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Risk management in urban tunnels using methods of game theory and multi-criteria decision-making

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Abstract

In general, underground spaces are associated with high risks because of their high uncertainty in geotechnical environments. Since most accidents and incidents in these structures are often associated with uncertainty, the development of risk analysis and management methods and prevention of accidents are essential. A deeper recognition of the factors affecting the implementation process can pave the way for this purpose. Risk rating of projects is a key part of the risk assessment stage in the risk management process of each project. Various multi-criteria decision-making methods, as quantitative approaches, are used to allow them to be used in the risk rating issue of each project. In this work, a new model is provided for risk management of Mashhad Urban Railway Line 3 using the game theory and multi-criteria decision-making methods. Based on the answers of the specialists and experts to the prepared questionnaires, various risk groups identified using the TOPSIS and AHP multi-criteria decision-making methods are ranked. Accordingly, the group of economic risks, as the most important risk and social risk group, is ranked as the least significant in both methods. In the following, the appropriate response to the main risks of the ratings is proposed based on the modeling of the game theory, and ranked in terms of importance. Also the worst risk scenario in the project is identified, and the appropriate responses for this state are also expressed in order of importance. The results obtained indicate that the risk of financing problems is the most significant risk, and other risks are ranked in terms of importance in the next ranks. Additionally, the use of new financing methods at times of credit scarcity and project financial problems is also considered as the most important response to the risk in this project.

1. Introduction

Nowadays the world is witnessing an ever-increasing need for tunnels because of their unique characteristics and potential applications. Tunnels are artificial underground spaces used to provide a capacity for particular goals including storage, underground transportation, mine development, power and water treatment plants, and other activities [1].

Therefore, tunneling is a key activity in the infrastructure projects. Tunneling imposes risks on all the parties involved as well as on those not directly involved in the project [2].

A risk is the potential of gaining or losing something of value. A risk can also be defined as the intentional interaction with uncertainty. Uncertainty is a potential, unpredictable, and uncontrollable outcome; a risk is a consequence of the action taken in spite of uncertainty. Risk management is the identification, evaluation, and prioritization of the risks defined in ISO 31000 as the uncertainty effect on the objectives [3].

The generic process for risk management is depicted in Figure 1.

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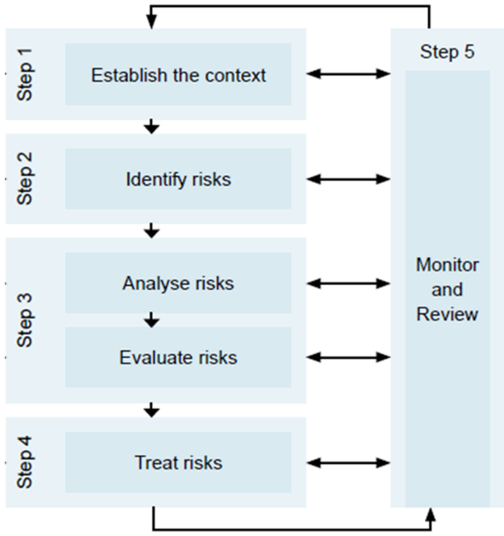

Figure 1. The generic process for risk management.

These risks may dramatically affect the operation requiring an unexpected time for renovation resulting in major cost and time delays. In order to avoid such problems, the managers are obliged to carry out a risk management program. Risk management involves a number of approaches including the identification, evaluation, and control of risk. Risk evaluation is a part of risk management, which can help the decision-makers to rank the existing risks, and finally, the appropriate reaction is accomplished [3].

Tunneling and underground construction works impose risks on all the parties involved as well as on those not directly involved in the project. The nature of tunnel projects normally involves significant amounts of risks such as large-scale accidents, which create catastrophic incidents. Due to the inherent uncertainties, there might be a significant cost over-run and delay risks as well as the environmental risks. Furthermore, for tunnels in urban areas, there is a risk of damage to people and their properties or even historical buildings. Finally, there is a social risk that the tunneling project may give rise to public protests, affecting the course of the project [4].

Most of the real-world decision problems occur in a complex environment, where conflicting systems of logic, uncertain, and imprecise knowledge are required to be considered. To face such a complexity, preference modeling requires the use of specific tools, techniques, and concepts to reveal the available information with the appropriate granularity [8].

Since the rating of risk groups in tunneling projects depends on many criteria and variables, making decisions in such areas can often be arduous and difficult. Thus the need for a mechanism capable of assisting the characterization of such complex scenarios arises. In spite of the studies conducted by Shahriar et al. (2008), Yan-Hui et al. (2009), Hamidi et al. (2010), Aliahmadi et al. (2011), Zhao et al. (2012), Xue and Shi (2016), Hui et al. (2016), Xia et al. (2017), and Haghshenas (2017) [5-13], the lack of a specific formulation for risk management is still a problem. The multi-criteria decision analysis (MCDA) and the game theory have emerged as a branch of the operational research works aiming at facilitating the resolution of these issues.

Risk management is the overall term that includes the identification, assessment, analysis, elimination, mitigation, and control of a risk. The primary focus of this paper is on assessing the different risk factors involved in the Metro Line 3 of Mashhad, i.e. the various players of client, consultant engineering, contractor, and the risk to organize the project. Considering importance of risk management and the fact that there is little work done on the risk management of tunneling using the game theory, in this work, the AHP and TOPSIS methods were first used to rank risk groups in the case study. Next, the relationship among the various aforementioned players was determined. Decision-makers' opinions were used to study the effects of different strategies and to determine appropriate combinations of these factors. Finally, the game theory was used for risk management.

2. Multi-criteria decision methods

Multi-criteria decision-making techniques are useful tools to help decision-maker(s) select options in the case of discrete problems. Especially with the help of computers, those methods have become easier for the users, so they have found great acceptance in many areas of decision-making processes in engineering, economy or management. Among many multi-criteria techniques, MAXMIN, MAXMAX, SAW, AHP, TOPSIS, SMART, and ELECTRE are the most frequently used methods [14]. In this work, the AHP and TOPSIS methods were used to rank the risk group of the case study. In the following, the basic concepts are explained in the AHP and TOPSIS methods.

