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Risk Management in Road Construction Projects: A Fuzzy ANP Approach for Prioritizing Critical Factors

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Abstract

Road construction projects are inherently associated with numerous risks and uncertainties that can significantly impact project objectives including cost, time, and quality. This paper presents a comprehensive risk assessment framework for road construction projects using fuzzy Analytic Network Process (ANP) methodology. A case study of road construction projects in Tonkabon city, Iran, is conducted to identify, evaluate, and prioritize risk factors affecting project performance. Through literature review and expert consultation, five main risk categories and ten sub-criteria were identified. The fuzzy ANP method was employed to handle the inherent uncertainty in expert judgments and capture interdependencies among risk factors. Results indicate that employer-related risks (weight: 0.27) rank first, followed by accident-related risks (0.23), machinery-related risks (0.18), contractor-related risks (0.16), and consultant-related risks (0.14). Among sub-criteria, lack of access to skilled and expert personnel emerged as the most critical risk factor (weight: 0.12). The findings provide valuable insights for project managers and stakeholders in developing proactive risk mitigation strategies for road construction projects. The proposed methodology offers a systematic approach for risk prioritization that can be adapted to various infrastructure project contexts.

Keywords: Risk management, Uncertainty, Road construction, Fuzzy ANP, Employer, Contractor.

1 | Introduction

Road construction projects constitute a substantial portion of infrastructure investments in developing countries, playing a pivotal role in economic development and regional connectivity [1]. However, these projects are inherently characterized by high levels of uncertainty and risk due to their complex nature, extended duration, significant capital requirements, and exposure to various environmental, technical, and managerial challenges [2], [3].

In project management standards, planning, having strategy, predicting events and project risks, and planning to respond to them before project commencement are among the most important matters [4]. Completing a

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project within the framework of time, cost, quality, and safety requires risk identification, analysis, and ranking for appropriate response [5]. Risk management is a branch of management science that has found a specific position in diverse fields, including road construction projects, which are undoubtedly accompanied by numerous risks [6]. Risk management is a systematic attempt to structurally manage changes in the project, involving the systematic application of management policies, procedures, activities, and processes related to risk analysis, evaluation, and control [7].

Despite the critical importance of risk management, many road construction projects in developing countries face significant challenges including cost overruns, schedule delays, and quality deficiencies [8]. Studies have shown that inadequate risk assessment and management are leading causes of disputes and claims in construction projects [9]. The complexity of road construction projects demonstrates that failure to address risk assessment and relying on traditional management approaches can be a primary factor in additional costs and implementation challenges.

Multiple-Criteria Decision-Making (MCDM) methods serve as quantitative approaches for project risk ranking problems [10]. From the earliest stage of decision-making to the construction and completion of road projects, numerous risks arise, including determination of correct and appropriate routes, land acquisition and interference with various land uses, design deficiencies revealed during implementation, environmental conditions, lack of supervision knowledge, and external factors affecting the project. These risks can cause irreparable damage to road projects and affect the three fundamental dimensions of each project: quality, time, and cost.

This study aims to identify and evaluate risks in road construction projects of Tonkabon city using fuzzy ANP methodology, providing a decision support tool for project managers and stakeholders to better allocate resources for risk mitigation.

2 | Literature Review

2.1 | Risk and Uncertainty in Construction Projects

Risk in construction projects can be defined as an uncertain event or condition that, if it occurs, has a positive or negative effect on at least one project objective [4]. Uncertainty represents a state of an event with a probable and indeterminate outcome that can produce risk or opportunity. The probability of occurrence refers to the statistical likelihood of any uncertain event, while risk impact represents the degree of effect that can influence one or more project objectives if the event occurs.

Construction projects are considered risky due to the substantial investments involved, which necessitates identification of risk drivers, assessment of risk levels, and selection of appropriate response strategies. Various classification approaches have been proposed in the literature for categorizing project risks. Perera et al. [3] identified that construction and design phases are susceptible to numerous major risks, with "delay in payment by the client" being the most significant risk factor in the construction phase. Perera et al. [11] further demonstrated that road construction projects in Sri Lanka are exposed to many risk sources while most risks are borne by parties to whom risks are allocated through contract clauses.

