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Intelligent Assessment of Construction Safety Risks in Civil Engineering Based on AHP-Fuzzy Algorithm

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Abstract: *To address the complexities, fuzziness, and dynamics of safety risks in civil engineering construction—along with the subjectivity, low accuracy, and difficulty in quantifying fuzzy indicators of traditional assessment methods—this study conducts an intelligent evaluation research based on the AHP-fuzzy algorithm. First, construction risks across the entire process are identified through literature research, expert interviews, and on-site investigations. Combining ISO 45001 standards, a three-tiered evaluation system is established, encompassing four criterion layers (personnel, equipment, environment, and management) and 14 core indicators. Screening and optimization are completed via expert scoring and Pearson correlation analysis. Second, an intelligent model is constructed by integrating AHP and the fuzzy algorithm. Indicator weights are determined and consistency tested through AHP, with deviations corrected using the entropy weight method. A trapezoidal membership function is developed via the fuzzy algorithm to quantify qualitative indicators, and risk levels are assessed using the weighted average method. A visualization system is implemented in Python. Finally, case studies demonstrate that the model's evaluation results align closely with on-site realities, with errors ≤5%, enabling precise risk point identification and providing a basis for safety management. This enriches relevant theoretical methods and holds significant theoretical and practical value.*

Keywords: *Civil Engineering; Construction Safety Risks; Analytic Hierarchy Process; Fuzzy Algorithm*

1. Introduction

Civil engineering construction is characterized by complex procedures, variable working environments, and intertwined risk factors, making it a high-risk field for workplace accidents. According to International Labour Organization data, the fatality rate in the construction industry is 2.7 times the global average. In China, the number of fatalities in construction accidents reached 12,000 in 2022, with direct economic losses exceeding 200 billion yuan. Falls from height, struck-by incidents, and collapses are the primary accident types, posing severe threats to human life, property safety, and the sustainable development of the industry. As China's urbanization accelerates, the investment in civil engineering reached 18 trillion yuan in 2023. The expansion of project scale and the increasing complexity of construction techniques further intensify the challenges of safety risk management, making the establishment of a scientific and efficient safety risk assessment system an urgent industry need.

Current safety risk assessments in civil engineering construction primarily rely on traditional methods, which exhibit significant limitations: qualitative assessment methods are highly subjective and lack quantitative support, while quantitative methods struggle to balance the fuzziness and interdependence of risk factors, making precise evaluations in complex scenarios difficult. Although the Analytic Hierarchy Process (AHP) can allocate hierarchical weights to multiple factors, it faces challenges in consistency testing and judgment deviations when handling fuzzy uncertain information. The fuzzy comprehensive evaluation method effectively addresses qualitative fuzzy indicators but struggles to reasonably determine the priority weights of individual risk factors.

The AHP-fuzzy algorithm effectively addresses the limitations of single methods by combining the hierarchical decision-making advantages of AHP with the fuzzy information processing capabilities of fuzzy algorithms, achieving an organic integration of qualitative and quantitative analysis[1]. In accordance with the mandatory implementation requirements of the ISO 45001 standard by 2026, constructing an intelligent evaluation model based on this algorithm enables precise identification of risk factors throughout the construction process and quantification of risk levels, providing a scientific basis for risk warning and prevention. This promotes the transformation of safety governance from "response during and after incidents" to "proactive prevention across the entire lifecycle".

Based on the aforementioned background, this paper introduces the AHP-fuzzy algorithm to establish an intelligent assessment system for construction safety risks in civil engineering. It clarifies the risk assessment indicator system, determines the weights of each indicator through AHP, and achieves quantitative risk level assessment by combining the fuzzy algorithm. This addresses the insufficient accuracy of traditional assessment methods, providing theoretical support and practical references for the management of construction safety risks in civil engineering, thereby contributing to the high-quality development of the construction industry.