2.1. TOPSIS method

The TOPSIS method has been presented by Chen and Hwang [15]. It is a multiple-criteria method used to identify solutions from a finite set of alternatives. Its basic principle is that the chosen alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution [16]. The TOPSIS procedure can be expressed in a series of steps mentioned below.

1. Constructing the decision matrix and determining the weight of criteria.
2. Calculating the normalized decision matrix. The normalized value n_{ij} is calculated as:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \quad i = 1, 2, \dots, m; \; j = 1, 2, \dots, n \tag{1}$$

3. Calculating the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as $v_{ij} = w_j \, n_{ij}$, $i = 1, 2, \dots, m$; $j = 1, 2, \dots, n$

where w_j is the weight of the ith attribute or criterion and $\sum_{j=1}^{n} w_j = 1$

$$E_j = -\frac{1}{Lnj} \sum_{i=1}^{j} p_{ij} \, Lnp_{ij} \tag{2}$$

$$D_j = 1 - E_j \tag{3}$$

$$W_j = \frac{D_j}{\sum D_j} \tag{4}$$

4. Determining the positive ideal and negative ideal solutions

$$A^+ = \{v_1^+, v_2^+, \dots, v_n^+\} = \{(maxv_{ij} | i \in I), (minv_{ij} | i \in J)\} \tag{5}$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\} = \{(minv_{ij} | i \in I), (maxv_{ij} | i \in J)\} \tag{6}$$

where I is associated with the benefit criterion and J is associated with the cost criterion.

5. Calculating the separation measures using the n-dimensional Euclidean distance. The separation of each alternative from the ideal solution is given as:

$$d_{i+} = \sqrt{\left\{ \sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2 \right\}} \tag{7}$$

Similarly, the separation from the negative ideal solution is given as:

$$d_{i-} = \sqrt{\left\{ \sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2 \right\}} \tag{8}$$

6. Calculating the relative closeness to the ideal solution. The relative closeness of the alternative A_i with respect to A^+ is defined as:

$$CL_{i+} = \frac{d_{i-}}{d_{i-} + d_{i+_-}}; \quad i = 1, 2, \dots, m \tag{9}$$

7. Ranking the preference order. For ranking the alternatives using this index, we can rank the alternatives in a decreasing order. The basic principle of the TOPSIS method is that the chosen alternative should have the ‘‘shortest distance’’ from the positive ideal solution and the ‘‘farthest distance’’ from the negative ideal solution [15]. The main advantages of this method are as follow [16]:

- A simple, rational, comprehensible concept
- An intuitive and clear logic that represents the rationale of human choice
- Ease of computation and good computational efficiency
- A scalar value that accounts for both the best and worst alternative abilities to measure the relative performance for each alternative in a simple mathematical form
- Possibility for visualization

2.2. AHP Method

The Analytic Hierarchy Process (AHP) method was developed by Thomas Saaty at the beginning of 1870s, and it represents a tool in a decision-making analysis. It was designed to assist planners in resolving complex decision-making problems, where a large number of planners participate and a number of criteria exist in several specific time periods [17]. Through AHP, experts' judgments are used to measure the relative weights of certain criteria [18]. For this action, initially, a pairwise comparison matrix of criterion (A) is established using a relative importance scale, as introduced by Saaty [19]. This 1–9 scale measures the intangibles in relative terms, and is presented in Table 1.

The pairwise comparison enables a decision-maker to evaluate the impact of each factor on the objective [18]. In an arbitrary random reciprocal matrix A, each criterion a_{ij} $(i, j = 1, 2, \ldots, n)$ is the relative importance of the i_{th} elements compared to the j_{th} ones. In fact, it expresses that higher values of a_{ij} indicate stronger preference of criterion a_i over a_j. In the matrix, $a_{ij} = 1$ when $i = j$ and $a_{ji} = \frac{1}{a_{ij}}$.

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \tag{10}$$

Some techniques like the eigenvalue method is used to calculate the relative weights of elements in each pairwise comparison matrix. The relative weight, W, of matrix A is obtained by:

$$(A - \lambda_{max} I) \times W = 0 \tag{11}$$

where λ_{max} is the biggest eigenvalue of matrix A and the unit matrix.

The consistency for pairwise comparisons in AHP is calculated by the consistency ratio (CR), which measures the probability that the pairwise comparison matrix is filled in, purely at random [20]. CI is the consistency index that can be obtained from Equation (3), where RI is the random index for matrix A, and is shown in Table 2 [21]. The closer the inconsistency index is to zero, the greater the consistency is. If it is high, it means that the input judgments are not consistent; hence, they have to be elicited again. In general, an inconsistency ratio of about 10% or less is usually considered acceptable, and then the derived weights may be used.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{12}$$

$$CR = \frac{CI}{RI} \tag{13}$$

Table 1. Scale of relative importance [19].

Numerical assessment	Linguistic meaning
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2,4,6,8	Intermediate values between the two adjacent judgments

Table 2. Random index values [22].

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

In the last step, the relative weights of the decision-making elements are aggregated to obtain an overall rating for the alternatives, as follows:

$$\mathrm{W}_{\mathrm{i}}^{\mathrm{s}} = \sum_{j=1}^{m} W_{ij}^{s} W_{j}^{a} \qquad (i = 1,2, \ldots, m) \tag{14}$$

where W_i^s is the total weight of alternative i, W_{ij}^s is the weight of alternative i associated with attribute j, W_j^a is the weight of attribute j, m the number of attributes, and n is the number of alternatives [21]. The strengths of the AHP method are:

- The advantages of AHP over other multi-criteria methods are its flexibility, intuitive appeal to the decision-makers, and its ability to check inconsistencies [23]. Generally, the users find the pairwise comparison form of data input straightforward and convenient.

- Additionally, the AHP method has the distinct advantage that it decomposes a decision problem into its constituent parts and builds hierarchies of criteria. Here, the importance of each element (criterion) becomes clear [24].
- AHP helps to capture both the subjective and objective evaluation measures. While providing a useful mechanism for checking the consistency of the evaluation measures and alternatives, AHP reduces bias in decision-making.
- The AHP method supports group decision-making through consensus by calculating the geometric mean of the individual pairwise comparisons [25].
- AHP is uniquely positioned to help model situations of uncertainty and risk since it is capable of deriving scales where measures ordinarily do not exist [26].