Zou et al. [12] investigated key risks in Chinese construction projects, identifying risks related to clients, contractors, subcontractors, finance, and government as common categories. Their study emphasized that appropriate risk management programs should be implemented from the project's outset to minimize risk impact. Similarly, Zayed et al. [2] assessed risk and uncertainty in Chinese highway projects using AHP methodology, identifying risks affecting highway projects at both company and project levels.

2.2 | Risk Management in Road Construction

Risk management in road construction involves identifying, analyzing, and responding to project risks throughout the project lifecycle [13]. Odumade et al. [14] studied sustainable risk management in the Nigerian road construction industry and found that Program Evaluation Review Technique (PERT) was the most effective risk management method. The study emphasized that early understanding of project risks helps project managers reduce their effects and complete projects more sustainably and efficiently. Odumade's research showed that the assessment program review technique is the most effective risk management method in Nigeria and aligns with sustainable development practices.

Perera et al. [3] investigated risk management practices in Sri Lankan road construction projects, finding that road construction projects are exposed to many risk sources while most risks are borne by parties to whom risks are allocated through contract clauses. The research concluded that there is no single best way to respond to a risk and that different risk management strategies should be adopted to effectively address risks [11].

Alamgir et al. [1] examined economic, socio-political, and environmental risks of road development in tropical regions, identifying that nearly 90% of new roads in developing countries are built in tropical and subtropical regions with high biodiversity and environmental values. They cautioned that inadequate planning or implementation could lead to heavy costs, corruption, and environmental impacts. Ganapthy et al. [15] specifically investigated flagman and risk involved in road construction sites, highlighting the high risk of fatal accidents for flagmen and proposing intelligent traffic light systems as alternatives to reduce human intervention.

Thomas et al. [16] modeled and assessed critical risks in BOT road projects, proposing a fuzzy fault tree and Delphi method framework for risk assessment in complex infrastructure projects. Alam et al. [17] conducted a comprehensive study of project risks in road transportation networks under CPEC, using the Delphi technique to examine risks including stakeholder support, political roles, terrorism, security situations, poverty, and economic crises.

2.3 | Risk Assessment Methodologies

Various methodologies have been applied for risk assessment in construction projects. Multi-attribute decision-making methods are considered among the most useful for solving ranking problems [10]. Moradpour et al. [18] used hybrid fuzzy PROMETHEE II and fuzzy binary goal programming for risk ranking in highway construction projects, demonstrating the effectiveness of combining MCDM methods for construction risk assessment.

The Analytic Network Process (ANP), developed by Saaty [19], is an advanced model for structuring and analyzing decision-making that captures interdependencies and feedback among decision elements. Unlike AHP, ANP accommodates complex interactions between clusters and elements, including inner and outer dependencies [19]. The supermatrix approach, more popularly known as ANP, has become an attractive tool for better understanding decision-making problems by overcoming the limitations of hierarchical structures [20].

The fuzzy ANP approach addresses the inherent uncertainty in expert judgments by incorporating triangular fuzzy numbers to represent linguistic variables [5]. Sohrabinejad and Rahimi [21] utilized hybrid fuzzy ANP, fuzzy DEMATEL, and fuzzy TOPSIS for risk prioritization in a Tehran construction project, demonstrating the superiority of fuzzy MCDM methods over traditional approaches for risk ranking concerning cost, time, and quality. Guo et al. [22] analyzed construction engineering project gray rhino risks with innovative MCDM methods including interference fuzzy analytical network process and DEMATEL.

2.4 | Previous Studies in Iran

Several studies have examined risks in Iranian construction projects. Jafarian et al. [23] designed a financial risk assessment model for Iranian road construction projects using public-private partnership financing,

finding political risk as the most influential variable and liquidity risk, market risk, inflation risk, and credit risk as the most affected variables. Using interpretive structural modeling and MICMAC analysis, they developed a five-level model with 14 indicators for financial risk assessment.