2. Relevant theoretical foundations

2.1 Theories related to safety risks in civil engineering construction

Construction safety risks in civil engineering refer to the possibility and potential losses caused by various uncertain factors such as personnel operations, environmental conditions, technical processes, and management systems throughout the entire construction process, resulting in casualties, property losses, project delays, or environmental damage to construction personnel. Its core characteristics are reflected in complexity, fuzziness, and dynamism: complexity arises from the intersection of construction processes, the diversity of participating parties, and the interweaving and strong correlation of risk factors; Ambiguity manifests as the difficulty in accurately quantifying most risk factors, such as personnel safety awareness and the severity of the working environment, which are qualitative fuzzy indicators; Dynamicity refers to the constant changes in risk factors as the construction phase progresses, such as the main risk of collapse during the foundation construction phase and the core risk of falling from heights during the main structure construction phase.

Risk assessment follows the core logic of "identification analysis evaluation prevention and control", combined with the requirements of ISO 45001 occupational health and safety management system. The safety risk assessment of civil engineering construction should cover the entire stages of construction preparation, construction implementation, and completion acceptance, clarify the scope of risk identification, classify risk levels, and provide scientific basis for the formulation of subsequent prevention and control measures. At present, risk levels are usually divided into four levels: major risk, major risk, general risk, and low risk. Evaluation criteria are constructed based on the probability of risk occurrence and the degree of loss, which is the basis for subsequent quantitative evaluation using AHP fuzzy algorithm.

2.2 AHP algorithm related theories

Analytic Hierarchy Process (AHP) is a multi criteria decision-making method proposed by American operations researcher Satty in 1977 [2]. Its core idea is to decompose complex decision-making problems into ordered hierarchical structures, and determine the weight and priority of each evaluation indicator through a combination of qualitative judgment and quantitative calculation. The core steps of this algorithm include hierarchical construction, judgment matrix construction, consistency verification, and weight calculation [3].

Firstly, take the evaluation objectives as the objective layer, the evaluation indicators as the criterion layer, and the specific influencing factors as the scheme layer, to construct a three-level hierarchical structure; Secondly, by comparing the importance of each indicator pairwise, a judgment matrix is constructed using a 1-9 scale method to quantify the relative importance between indicators; Again, by calculating the maximum eigenvalue and eigenvector of the judgment matrix, a consistency check is performed to ensure the rationality of the judgment logic (when the consistency index $CI<0.1$, the judgment matrix meets the consistency requirement); Finally, by normalizing the feature vectors, the weight values of each indicator are obtained. The advantage of the AHP algorithm lies in its ability to convert qualitative judgments into quantitative weights, solving the problem of weight allocation in multi factor decision-making. However, its limitation lies in its difficulty in handling fuzzy and uncertain information, and its susceptibility to subjective judgment bias.

2.3 Fuzzy algorithm related theories

Fuzzy algorithm is based on fuzzy mathematics theory and was proposed by Zadeh in 1965. Its core is to use tools such as fuzzy sets and membership functions to handle fuzzy problems that are difficult to quantify accurately in reality, and to transform qualitative descriptions into computable quantitative indicators [4]. The core principle is to break the rigid logic of "either or" in classical sets, introduce the concept of membership degree, and use numerical values within the [0,1] interval to represent the degree to which the research object belongs to a certain set, achieving quantitative processing of fuzzy information.

In the safety risk assessment of civil engineering construction, fuzzy algorithms are mainly used to handle qualitative risk indicators (such as the safety literacy of operators, the integrity of construction equipment, etc.). By constructing a membership function, the qualitative evaluation level (such as "good", "good", "average", "poor", "poor") is converted into corresponding membership values, and then a fuzzy evaluation matrix is constructed. The commonly used membership functions include triangular membership functions, trapezoidal membership functions, etc. Among them, trapezoidal membership functions are the most widely used in safety risk assessment due to their simple calculation and practical application in engineering. The advantage of fuzzy algorithms lies in their ability to accurately handle fuzzy uncertain information, but when used alone, it is difficult to reasonably determine the weights of each indicator, which can easily lead to bias in the evaluation results.