Different approaches to risk management are used; one of the newly developed methods is a combination of the game theory and the multi-criteria decision-making methods. In the following, the game theory is described.

2.3. Game Theory

The game theory is often described as a branch of applied mathematics and economics that studies situations where multiple players make decisions in an attempt to maximize their returns. Generally, the publication of the Theory of Games and Economic Behavior by Morgenstern and Von Neumann in 1944 symbolizes the foundation of the game theory system [27]. The modern game theory was developed from 1950s to 1960s, and in 1970s, the modern game theory became a popular economic theory [27]. The primary basic concept of the game theory includes player, action, strategy, information, income, and equilibrium. Players can be the individuals or groups such as the manufacturer, government, and nation.

A game is played by two opponents with strictly opposite interests [28]. This means, formally, that on passing from one game situation to another, an increase in the pay-off of one player results in a numerically equal decrease in the pay-off of the other so that in any situation, the sum of the pay-offs of the players is constant (this sum may be considered as zero since the pay-off of one player is equal to the loss of the other). For this reason, two-person zero-sum games are also called two-person games with zero sum or antagonistic games. The mathematical concept of two-person zero-sum game pay-off functions that are numerically equal and opposite in sign is a formal concept, which differs from the corresponding philosophical concept.

If in a two-person zero-sum game one of the players manages to increase his pay-off by a definite amount of money as a result of agreements and negotiations, his opponent will lose an equal sum [28]. Consequently, any agreement would be disadvantageous to one of the players, and therefore, impossible. Real conflict situations, which may be adequately modelled by two-person zero-sum games, are some (but not all) military operations, sport matches, and parlor games as well as situations that involve bilateral decision-making under a strict competition. Games played against nature and, in general, decision- making under uncertainty conditions (statistical game) may be regarded as two-person zero-sum games if it is assumed that the real laws of nature, which are unknown to the player, will produce effects least favorable to the player [29].

A two-person zero-sum game in its normal form is defined as the sets of strategies A and B of players I and II, respectively, and sets of the pay-off function H of player I, defined on the set $A \times B$ of all situations (the pay-off function of player II is $-H$ by definition). Formally, a two-person zero-sum game Γ is given by a triplet $\Gamma = \langle A, B, H \rangle$ [30]. In this game, each player selects a unique strategy, for example, player 1 selects…. Such a definition of a two-person zero-sum game is sufficiently general to include all variants of two-person zero-sum games including dynamic, differential, and positional games, provided that the sets of strategies and the pay-off function are properly described. A rational choice of actions (strategies) of the players in the course of a two-person zero-sum game is based on a minimax principle. If

$$\underset{a \in A}{max} \ \underset{b \in B}{inf} H(a, b) = \underset{b \in B}{min} \ \underset{a \in A}{sup} H(a, b) \tag{15}$$

or

$$\underset{a \in A}{sup} \ \underset{b \in B}{inf} H(a, b) = \underset{b \in B}{inf} \ \underset{a \in A}{sup} H(a, b) \tag{16}$$

the following equalities are valid:

$$\max\min a_{ij} = -1\,, \qquad minmaxa_{ij} = 1 \tag{17}$$

Therefore, the sets of players' strategies are extended to a set of mixed strategies, which consist of a random choice of initial strategies by the players while the pay-off function is defined as the mathematical expectation of the pay-off under the condition of the mixed strategy application.

In the above example, the optimal mixed strategies of both players are the choice of the two strategies with probabilities $\frac{1}{2}$, while the value of the game in the mixed strategies is zero. If the sets A and B are finite, the two-person zero-sum game is called a matrix game, for which the value of the game and optimal mixed strategies of each player exist in all cases. If both sets A and B are infinite, optimal strategies may fail to exist. The matrix of the game $A = \left(a_{ij}\right)_{m\times n}$, which is $a_{ij} \geq 0$ and also assumed that $P_0 = (p_1^0, p_2^0, \dots, p_n^0)$ and $Q_0 = (q_1^0, q_2^0, \dots, q_n^0)$ is the optimal answer; in this case the following equations are presented [31].

$$\begin{cases} \sum_{i=1}^{m} p_i a_{ij} \geq V\,, \quad \sum_{i=1}^{m} p_i = 1 \rightarrow \sum_{i=1}^{m} \frac{p_i}{V} a_{ij} \geq 1 \\ \sum_{j=1}^{n} a_{ij} q_j \leq V\,, \quad \sum_{j=1}^{n} q_j = 1 \rightarrow \sum_{j=1}^{n} \frac{q_j}{V} a_{ij} \leq 1 \end{cases} \tag{18}$$

Now assume $y_j = \frac{q_j}{V} \geq 0$ and $x_i = \frac{p_i}{V} \geq 0$. Thus:

$$\begin{cases} \sum_{i=1}^{m} x_i a_{ij} \geq 1, x_i \geq 0 \\ \sum_{j=1}^{n} a_{ij} y_j \leq 1, y_i \geq 0 \end{cases} \tag{19}$$

Therefore, it is sufficient to minimize $\sum_{i=1}^{m} x_i$. On the other hand, the goal of player A is to maximize his profit (maximizing V). Thus:

$$\sum_{i=1}^{m} x_i = \sum_{i=1}^{m} \frac{p_i}{V} = \frac{1}{V} \sum_{i=1}^{m} p_i = \frac{1}{V} \tag{20}$$

Also the goal of player B is to minimize his profit (minimizing V). Thus:

$$\sum_{i=1}^{n} y_i = \sum_{j=1}^{n} \frac{q_j}{V} = \frac{1}{V} \sum_{j=1}^{n} q_j = \frac{1}{V} \tag{21}$$

It is sufficient to maximize $\sum_{i=1}^{m} y_j$. Therefore, the matrix game becomes a linear programming problem.