Mohajeri et al. [24] investigated delay reasons from a risk management perspective in road construction projects, identifying financial and credit problems as the primary risk among main criteria, followed by land acquisition, management problems, technical issues, and natural disasters. Using Ishikawa diagrams and Expert Choice software, they quantitatively ranked delay risks and identified critical sub-criteria including incomplete allocation, land prices, incomplete feasibility studies, incorrect scheduling, provincial credits, non-deposit of funds, and weather conditions.

Rezaeian and Iranian [6] evaluated risks in a cable-stayed bridge construction project based on PMBOK standard using ANP, finding cost management and time management as the most critical risk areas. Their research demonstrated that risk identification and allocation are two powerful factors in risk management decisions. Taherian Amiri et al. [13] applied critical chain method in linear-repetitive road construction projects considering uncertainty and risk conditions, using fuzzy numbers to model activity duration uncertainty while maintaining deterministic scheduling with project buffers.

Rezaee Arjroody et al. [25] identified and prioritized road project risks using failure modes and effects analysis in a fuzzy environment, finding that inflation (increased material price), late financial provisions, equipment deficiency/failure, and employer-driven design changes exceeding 25% were the most important risks in Iranian road projects.

3 | Research Methodology

3.1 | Research Framework

This research is applied in terms of objective and descriptive-survey in terms of execution method. The study uses a quantitative approach for data analysis [10]. The research framework consists of the following phases [19], [20]:

I. Goal definition: Identifying the most critical risk factors in road construction projects.

II. Risk identification: Through literature review and expert consultation.

III. Model development: Building the fuzzy ANP network structure.

IV. Data collection: Expert pairwise comparison questionnaires.

V. Data analysis: Fuzzy ANP computations.

VI. Results and recommendations: Risk ranking and mitigation strategies.

3.2 | Study Population and Sample

The statistical population consists of experts in the road construction field of Tonkabon city with more than 20 years of executive and administrative experience and relevant education. Based on the specified criteria, 10 experts from the Tonkabon Road Administration were selected as the statistical sample [23].

3.3 | Research Instrument

The measurement instrument was a questionnaire designed by the researcher [5]. For validity assessment, the Content Validity Ratio (CVR) method was employed [26]. The questionnaire was provided to five university professors who indicated whether each item was "essential" or "not essential." The CVR for all components exceeded 0.99, confirming validity of all questions as shown in *Table 1*.

Table 1. CVR scores for each question.

Question No.	CVR Score	Question No.	CVR Score
1	1.00	7	1.00
2	1.00	8	1.00
3	1.00	9	1.00
4	0.99	10	1.00
5	1.00	11	1.00
6	1.00	12	1.00

For reliability assessment, Cronbach's alpha coefficient was calculated for each risk component [27], with all values exceeding 0.7 as shown in *Table 2* [13], confirming reliability.

Table 2. Cronbach's Alpha for each component.

Risk Component	Cronbach's Alpha	Result
Contractor-related Risks	0.78	Confirmed
Employer-related Risks	0.85	Confirmed
Consultant-related Risks	0.95	Confirmed
Accident-related Risks	0.88	Confirmed
Machinery-related Risks	0.92	Confirmed

3.4 | Risk Identification

Based on literature review and expert consultation [2], [3], [6], [12], five main risk categories and ten sub-criteria were identified as shown in *Table 3* [10].

Table 3. Identified risk categories and sub-criteria.

Risk Category	Sub-Criteria	Code
Contractor-related risks (A)	Failure to perform work optimally with maximum quality	C1
	Lack of access to skilled and expert personnel	C2
Employer-related risks (B)	Delayed provision of financial resources	C3
	Failure to select capable and sufficiently qualified contractor	C4
Consultant-related risks (C)	Lack of project planning and time control	C5
	Failure to utilize expert and experienced personnel	C6
Accident-related risks (D)	Occurrence of natural disasters (floods, earthquakes)	C7
	Worker injury during activities	C8
	Rainfall and freezing after pavement layer testing	C9
Machinery-related risks (E)	Repair and maintenance costs of machinery	C10

3.5 | Fuzzy ANP Methodology

The fuzzy ANP method was employed to prioritize risks, following these steps [5], [19], [20]:

Step 1 (Fuzzy conversion of expert opinions). Triangular fuzzy numbers were used to convert linguistic variables into fuzzy numbers as shown in *Table 4* [18], [25].