2.4 Fusion principle of AHP fuzzy algorithm

The fusion core of AHP fuzzy algorithm is to complement the limitations of a single algorithm and achieve the organic unity of "precise weight allocation" and "quantitative fuzzy information". Its fusion logic is in line with the core requirements of civil engineering construction safety risk assessment. The specific fusion principle is based on the AHP algorithm, which determines the weight priority of each construction safety risk indicator through hierarchical construction and weight calculation, and solves the problem of unreasonable weight allocation in fuzzy algorithms; By supplementing with fuzzy algorithms and using membership functions and fuzzy evaluation matrices, we can handle fuzzy uncertain indicators that are difficult for AHP algorithms to handle, and achieve quantitative transformation of qualitative indicators[5].

The fusion process mainly consists of three steps: firstly, constructing a risk assessment hierarchy structure through the AHP algorithm, calculating the weights of each indicator, and ensuring the rationality of weight allocation through consistency testing; Secondly, the membership functions of each indicator are constructed through fuzzy algorithms, and the fuzzy evaluation matrix of each indicator is determined by combining expert evaluation methods; The third step is to multiply the weights of the indicators calculated by AHP with the fuzzy evaluation matrix to obtain a comprehensive evaluation result, and then determine the construction safety risk level. This fusion algorithm not only retains the hierarchical decision-making advantage of AHP algorithm, but also leverages the fuzzy information processing capability of fuzzy algorithm, effectively solving the problems of strong subjectivity and insufficient accuracy of traditional evaluation methods, and providing reliable theoretical support for intelligent assessment of safety risks in civil engineering construction.

3. Identification of safety risks in civil engineering construction and construction of indicator system

3.1 Identification of construction safety risks

The identification of safety risks in civil engineering construction is a prerequisite for assessment work. The core is to comprehensively and systematically sort out various uncertain factors that may cause safety accidents in the entire construction process, following the principles of comprehensiveness, systematicity, pertinence, and dynamism, ensuring no omissions or redundancies. Based on the actual engineering situation, a combination of literature research method, expert interview method, and on-site research method is used to carry out risk identification, covering the entire stages of construction preparation, foundation construction, main structure construction, decoration and completion acceptance.

According to system identification, the safety risks in civil engineering construction are mainly divided into four categories: personnel risks, including weak safety awareness of operators, non-standard operations, insufficient professional skills, and inadequate supervision by management personnel; Equipment risks, including aging of construction machinery, untimely maintenance of equipment, and failure to test special equipment according to specifications; Environmental risks, including high temperature, rainstorm, typhoon and other severe weather, as well as complex geological conditions and insufficient lighting and ventilation at the construction site; Managing risks, including incomplete safety management systems, inadequate safety training, lack of emergency plans, and unclear risk control responsibilities, lays the foundation for the construction of subsequent indicator systems.

3.2 Construction of risk assessment indicator system

Based on the results of risk identification, combined with the ISO 45001 occupational health and safety management system standard, following the principles of scientificity, systematicity, operability, and quantitative and qualitative combination, a three-level civil engineering construction safety risk assessment index system is constructed. The target layer is the comprehensive assessment of safety risks in civil engineering construction; The standard layer corresponds to four major types of risks, namely personnel risk, equipment risk, environmental risk, and management risk; The indicator layer consists of specific risk influencing factors, and a total of 16 core indicators have been selected.

Among them, the personnel risk indicators include three items: the safety training rate of operators, the certification rate of special operation personnel, and the frequency of supervision by management personnel; The equipment risk indicators include three items: the intact rate of construction equipment, the qualified rate of special equipment testing, and the equipment maintenance cycle; The environmental risk indicators include the response rate of severe weather warnings, geological stability of construction sites, and the compliance rate of lighting and ventilation in the working environment; The risk management indicators include 7 items, such as the completeness of the safety management system, the feasibility of the safety emergency plan, and the implementation of risk control responsibilities, forming a clear and comprehensive indicator system that provides support for subsequent quantitative evaluations.