3. Case study (Mashhad urban railway line 3)

Mashhad Metro is a rail system operating in the city of Mashhad, located in the Khorasan-e-Razavi Province in Iran. Operated by Mashhad Urban Railway, the project is also referred to as Mashhad Light Rail and Mashhad Urban Rail. Line 3 has currently undergone more than 4.5 km (2.8 mi) of excavation (Figure 2).
The total length of the route is 28.5 km from the end of Amirieh St. to the end of Saba Blvd. The length of the route in Phase 1 is 11.5 km from Ferdowsi Blvd. to the intersection of Saba Blvd. Moreover, the total number of stations is 24 (Mashhad Urban Railway Corporation).
Around 13 km of the tunnel of Mashhad Urban Railway Line 3 has been operated through a tunnel boring machine. The rail depth in this area varies from 17 to 35 m. 7 km of the route has been designed via the Lining and Excavation Method, and where necessary, on some limited parts of the route, the Austrian Method has been applied.

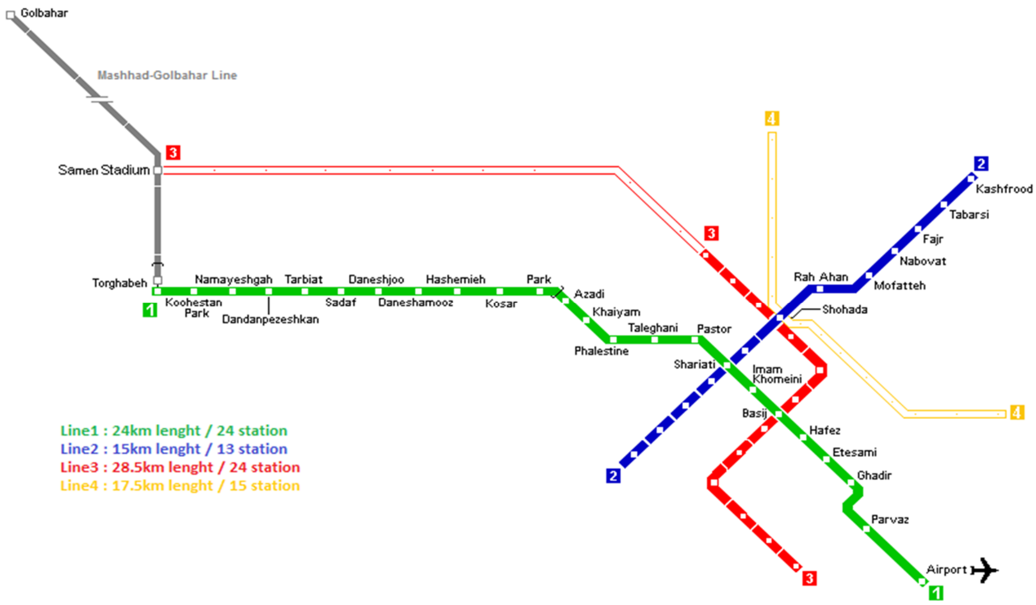

Figure 2. Mashhad Urban Railway Networks (Mashhad Urban Railway Operation Company).

4. Effective criteria and risk group

Tunnels and underground structures are indispensable when installing new infrastructures in congested areas and when raising the quality of the existing urban living occurs. Tunnels, however, are expensive structures to build, and mistakes may lead to serious consequences for the various stakeholders both during the construction and later in the exploitation stage. Particular issues are the possible high costs of maintenance, damage, and protection from the environment and consequences of hazards both during the execution and the exploitation [32].

A hazard may be defined as an event that has the potential of harm. Both the probability of such an event as well as the consequences depend on circumstances. In the present day tunnel design, the issue of hazards is treated in many different ways. Nine risk groups have been identified as the most important ones in mechanized tunneling, as presented in Table 3.

Technical risks are one of the most important risks in tunneling projects, the most important of which are given in Figure 3.

In this work, six attributes were considered in the rating of tunnel risk groups. The rating of risk groups in this work includes 6 attributes and 10 alternatives, the hierarchical structure of which is shown in Figure 4. The important criteria for ranking the risk group of the case study are summarized in Table 4.

Ranking indicators are based upon the extent of risk impacts on the main objectives of the project, and the probability of risk and its manageability. With the help of multi-criteria decision-making methods, risks are better evaluated according to different indicators and thus ranked more realistically.

To increase the level of confidence and achieve more accurate results, the AHP and TOPSIS methods were used. These methods were used for simplicity and generality, and the results obtained from them were used as the inputs to the game theory.

The ranking of the risk group for the case study was carried out using the TOPSIS and AHP methods, as what follows.

Table 3. Risk group.

A_i	Risk group
A_1	Geological and geotechnical risks
A_2	Technical risk
A_3	Human factor risk
A_4	Organizational risk
A_5	Contractual risk
A_6	Reso1urces and equipment risk
A_7	Political risk
$A_{;8}$	Economical risk
A_9	Social risk
A_{10}	Natural disaster risk

Table 4. Criteria for Ranking Risk group.

C_i	Effective criteria
C_1	Manageability
C_2	Probability of occurrence
C_3	Impact on project time
C_4	Impact on costs of project
C_5	Impact on quality of project
C_6	Impact on performance of project

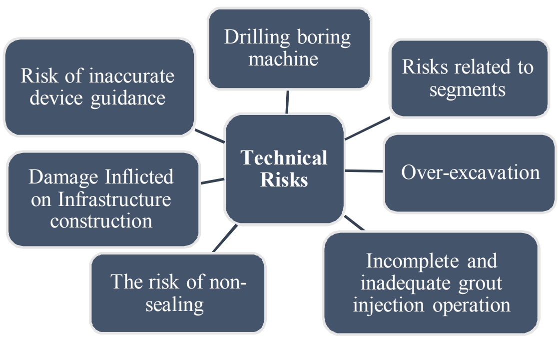

Figure 3. Technical risks of tunneling projects.

4.1. Ranking of risk group using TOPSIS method

The first step was to collect the experts' opinions using the prepared questionnaires. The team of experts involved in the survey included 13 people. After completing the questionnaire forms by the experts, the decision matrix was obtained (Table 5).

In this procedure, using Eq. 1, the normalized weighted decision matrix (Table 8) is composed according to the normalized decision matrix (Table 6) and the criteria weight matrix (Table 7). The criteria weight matrix was obtained as shown in Eqs. 2 to 4.

Table 5. Decision matrix.