Table 4. Triangular fuzzy numbers used in the research.

Code	Fuzzy Number	Linguistic Variable
1	(0, 0, 0)	Completely ineffective
2	(0, 0, 0.25)	Very low effect
3	(0, 0.25, 0.5)	Low effect
4	(0.25, 0.5, 0.75)	Medium effect
5	(0.5, 0.75, 1)	High effect
6	(0.75, 1, 1)	Very high effect
7	(1, 1, 1)	Completely effective

Step 2 (Geometric mean calculation). Using geometric mean aggregation [28], expert opinions were combined for pairwise comparisons of main criteria [5].

Step 3 (Normalization). The aggregated fuzzy numbers were normalized [19].

Step 4 (Possibility degree calculation). The degree of possibility of one fuzzy number being greater than another was calculated using [29]:

$V(M2 \geq M1) = 1$, if $m2 \geq m1$.

$V(M2 \geq M1) = 0$, if $l1 \geq u2$.

$V(M2 \geq M1) = (l1 - u2) / ((m2 - u2) - (m1 - l1))$, otherwise,

where:

$M1 = (l1, m1, u1)$ and $M2 = (l2, m2, u2)$ are two triangular fuzzy numbers.

l = lower bound (minimum value).

m = most likely value (mean).

u = upper bound (maximum value).

Step 5 (Weight calculation). Weights were derived from the minimum values of each row in the possibility degree matrix and normalized to sum to 1 [19], [20].

The network structure of the fuzzy ANP model is illustrated in *Fig 1* [22], showing the hierarchical and network relationships among criteria and sub-criteria.

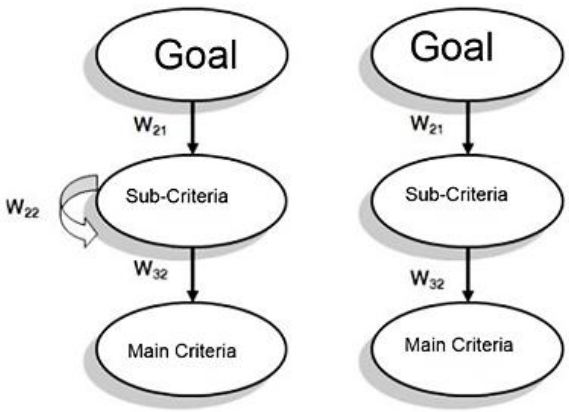


Fig. 1. Hierarchical and network structure of the ANP model.

4 | Results and Analysis

4.1 | Main Criteria Ranking

The fuzzy ANP analysis of main criteria yielded the weights shown in *Table 5* [5], [19]. The pairwise comparison matrix was calculated using the possibility degree formula [29].

Table 5. Main criteria weights and ranking.

Risk Category	Weight	Rank
Employer-related risks (B)	0.27	1
Accident-related risks (D)	0.23	2
Machinery-related risks (E)	0.18	3
Contractor-related risks (A)	0.16	4
Consultant-related risks (C)	0.14	5

Fig 2 illustrates the prioritization of main risk categories [18].

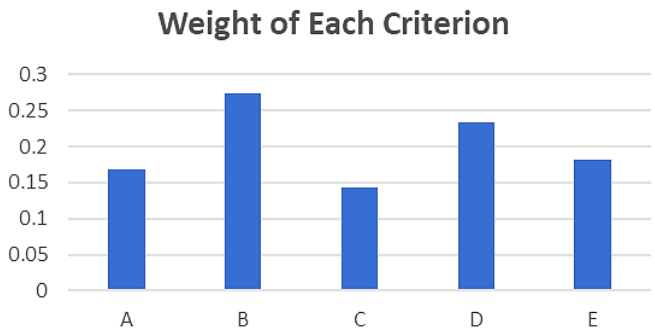


Fig. 2. Prioritization of main risk categories.

The results indicate that employer-related risks are the most critical category, followed by accident-related risks, machinery-related risks, contractor-related risks, and consultant-related risks. This finding aligns with previous research by Jafarian et al. [23] who identified political risk as the most influential variable in Iranian PPP road projects.