3.3 Indicator screening and optimization

To avoid redundant indicators and improve evaluation efficiency, a combination of expert scoring method and correlation analysis is used to screen and optimize the initially constructed indicator system. Ten experts in the field of civil engineering safety management (including 3 professors, 4 senior engineers, and 3 frontline safety managers) are invited to score the importance of each indicator using a 5-point scale, and indicators with scores lower than 3 points are excluded. Meanwhile, through Pearson correlation analysis, redundant indicators with correlation coefficients greater than 0.85 are removed to avoid information overlap between indicators.

After optimization, the final 14 core indicators were determined, and the redundant indicators of "equipment maintenance cycle" and "work environment lighting and ventilation compliance rate" were deleted to ensure the independence and representativeness of each indicator. At the same time, based on the actual engineering situation, the connotation of the indicators is clearly defined, evaluation standards for each indicator are formulated, the specific value range of quantitative indicators is clarified, and the evaluation level of qualitative indicators is clarified, taking into account the operability and scientificity of the indicators. This provides a standardized and unified evaluation basis for the subsequent application of AHP fuzzy algorithm, ensuring accurate and reliable evaluation results.

4. Construction safety risk intelligent assessment model based on AHP fuzzy algorithm

4.1 Overall framework design of the model

Based on the previous indicator system and AHP fuzzy fusion principle, following the core logic of "data input weight calculation fuzzy evaluation result output intelligent optimization", the overall framework of the civil engineering construction safety risk intelligent assessment model is designed, which is divided into four layers: data layer, algorithm layer, evaluation layer, and application layer. The data layer is responsible for inputting the raw data of 14 optimized core indicators, covering the measured values of quantitative indicators and the expert evaluation results of qualitative indicators; The algorithm layer integrates AHP algorithm and fuzzy algorithm to achieve weight calculation and fuzzy information quantification; The evaluation layer completes the comprehensive risk level determination and outputs the evaluation results; The application layer realizes the visualization of evaluation results and risk warning, supporting construction safety control decisions. The framework design balances scientificity and operability, achieving intelligent and standardized risk assessment, effectively avoiding the subjectivity and lag of traditional assessments.

4.2 Calculation of indicator weights based on AHP

Based on the optimized three-level indicator system, the AHP algorithm is used to calculate the weights of each indicator, strictly following the four step process of hierarchical construction, judgment matrix construction, consistency testing, and weight calculation. Using 14 indicators from the criteria layer (personnel, equipment, environment, management risk) and indicator layer as the core, 10 domain experts were invited to use a 1-9 scale method to compare the relative importance of each indicator pairwise, and construct a two-level judgment matrix of target layer criteria layer and criterion layer indicator layer. This study uses MATLAB software to calculate the maximum eigenvalue and eigenvector of the judgment matrix and conducts consistency checks. If the consistency index (CI) is greater than or equal to 0.1, the judgment matrix is revised repeatedly until the consistency requirements are satisfied. After normalization, the weights of each criterion layer and indicator layer were obtained, among which the weights of management risk and personnel risk accounted for the highest proportion, at 0.382 and 0.295 respectively, which is in line with the characteristics of management deficiency and improper personnel operation as the main risk factors in engineering practice.

4.3 Comprehensive evaluation based on fuzzy algorithm

Fuzzy comprehensive evaluation is based on the weight of indicators calculated by AHP, and its core is to complete the quantification of qualitative indicators and the determination of comprehensive risk levels. Firstly, construct a 5-level evaluation set (V={excellent, good, average, poor, extremely poor}), corresponding to risk levels (low risk, average risk, high risk, major risk, extremely high risk); Secondly, using a trapezoidal membership function and combining various indicator evaluation criteria, the measured values of quantitative indicators and the expert evaluation results of qualitative indicators are converted into membership values, and a fuzzy evaluation matrix is constructed; Finally, the weight vector of the indicators is combined with the fuzzy evaluation matrix, and the weighted average method is used to calculate the comprehensive membership degree. The final risk level is determined based on the principle of maximum membership degree, achieving accurate quantification of fuzzy information and scientific determination of risk level.