	C_1	C_2	C_3	C_4	C_5	C_6
A_1	5.8	5.5	4.5	4.4	4.7	4.2
A_2	5.5	5.7	5.5	6.7	6	5.5
A_3	3.8	5.7	4.2	4.4	5.5	5.2
A_4	5.5	4.2	4.2	4.7	5	3.7
A_5	5	5	5	5.5	4.7	4.5
A_6	6.5	5.2	6	6.1	5.5	4.5
A_7	5.7	3.2	5	3.8	4.2	4.2
A_8	7.6	6.2	6.7	5.8	5.8	5.8
A_9	5.2	3.7	3.5	3.2	2.5	3.5
A_{10}	5	2.4	4.5	3.8	4.2	4.5

Table 6. Normalized decision matrix in TOPSIS method.

	C_1	C_2	C_3	C_4	C_5	C_6
A_1	0.3238	0.3576	0.2851	0.2799	0.3044	0.2897
A_2	0.3071	0.3738	0.3485	0.4250	0.3845	0.3749
A_3	0.2149	0.3738	0.2693	0.2799	0.3538	0.3578
A_4	0.3110	0.2763	0.2693	0.2983	0.3204	0.2556
A_5	0.2792	0.3251	0.3168	0.3528	0.3044	0.3067
A_6	0.3629	0.3413	0.3802	0.3889	0.3538	0.3067
A_7	0.3211	0.2113	0.3168	0.2406	0.2724	0.2897
A_8	0.4255	0.4063	0.4277	0.3705	0.3749	0.3987
A_9	0.2931	0.2438	0.2059	0.2077	0.1602	0.2385
A_{10}	0.2792	0.1573	0.2851	0.2438	0.2724	0.3067

Table 7. The final weight of alternatives based on TOPSIS method.

	C_1	C_2	C_3	C_4	C_5	C_6
E_j	0.9936	0.9847	0.9918	0.9891	0.9899	0.9946
D_j	0.0064	0.0153	0.0082	0.0109	0.0101	0.0054
W_j	0.1136	0.2717	0.1456	0.1936	0.1793	0.0959

Table 8. The normalized weighted decision matrix.

	C_1	C_2	C_3	C_4	C_5	C_6
A_1	0.0434	0.0860	0.0367	0.0640	0.0643	0.0162
A_2	0.0411	0.0898	0.0448	0.0971	0.0813	0.0210
A_3	0.0288	0.0898	0.0346	0.0640	0.0748	0.2007
A_4	0.0417	0.0664	0.0346	0.0682	0.0677	0.0143
A_5	0.0374	0.0781	0.0408	0.0806	0.0643	0.0172
A_6	0.0486	0.0820	0.0489	0.0889	0.0748	0.0172
A_7	0.0430	0.0508	0.0408	0.0550	0.0576	0.0162
A_8	0.0570	0.0977	0.0550	0.0847	0.0792	0.0223
A_9	0.0393	0.0586	0.0265	0.0475	0.0338	0.0133
A_{10}	0.0374	0.0378	0.0367	0.0557	0.0576	0.0172

The positive and negative ideal solutions were calculated using Eqs. 5 and 6, as follow:

$$A^{+} = \{0.04301, 0.1006, 0.0830, 0.0736, 0.0588, 0.0351\}$$

$$A^{-} = \{0.0217, 0.0374, 0.0356, 0.0359, 0.0245, 0.0210\}$$

The separation of each alternative from the ideal solution is given in Table 9. The relative closeness to the ideal solution is also calculated using Eqs. 7 to 9. The results of the calculations are given in Table 9.

Given the performed calculations and the closeness of the number to 1, the rankings of the alternatives are stated in the order of preference in Table 10.

Risk rating was carried out using the TOPSIS method, as a result of which, the groups of economic risks and social risks were, respectively, rated as the most and least important risks.

Table 9. The separation of positive and negative ideal solutions and the relative closeness to the ideal solution.

A_i	d_{i+}	d_{i-}	CL_i
A_1	0.0455	0.0620	0.5771
A_2	0.0205	0.0892	0.8131
A_3	0.0491	0.0690	0.5840
A_4	0.0520	0.0512	0.4959
A_5	0.0394	0.0627	0.6138
A_6	0.0221	0.0790	0.7812
A_7	0.0703	0.0347	0.3304
A_8	0.0125	0.0933	0.8812
A_9	0.0769	0.0232	0.2323
A_{10}	0.0811	0.0376	0.3177

Table 10. The ranking of the alternatives by TOPSIS.

Rank	A_i	Risk group
1	A_8	Economical risk
2	A_2	Technical risk
3	A_6	Resources and equipment risk
4	A_5	Contractual risk
5	A_3	Human factor risk
6	A_1	Geological and geotechnical risks
7	A_4	Organizational risk
8	A_7	Political risk
9	A_{10}	Natural disaster risk
10	A_9	Social risk

4.2. Ranking of risk group using AHP method

The first step in the AHP procedure is to decompose the decision problem into a hierarchy of the most important elements of the decision problem. The hierarchy of ranking the risk group for the case study is illustrated in Figure 4. The pairwise comparison matrix established using a nine-point scale is given in Table 11. Then the final weight of the criteria is calculated to determine the priority through the concept of normalization. The value of each option is yielded through the priority value of the option based on criterion i multiplied by the weight of the criterion, as calculated in Eq. 14 and stated in Table 12.

According to the calculations, the ranking of the risk group in the order of priority is given in Table 12.