4.2 | Sub-Criteria Ranking

The fuzzy ANP analysis of sub-criteria yielded the weights shown in *Table 6* [25], [18].

Table 6. Sub-criteria weights and ranking.

Sub-Criteria	Weight	Rank
Lack of access to skilled and expert personnel (C2)	0.120	1
Lack of project planning and time control (C5)	0.115	2
Delayed provision of financial resources (C3)	0.115	3
Worker injury during activities (C8)	0.099	4
Rainfall and freezing after pavement layer testing (C9)	0.097	5
Failure to utilize expert and experienced personnel (C6)	0.096	6
Natural disasters (C7)	0.089	7
Failure to perform work optimally with maximum quality (C1)	0.086	8
Repair and maintenance costs of machinery (C10)	0.077	9

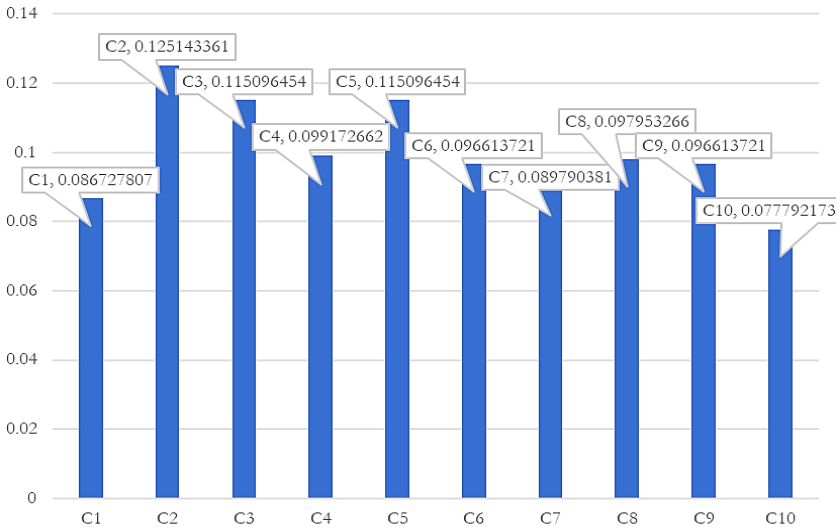


Fig 3. Sub-criteria weights.

The results reveal that lack of access to skilled and expert personnel is the most critical sub-criterion, consistent with findings by Dixit et al. [8] who identified maintaining good worker quality as having the highest impact globally in the construction sector, and Perera et al. [3] who emphasized the importance of human resource management in road construction. Planning and time control risks, along with delayed financial provisions, rank second and third, reflecting common challenges in Iranian infrastructure projects [6], [13].

4.3 | Discussion of Findings

The findings of this study are consistent with several previous investigations. The primary importance of employer-related risks aligns with Jafarian et al. [23] findings on political risk as the most influential variable in Iranian PPP road projects. The high ranking of financial risks corresponds to findings by Rezaee Arjroody et al. [25] who identified inflation and late financial provisions as critical risks in Iranian road projects.

The critical nature of human resource risks, specifically lack of access to skilled personnel, reflects broader challenges in the construction industry. Dixit et al. [8] global study identified that maintaining quality of workers has the highest impact in the construction sector worldwide, with client-related, subcontractor, financial, contractor, and government risk categories being common across contexts. Perera et al. [11] similarly emphasized the importance of proper risk allocation in contracts, noting that parties without allocated risks also bear consequences of such risks.

The ranking of accident-related risks, particularly worker injury and natural disasters, emphasizes the importance of safety management and environmental considerations in road construction. Odumade et al. [14] study on Nigerian road construction similarly highlighted the significance of risk assessment techniques aligned with sustainable development practices. Alamgir et al. [1] cautioned that poor planning or implementation of road projects in tropical regions could lead to heavy costs, corruption, and environmental impacts.