4.4 Model optimization and intelligent implementation

To improve the accuracy and practicality of the model evaluation, a dual optimization of the model is carried out: firstly, the entropy weight method is introduced to modify the AHP weights, reduce the subjective judgment bias of experts, and calculate the objective weights of indicators through the entropy weight method, which are weighted and fused with the subjective weights of AHP (subjective weight accounts for 0.7, objective weight accounts for 0.3); The second is to optimize the parameters of the membership function, calibrate the trapezoidal membership function interval based on engineering case data, and improve the accuracy of fuzzy evaluation. In terms of intelligent implementation, a visualization evaluation system based on Python language is developed, integrating functions such as data input, weight calculation, fuzzy evaluation, and result output. It supports batch import and real-time update of indicator data, automatically generates evaluation reports and risk warning prompts, realizes dynamic and intelligent evaluation of construction safety risks, provides efficient and convenient technical support for on-site safety control, and ensures that evaluation results can be implemented and applied.

5. Example verification and analysis

5.1 Overview of example projects

To verify the feasibility and practicality of the AHP fuzzy algorithm civil engineering construction safety risk intelligent assessment model constructed earlier, a new residential engineering project in a certain city was selected as an example project. The project is located in the core urban area of the city, with a total construction area of 86000 square meters, 28 floors above ground and 2 floors underground. The structural type is reinforced concrete frame shear wall structure, with a construction cost of about 320 million yuan and a construction period of 24 months, covering multiple construction stages such as foundation engineering, main structure engineering, decoration and renovation engineering, and supporting municipal engineering. The project construction site is narrow, adjacent to residential areas and urban main roads, and the construction environment is complex; There are a total of 120 on-site workers, including 32 special workers involved in high-risk operations such as crane operation and high-altitude work; During the construction process, more than 40 sets of various construction equipment such as tower cranes, construction elevators, and concrete transfer pumps are required. The equipment operates with high intensity and is difficult to control safely. The construction characteristics and risk distribution of this project have typical civil engineering representativeness, which can comprehensively test and evaluate the applicability of the model, and provide practical support for the promotion and application of the model.

5.2 Instance data collection and processing

The data collection follows the principles of comprehensiveness, authenticity, and pertinence, combined with the actual construction of example projects, using various methods such as on-site measurement, data review, expert evaluation, equipment testing, etc., to collect the original data of 14 optimized core risk indicators. Quantitative indicator data is mainly obtained through on-site measurement and data verification, such as the safety training rate of operators, the certification rate of special operation personnel, etc., which are determined by verifying training records and certification files. The integrity rate of construction equipment is obtained through on-site equipment testing, and the response rate of severe weather warnings is calculated by consulting meteorological warning records and on-site response ledgers; Qualitative indicator data was obtained using expert evaluation method. Five project safety management managers, three professors in the field of civil engineering safety, and two senior engineers were invited to score qualitative indicators such as the completeness of the safety management system and the feasibility of emergency plans on a 5-point scale. The average value was taken as the raw data for the indicators.

In the data processing stage, the collected raw data is first subjected to outlier removal, using the 3 σ principle to remove outlier data that exceeds the normal range, ensuring the authenticity of the data; Secondly, the quantitative indicators are standardized by using the range normalization method to convert quantitative indicators of different dimensions into standardized data within the [0,1] interval, eliminating the influence of dimensionality; Finally, a consistency test was conducted on the qualitative indicator scoring results, using Kendall's harmony coefficient test method. The calculated harmony coefficient W was 0.82, $P<0.05$, indicating that the expert evaluation results have good consistency and can be used for subsequent fuzzy evaluation analysis. The processed standardized data and expert evaluation results are used as input data for the evaluation model to ensure the accuracy and reliability of the model application.

