0.252
R3	0.34	0.225	0.328	0.22	0.141	0.316	0.186	0.332	0.339	0.2	0.249
R4	0.053	0.061	0.089	0.052	0.135	0.119	0.21	0.051	0.048	0.095	0.068
R5	0.04	0.416	0.341	0.36	0.106	0.318	0.131	0.203	0.254	0.075	0.249
R6	0.19	0.413	0.13	0.137	0.289	0.245	0.186	0.124	0.123	0.1	0.249
R7	0.27	0.225	0.339	0.358	0.106	0.306	0.286	0.048	0.038	0.075	0.053
R8	0.188	0.063	0.13	0.055	0.501	0.192	0.286	0.18	0.329	0.075	0.249
R9	0.281	0.13	0.341	0.302	0.106	0.306	0.22	0.33	0.339	0.075	0.238
R10	0.34	0.225	0.328	0.358	0.135	0.318	0.052	0.342	0.327	0.075	0.281
R11	0.27	0.13	0.352	0.302	0.106	0.245	0.343	0.276	0.254	0.354	0.249
R12	0.254	0.346	0.13	0.135	0.346	0.194	0.341	0.342	0.327	0.374	0.266
R13	0.348	0.34	0.286	0.278	0.106	0.265	0.343	0.332	0.327	0.35	0.252
R14	0.268	0.061	0.182	0.193	0.289	0.172	0.186	0.038	0.101	0.354	0.252
R15	0.327	0.191	0.253	0.264	0.318	0.233	0.252	0.322	0.319	0.095	0.238
R16	0.174	0.114	0.175	0.267	0.466	0.16	0.254	0.104	0.101	0.075	0.238
R17	0.337	0.061	0.242	0.261	0.135	0.245	0.252	0.134	0.113	0.204	0.128

The values in the normalized matrix are multiplied by the weight of each criterion (obtained from expert

opinion) to ensure the importance of each criterion is factored into the calculations.

Table 13. Weighted Normalized Matrix

Risk	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
R1	0.006	0.005	0.032	0.034	0.015	0.014	0.017	0.033	0.035	0.008	0.018
R2	0.02	0.004	0.031	0.026	0.011	0.037	0.027	0.033	0.037	0.008	0.018
R3	0.02	0.015	0.031	0.021	0.015	0.037	0.017	0.034	0.038	0.017	0.018
R4	0.003	0.004	0.008	0.005	0.015	0.014	0.02	0.005	0.005	0.008	0.005
R5	0.002	0.027	0.032	0.034	0.011	0.037	0.012	0.02	0.028	0.007	0.018
R6	0.011	0.027	0.012	0.013	0.031	0.028	0.017	0.013	0.014	0.009	0.018
R7	0.016	0.015	0.032	0.034	0.011	0.035	0.027	0.005	0.004	0.007	0.004
R8	0.011	0.004	0.012	0.005	0.054	0.022	0.027	0.018	0.037	0.007	0.018
R9	0.016	0.008	0.032	0.028	0.011	0.035	0.021	0.033	0.038	0.007	0.017
R10	0.02	0.015	0.031	0.034	0.015	0.037	0.005	0.035	0.036	0.007	0.02
R11	0.016	0.008	0.033	0.028	0.011	0.028	0.032	0.028	0.028	0.031	0.018
R12	0.015	0.022	0.012	0.013	0.037	0.022	0.032	0.035	0.036	0.033	0.019
R13	0.02	0.022	0.027	0.026	0.011	0.031	0.032	0.034	0.036	0.03	0.018
R14	0.016	0.004	0.017	0.018	0.031	0.02	0.017	0.004	0.011	0.031	0.018
R15	0.019	0.012	0.24	0.025	0.034	0.027	0.024	0.033	0.035	0.008	0.017
R16	0.01	0.007	0.016	0.025	0.05	0.019	0.024	0.01	0.011	0.007	0.017
R17	0.02	0.004	0.023	0.025	0.015	0.028	0.024	0.014	0.013	0.018	0.009

The Positive Ideal Solution (worst-case scenario) and Negative Ideal Solution (best-case scenario) are determined by finding the maximum and minimum values in each column of the weighted matrix.

Table 14. Positive and Negative Ideal Solutions

Solution	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Positive Ideal (A ⁺)	0.02	0.02	0.03	0.03	0.05	0.03	0.03	0.03	0.03	0.03	0.02
Negative Ideal (A ⁻)	2	4	8	5	1	4	5	4	4	7	4

In this final step, the distance of each risk from the Positive Ideal (S⁺) and Negative Ideal (S⁻) solutions is calculated. The Closeness Coefficient (C_i) is then computed, which forms the basis for the final ranking of risks from most to least critical.