The relatively lower ranking of machinery-related risks suggests that while equipment issues are relevant, they are perceived as more manageable compared to human and financial risks. This finding is supported by research by El-Sayegh and Mansour [9] who identified that proper equipment management, though important, is often less critical than contractual and financial risks in construction projects. Ganapthy et al. [15] specifically addressed machinery and equipment risks in road construction, proposing technological solutions for safety improvement.

The results also support the findings of Taherian Amiri et al. [13] who emphasized the importance of considering uncertainty and risk in linear-repetitive road construction projects using critical chain methods.

The effectiveness of fuzzy approaches for risk assessment in construction, as demonstrated by Sohrabinejad and Rahimi [21] and Guo et al. [22], is confirmed by this study's successful application of fuzzy ANP.

5 | Conclusion and Recommendations

5.1 | Summary of Findings

This research aimed to investigate factors affecting risk management and reliability in road construction projects through a case study of Tonkabon city. Using fuzzy ANP methodology [5], [19], five main risk categories and ten sub-criteria were prioritized based on expert judgments [2], [3], [12]. The main findings are [18], [25]:

I. Employer-related risks are the most critical category (0.27), emphasizing the importance of client management, timely payment, and proper project planning [23].

II. Accident-related risks rank second (0.23), highlighting the need for robust safety protocols and environmental risk management [1], [14].

III. Machinery-related risks rank third (0.18), followed by contractor-related risks (0.16) and consultant-related risks (0.14) [9], [15].

IV. Among sub-criteria, lack of access to skilled and expert personnel is the most critical risk, followed by lack of planning and time control and delayed financial provisions [8], [11].

V. Worker injury, adverse weather conditions, and natural disasters also rank highly, emphasizing the multi-dimensional nature of risks in road construction [13], [17].

5.2 | Comparison with Previous Studies

The emphasis on human resource risks corresponds to Dixit et al.'s [8] global study identifying worker quality as having the highest impact and Perera et al.'s [3] emphasis on human resource management in road construction.

The ranking of financial risks is consistent with Rezaee Arjroody et al.'s [25] identification of inflation and delayed financial provisions as critical risks and Taherian Amiri et al.'s [13] findings on the importance of considering uncertainty in road construction projects. The recognition of accident-related risks aligns with Odumade et al.'s [14] findings on sustainable risk management and Alamgir et al.'s [1] work on environmental risks of road development.

However, the relatively higher ranking of accident-related risks in this study compared to some previous research may reflect the specific geographical and climatic conditions of the Tonkabon region, which is mountainous and prone to weather-related challenges.

6 | Conclusion

This study was conducted with the aim of investigating the factors affecting risk management and reliability in road construction projects in Tonkabon city. Using the Fuzzy Analytic Network Process (Fuzzy ANP) methodology and the opinions of 10 experts in the field of road construction, five main risk categories including employer-related risks, accident-related risks, machinery-related risks, contractor-related risks, and consultant-related risks were evaluated and prioritized. The results showed that employer-related risks with a weight of 0.27 rank first, followed by accident-related risks (0.23), machinery-related risks (0.18), contractor-related risks (0.16), and consultant-related risks (0.14) in subsequent ranks. At the sub-criteria level, "lack of access to skilled and expert personnel" with a weight of 0.120 was identified as the most critical risk factor, followed by "lack of project planning and time control" and "delayed provision of financial resources" with weights of 0.115 ranking second and third, respectively.

The findings of this research are consistent with previous studies including those by Jafarian et al. [23], Dixit et al. [8], and Perera et al. [11], indicating that management of skilled human resources, precise time planning, and timely provision of financial resources are the most fundamental factors in the success of road construction projects.

Therefore, it is recommended that road administrations take effective steps toward reducing risks and increasing reliability in road construction projects by utilizing skilled and experienced personnel, selecting capable contractors, implementing integrated planning, performing periodic machinery maintenance, and employing HSE specialists in projects, thereby preventing additional costs, time delays, and reduced quality of project implementation.

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Author Contributions

Nasser Pourgholam was responsible for conceptualization, methodology, investigation, data collection, formal analysis, application of the fuzzy ANP method, interpretation of results, and writing – original draft, review, and editing. The author reviewed and approved the final version of the manuscript.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflict of interest.

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