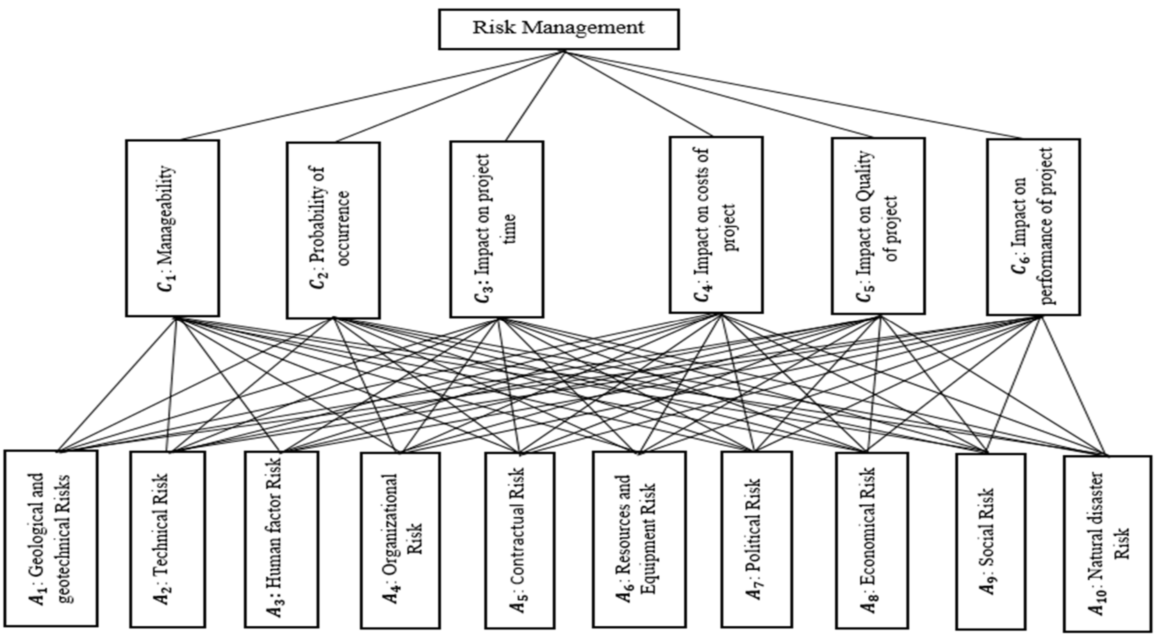

Figure 4. Hierarchical structure of the decision problem.

Table 11. Pairwise comparison matrix.

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1	0.3745	3.671	0.3533	0.3164	3.334
C_2	2.671	1	4.833	0.8620	0.5988	4.166
C_3	0.2724	0.2070	1	0.2724	0.2610	0.8620
C_4	2.833	1.166	3.671	1	0.8620	2.671
C_5	3.166	1.671	3/833	2.166	1	4.166
C_6	0.3003	0.2403	1.166	0.3745	0.2403	1

Table 12. Total weight of alternatives and ranking of the alternatives.

A_i	Risk group	Total weight	Rank
A_1	Geological and geotechnical risks	0.0704	5
A_2	Technical risks	0.2146	2
A_3	Human factor risks	0.0965	4
A_4	Organizational risks	0.0482	7
A_5	Contractual risk	0.0692	6
A_6	Resources and equipment risk	0.1501	3
A_7	Political risks	0.0330	8
A_8	Economical risks	0.2628	1
A_9	Social risks	0.0148	10
A_{10}	Natural disaster risk	0.0249	9

Risk rating was carried out through the AHP method, as a result of which, the groups of economic risks and social risks were, respectively, rated as the most and least important risks.

In the following part, using the game theory and modeling, the worst case scenario in the project and the ranking of the risks in the first three groups are derived, and appropriate answers for the existing risks are presented based on the degree of importance.

4.3. Risk assessment using game theory

The game theory provides a mathematical framework for analyzing the decision-making processes and strategies of adversaries (or players) in different types of competitive situations. The simplest types of competitive situations are two-person, zero-sum games.

These games involve only two players; they are called zero-sum games because one player wins whatever the other player loses. Poker exemplifies a zero-sum game because one wins exactly the amount one's opponents lose. Other zero-sum games include most classical board games including chess. The main elements in this game are as what follow.

A. Players

The players include the individual or a group of decision-makers. The game consists of two players: 1. the risks involved in the Mashhad Urban Railway Line 3 (the first three groups are derived from the ranking of the existing risks in the project, obtained from the TOPSIS and AHP methods) 2. The team involved in the tunnel project.

B. The strategies of each player

The first player strategies in this research work are:

x_1: Warranty and quality of equipment
x_2: Damage to tools and equipment
x_3: Safety and maintenance warehouses
x_4: Timely access to tools and equipment
x_5: Risk of increasing the currency rate
x_6: Inflation
x_7: Financing problems
x_8: Timely payment of bill and invoices
x_9: Drilling boring machine
x_{10}: Risks related to segments
x_{11}: Over-excavation
x_{12}: Risk of inaccurate device guidance
x_{13}: Damage inflicted on infrastructure construction
x_{14}: Risk of non-sealing
x_{15}: Incomplete and inadequate grout injection operation

The strategies of the second player selected for research:

y_1: Provision of injection slurries according to technical specifications in adequate quantities
y_2: Health of the components of the injection system (pumps, injection lines) and the simultaneous injection with progress
y_3: Experienced and trained operator and personnel in installing segments and training existing operators

y_4: Performing dual mapping control at specified lengths to ensure proper drilling machine track
y_5: Identifying route complications
y_6: Observing and implementing the correct and timely technical drilling instructions to restrict the induced subsidence caused by the tunnel drill (face pressure, segment back injection)
y_7: Evaluating and comparing the output volume of the materials with the volume of drilling theory and the use of control systems for the weight and volume of drilling materials (such as laser scanners on the conveyor)
y_8: Proper sealing of the tunnel
y_9: Appropriate connector and quality confirmation for connecting the segment
y_{10}: Applying the professional and experienced assembly team of drilling tools and equipment
y_{11}: Obtaining sufficient guarantees and warranties from the sellers of the required used tools and equipment
y_{12}: Observance of international, national, and factory standards for product selection and implementation of quality control program before and after the purchase of necessary tools and equipment
y_{13}: Safety and health principles
y_{14}: Insurance of equipment
y_{15}: A strong support team to provide timely access to equipment and to anticipate future needs for equipment and timely delivery of them
y_{16}: Compliance with the standards and technical principles in the construction of warehouses
y_{17}: Predicting foreign purchases required and taking action as soon as possible
y_{18}: Use of new financing methods at times of credit shortage and financial problems of project
Thus the game is displayed as follows:

$$
\begin{aligned}
&N = \{A, B\} \\
&S_A^C = \{x_1, x_2, x_3, \dots, x_m\} \\
&S_B^C = \{y_1, y_2, y_3, \dots, y_n\} \\
&u_A(A_i, B_j) = a_{ij} \\
&u_B(A_i, B_j) = b_{ij}
\end{aligned}
\tag{22}
$$

S_A^C And S_B^C are a set of strategies for each player, which are fully introduced. If a player is guessing which activity is to be selected by the other on any particular occasion, a probabilistic situation is obtained, and the objective function is to maximize the expected gain. Thus the mixed strategy is a selection among pure strategies with fixed probabilities. In this game, the mixed strategies are used. Therefore, the set of strategies A and B will be as follow:

$$S_A = \left\{(p_1, p_2, \dots, p_m) \middle| \sum_{i=1}^{m} p_i = 1, \quad p_i \geq 0\right\} \tag{23}$$

$$S_B = \left\{(q_1, q_2, \dots, q_m) \middle| \sum_{i=1}^{m} q_i = 1, \quad q_i \geq 0\right\} \tag{24}$$

Due to the players' strategies, the matrix results from the desired game. The resulting matrix is obtained as shown in Table 13.