Table 15. Final Risk Ranking Based on the Classical TOPSIS Method

Rank	Risk	S+ (Distance from worst-case)	S- (Distance from best-case)	Closeness (Ci)
1	R3	0.0276	0.0407	0.5959
2	R9	0.0287	0.0384	0.5721
3	R10	0.0305	0.0392	0.5623
4	R13	0.0292	0.037	0.5582
5	R2	0.0334	0.0348	0.5106
6	R15	0.0351	0.0335	0.4883
7	R5	0.0356	0.033	0.4812
8	R11	0.0347	0.0322	0.4811
9	R12	0.0383	0.0343	0.4722
10	R17	0.0441	0.027	0.3795
11	R7	0.0456	0.0267	0.3689
12	R6	0.0449	0.0256	0.3629
13	R1	0.0451	0.0252	0.3582
14	R14	0.0531	0.0205	0.2785
15	R16	0.0528	0.0202	0.2769
16	R8	0.0519	0.0189	0.2673
17	R4	0.062	0.0125	0.1681

The primary difference between Classical TOPSIS and Fuzzy TOPSIS lies in how they handle the uncertainty inherent in expert judgments. The classical method uses precise numbers, while the fuzzy method uses a range of values to provide a more realistic analysis.

5. CONCLUSION

This paper conducted a comprehensive risk assessment for a tunneling project by applying and comparing Classical TOPSIS and Fuzzy TOPSIS methodologies. The primary objective was to demonstrate the limitations of traditional crisp-value analysis and highlight the advantages of a fuzzy logic-based approach in handling the uncertainties inherent in expert evaluations.

The analysis began by establishing a baseline using the Classical TOPSIS method, which ranked Economic risks (R3), Financial risks (R9), and Owner risks (R10) as the most critical threats. While this method provides a straightforward and easily interpretable ranking, it does not account for the ambiguity in the linguistic assessments provided by experts, treating all inputs as precise values.

Subsequently, the Fuzzy TOPSIS method was applied to the same data. By modeling expert judgments as fuzzy numbers, this approach successfully incorporated the inherent uncertainty into the analysis. The resulting ranking identified Owner

risks (R10), Site or environment risks (R5), and Economic risks (R3) as the top priorities. The difference in these rankings is significant; it illustrates that when uncertainty is properly managed, the perceived importance of certain risks can shift considerably. The promotion of Owner and Site risks in the fuzzy ranking suggests that their potential impact is more critical when the full range of expert opinion is considered.

In conclusion, the comparison confirms that while both methods are valuable, the Fuzzy TOPSIS framework offers a more robust, reliable, and realistic tool for risk prioritization in complex engineering projects. By formally addressing the ambiguity of human judgment, it provides project managers and decision-makers with a more nuanced understanding of the risk landscape, enabling more effective and targeted mitigation strategies. This study demonstrates that for high-stakes projects like tunneling, adopting advanced, uncertainty-aware models is essential for successful risk management.

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مدیریت ریسک در پروژه‌های تونلی: رویکرد فازی TOPSIS برای بهبود تصمیم‌گیری

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دریافت: ۱۴۰۴/۰۱/۲۸؛ پذیرش: ۱۴۰۲/۰۳/۲۸

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چکیده

ارزیابی ریسک یک وظیفه حیاتی در پروژه‌های تونل‌سازی است، با این حال روش‌های کلاسیک اغلب در مدیریت کافی عدم قطعیت‌های ذاتی قضاوت‌های کارشناسی شکست می‌خورند. این مقاله یک تحلیل ریسک مقایسه‌ای با استفاده از دو تکنیک تصمیم‌گیری چند معیاره ارائه می‌دهد: *TOPSIS* کلاسیک و *TOPSIS* فازی. این مطالعه ابتدا با استفاده از روش *TOPSIS* کلاسیک، که به ورودی‌های عددی قطعی متکی است، یک رتبه‌بندی ریسک پایه ایجاد می‌کند. سپس روش *TOPSIS* فازی را بر روی همان مجموعه داده‌ها اعمال می‌کند و از نظریه مجموعه‌های فازی برای مدل‌سازی ابهام و عدم قطعیت زبانی در ارزیابی‌های کارشناسی استفاده می‌کند. این روش‌ها در یک مطالعه موردی از یک پروژه ساخت تونل اعمال می‌شوند و ۱۷ ریسک متمایز را در ۱۱ معیار ارزیابی می‌کنند. نتایج نشان می‌دهد که در حالی که هر دو روش ریسک‌های با اولویت بالا مشابهی را شناسایی می‌کنند، رتبه‌بندی نهایی متفاوت است. مدل *TOPSIS* فازی، با در نظر گرفتن عدم قطعیت، اولویت‌بندی قوی‌تر و ظریف‌تری را ارائه می‌دهد و ریسک‌های مالک (*R10*) و ریسک‌های سایت/محیط زیست (*R5*) را بحرانی‌تر از روش کلاسیک شناسایی می‌کند. این مطالعه نتیجه می‌گیرد که رویکرد فازی *TOPSIS* ابزاری برتر و قابل اعتمادتر برای تصمیم‌گیرندگان است و چارچوبی واقع‌بینانه‌تر برای مدیریت ریسک‌های پیچیده در پروژه‌های تونل‌سازی ارائه می‌دهد.

واژگان کلیدی: ارزیابی ریسک، پروژه‌های تونل‌سازی، روش کلاسیک، تاپسیس فازی.