Table 13. Outcome matrix.

Player B \ Player A	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	min
y_1	0	0	0	10	2	8	8	8	0	0	8	8	8	5	10	0
y_2	0	5	7	7	2	3	3	5	5	8	8	8	8	6	9	0
y_3	0	10	0	8	0	0	0	5	2	10	0	0	7	10	7	0
y_4	10	8	9	9	0	0	5	5	0	2	3	8	10	0	2	0
y_5	0	0	8	8	0	0	5	5	0	0	0	4	6	0	0	0
y_6	0	7	5	0	0	5	7	7	5	5	8	10	8	8	7	0
y_7	7	8	0	7	0	0	2	0	0	0	8	8	8	8	2	0
y_8	8	8	2	8	7	7	7	7	0	0	5	0	5	10	10	0
y_9	8	8	3	8	2	0	0	3	5	10	0	5	5	5	0	0
y_{10}	7	7	5	7	0	8	4	8	10	8	7	7	7	7	7	0
y_{11}	10	7	7	3	5	5	6	7	8	7	5	5	5	7	5	3
y_{12}	10	8	10	0	8	4	4	4	8	5.5	0	0	0	5	2	0
y_{13}	0	7	10	7	0	2	2	5	5	5	0	0	0	0	0	0
y_{14}	10	10	7	7	0	3	3	3	10	4	0	0	0	0	0	0
y_{15}	3	5	7	8	3	3	3	3	10	0	4	4	5	5	5	0
y_{16}	0	7	10	8	0	0	0	4	2	0	0	0	0	0	0	0
y_{17}	5	0	8	8	10	8	7	7	10	4	0	0	0	0	0	0
y_{18}	0	0	7	3.5	8	7	7	7	10	4	0	0	0	3	0	0
max	10	10	10	10	10	8	8	8	10	10	8	10	10	10	10	----

According to Table 13:

$$\max\min a_{ij} = 3 \ , \qquad minmaxa_{ij} = 8$$

In the following, the optimal solution of the problem, namely q_j^* and p_j^*, is presented in Tables 14 and 15.

Table 14. The calculated optimal values for p_j^*.

p_j^*	Calculated values
p_1^*	0.3945 e^{-15}
p_2^*	0.2503
p_3^*	0.0137
p_4^*	0.3126
p_5^*	0.1115 e^{-14}
p_6^*	0.3011 e^{-15}
p_7^*	0.3214
p_8^*	0.9035 e^{-14}
p_9^*	0.0156
p_{10}^*	0.1665 e^{-14}
p_{11}^*	0.1906 e^{-15}
p_{12}^*	0.2233 e^{-15}
p_{13}^*	0.0520 e^{-14}
p_{14}^*	0.0168
p_{15}^*	0.1609 e^{-16}

Table 15. The calculated optimal values for q_j^*.

q_j^*	Calculated values
q_1^*	0.9306 e^{-9}
q_2^*	0.9193 e^{-10}
q_3^*	0.0557
q_4^*	0.2483 e^{-10}
q_5^*	0.0016
q_6^*	0.1048
q_7^*	0.2983
q_8^*	0.2532 e^{-10}
q_9^*	0.5027 e^{-10}
q_{10}^*	0.1828 e^{-10}
q_{11}^*	0.2792 e^{-10}
q_{12}^*	0.5112 e^{-10}
q_{13}^*	0.5252 e^{-10}
q_{14}^*	0.2042 e^{-10}
q_{15}^*	0.2293 e^{-10}
q_{16}^*	0.1747
q_{17}^*	0.2880 e^{-10}
q_{18}^*	0.3745

Due to the result of ranking using TOPSIS, AHP and the game results are the worst case scenarios of risks in the project, as shown in Table 16.

A worst-case scenario is a concept in risk management wherein the planner in planning for potential disasters considers the most severe possible outcome that can reasonably be projected to occur in a given situation. The conception of worst-case scenarios is a common form of strategic planning, specifically for scenario planning, to prepare for and minimize the contingencies that could result in quality problems or other similar issues.

The ranking of economical, technical, material, and equipment risks is presented in Table 17 in the degree of importance. By ranking, it means that the priority of each risk against other risks is based on the degree of importance, and thus the decision-maker can plan on how much resources are allocated to deal with each risk based on their importance and the response. Therefore, by allocating more resources to higher risks, they should eliminate or mitigate the adverse effects of these risks on the project goals.

To cope with these conditions, the ranking of strategies was used to respond to risks based on the degree of importance given in Table 18.

According to Table 18, the first item is the most important one among the responses. The degree of importance is indicated in this table.

Table 16. The calculated optimal values for p_j^*.

Risk	Degree of importance
Financing problems	0.3214
Timely access to tools and equipment	0.3126
Damage to tools and equipment	0.2503
Risk of non-sealing tunnels	0.0168
Drilling boring machine	0.0156
Safety and maintenance warehouses	0.0137

Table 17. The ranking of economic, technical, material, and equipment on the degree of importance.

Rank	Risk	Degree of importance
1	Financing problems	0.3214
2	Timely access to tools and equipment	0.3126
3	Damage to tools and Equipment	0.2503
4	The risk of non-sealing tunnels	0.0168
5	Drilling boring machine	0.0156
6	Safety and maintenance warehouses	0.0137
7	Timely payment of bill and invoices	0.9035 e^{-14}
8	Risks related to segments	0.1665 e^{-14}
9	Risk of increasing the currency rate	0.1115 e^{-14}
10	Damage Inflicted on Infrastructure construction	0.0520 e^{-14}
11	Warranty and quality of equipment	0.3945 e^{-15}
12	Inflation	0.3011 e^{-15}
13	Invalid device conduct	0.2233 e^{-15}
14	Over-excavation	0.1906 e^{-15}
15	Incomplete and inadequate injection operation	0.1609 e^{-16}

Table 18. The ranking of strategies used to respond to risks based on the degree of importance.

Rank	Risk response	Degree of importance
1	Use of new financing methods at times of credit shortage and financial problems of project	0.3745
2	Evaluating and comparing the output volume of the materials with the volume of drilling theory and the use of control systems for the weight and volume of drilling materials (such as laser scanners on the conveyor)	0.2983
3	Compliance with the standards and technical principles in the construction of warehouses	0.1747
4	Observing and implementing the correct and timely technical drilling instructions to restrict the induced subsidence caused by the tunnel drill (face pressure, segment back injection)	0.1048
5	Experienced and trained operator and personnel in installing segments and training existing operators	0.0557
6	Identify route complications	0.0016
7	Provision of injection slurries according to technical specifications in adequate quantities	$0.9306\ e^{-9}$
8	The health of the components of the injection system (pumps, injection lines) and the simultaneous injection with progress	$0.9193\ e^{-10}$
9	The safety and health principles	$0.5252\ e^{-10}$
10	Observance of international, national and factory standards for product selection and implementation of quality control program before and after the purchase of necessary tools and equipment	$0.5112\ e^{-10}$
11	Appropriate connector and quality confirmation for connecting the segment	$0.5027\ e^{-10}$
12	Predicting foreign purchases required and taking action as soon as possible	$0.2880\ e^{-10}$
13	Obtaining sufficient guarantees and warranties from the sellers of the required used tools and equipment	$0.2792\ e^{-10}$
14	Proper sealing of the tunnel	$0.2532\ e^{-10}$
15	Performing dual mapping control at specified lengths to ensure proper drilling machine track	$0.2483\ e^{-10}$
16	A strong support team to provide timely access to equipment and to anticipate future needs for equipment and timely delivery of them	$0.2293\ e^{-10}$
17	Insurance of equipment	$0.2042\ e^{-10}$
18	Applying the professional and experienced assembly team of drilling tools and equipment	$0.1828\ e^{-10}$

5. Conclusions

Risk ranking involves the interaction of several subjective factors or criteria. One of the key parts of any project, especially in the tunneling projects, is risk management. Since many parameters and criteria influence risk management, the decision-making in this field is a complicated process.

In this work, a new model for risk management was presented for the Mashhad Metro Line 3 with the help of the game theory and the multi-criteria decision-making methods. Based on the specialists' and experts' replies to the prepared questionnaires, various risk groups identified using the TOPSIS and AHP multi-criteria decision-making methods were ranked. Accordingly, the economic and social risk groups were, respectively, ranked as the most important and the least significant risks in both methods. Furthermore, the worst risk scenario in the project was identified, and the appropriate responses for this state were also expressed in order of importance. Obtaining the worst-case scenario using the game theory is one of the reasons for the importance of this method and its superiority over other methods in risk management. The results obtained identified the risk of financial problems as the most significant risk in this project, while other risks were ranked in the next rows in terms of importance. The first item use of the new financing methods at times of credit shortage and financial problems of the project were found to be the most important responses.

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مدیریت ریسک تونل‌های شهری با استفاده از تئوری بازی و تصمیم‌گیری چند معیاره

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چکیده:

به طور کلی، فضاهای زیرزمینی به علت عدم اطمینان بالایی که در محیط‌های ژئوتکنیکی دارند با خطرات زیادی مواجه هستند. از آنجایی که اکثر حوادث و رخدادها در این سازه‌ها با عدم اطمینان همراه است، توسعه تحلیل ریسک و روش‌های مدیریت و پیشگیری از آن‌ها ضروری است. شناخت عمیق‌تر عوامل مؤثر بر فرآیند پیاده‌سازی می‌تواند راه را برای این هدف فراهم سازد. رتبه ریسک پروژه‌ها بخش مهمی از مرحله ارزیابی ریسک در فرآیند مدیریت ریسک هر پروژه است. روش‌های مختلف تصمیم‌گیری چند منظوره، به عنوان رویکردهای کمی، مورد استفاده قرار می‌گیرند تا آن‌ها را در رتبه‌بندی ریسک هر پروژه به کار برد. در این پژوهش، یک مدل جدید برای مدیریت ریسک راه‌آهن شهری خط ۳ مشهد، با استفاده از تئوری بازی و روش تصمیم‌گیری چند منظوره، ارائه شده است. بر اساس پاسخ متخصصان و کارشناسان به پرسشنامه‌های آماده شده، گروه‌های مختلف ریسک‌ها شناسایی شده توسط روش‌های تصمیم‌گیری TOPSIS و AHP چند معیاره رتبه‌بندی شده‌اند. طبق نتایج حاصله، گروه ریسک‌های اقتصادی به عنوان مهم‌ترین ریسک و گروه ریسک اجتماعی، در هر دو روش کمترین میزان را داشته‌اند. در ادامه، پاسخ مناسب به ریسک‌های اصلی رتبه‌ها مبتنی بر مدل‌سازی نظریه‌ی بازی و بر اساس اهمیت رتبه‌بندی شده است. همچنین بدترین سناریو ریسک در پروژه شناسایی شده و پاسخ‌های مناسب برای این حالت نیز به ترتیب اهمیت بیان شده است. نتایج به دست آمده حاکی از آن است که خطر مشکلات مربوط به تأمین مالی مهم‌ترین ریسک در پروژه بررسی شده است و ریسک‌های دیگر به لحاظ اهمیت در رتبه‌های بعدی قرار دارند. علاوه بر این، استفاده از روش‌های جدید تأمین مالی در زمان کمبود اعتبار و مشکلات مالی پروژه نیز به عنوان مهم‌ترین پاسخ به خطر در این پروژه محسوب می‌شود.

کلمات کلیدی: ریسک، تصمیم‌گیری چند معیاره، تئوری بازی، AHP، TOPSIS.