5.3 Model application and result analysis

Input the processed instance engineering data into the AHP fuzzy intelligent evaluation model constructed earlier, and complete the risk assessment according to the model operation process. Firstly, call the AHP weight calculation module in the model, substitute the instance engineering indicator data, re verify the consistency of the judgment matrix, and calculate the criterion layer weights: management risk 0.378, personnel risk 0.292, equipment risk 0.185, environmental risk 0.145, which are basically consistent with the weight distribution mentioned earlier. The consistency test $CI=0.072<0.1$, meeting the consistency requirements; Secondly, through the fuzzy evaluation module, an optimized trapezoidal membership function is used to convert standardized data and expert evaluation results into membership values, and a fuzzy evaluation matrix of 14 indicators is constructed; Finally, through matrix synthesis operation, the comprehensive membership vector is obtained as [0.12, 0.35, 0.41, 0.09, 0.03]. According to the principle of maximum membership, the construction safety risk level of the example project is "general risk", which is consistent with the actual safety control situation on the project site.

The result analysis shows that the model can accurately identify the main risk points of the instance project: inadequate safety training in risk management, incomplete implementation of risk control responsibilities, and non-standard operation of special operators in personnel risk are the main risk factors, which are consistent with the problems found in on-site research; Meanwhile, compared with traditional evaluation methods (expert scoring method), the error control of the model evaluation results is within 5%, indicating that the model has high evaluation accuracy. In addition, the model outputs an evaluation report through a visualization system, clarifying the risk level and improvement priority of each risk indicator, providing accurate decision-making basis for the safety control of the example project, and verifying the feasibility and practicality of the model.

5.4 Model improvement suggestions

Based on the results of instance verification and combined with practical engineering application scenarios, the following improvement suggestions are proposed to address the shortcomings of the model and further enhance its applicability and accuracy. One is to optimize the weight calculation system. The current model adopts the weighted fusion of AHP and entropy weight method to determine the weights. Bayesian theory can be introduced to dynamically update the indicator weights by combining historical engineering data and real-time construction data, reducing subjective judgment bias and improving the scientificity of weight allocation; The second is to improve the adaptability of the membership function, optimize the interval parameters of the trapezoidal membership function according to the construction characteristics of different types of civil engineering (such as residential engineering, municipal engineering, bridge engineering), construct a membership function library for classification adaptation, and expand the application scope of the model.

The third is to strengthen the intelligence level of data collection. Currently, data collection still relies on manual measurement and expert evaluation. IoT technology can be introduced to deploy sensors, video surveillance and other equipment on construction sites to achieve real-time collection and automatic upload of indicators such as construction personnel operation, equipment operation, environmental parameters, etc., reducing manual intervention and improving the efficiency and accuracy of data collection; The fourth is to supplement the risk warning function by setting warning thresholds for different risk levels based on the risk assessment results of example projects. When the indicator data exceeds the threshold, automatic warning prompts will be triggered and targeted prevention and control measures will be pushed to achieve early prediction and active prevention and control of risks. Through the above improvements, the functionality of the evaluation model can be further improved, enhancing its application value in civil engineering construction safety risk control, and providing stronger technical support for the high-quality development of the construction industry's safety.

6. Conclusion

This article focuses on the practical needs of safety risk control in civil engineering construction. In response to the pain points of strong subjectivity, insufficient accuracy, and difficulty in handling fuzzy and uncertain information in traditional evaluation methods, intelligent evaluation research based on AHP fuzzy algorithm is carried out. Through theoretical analysis, indicator construction, model design, and case verification, the following core conclusions are formed. The research system identified safety risks throughout the entire process of civil engineering construction and constructed a three-level evaluation index system covering four criteria layers: personnel, equipment, environment, and management, with 14 core indicators. After screening and optimization, the indicators have good independence and representativeness, providing a standardized basis for risk quantification assessment.

Based on the fusion principle of AHP and fuzzy algorithm, an intelligent assessment model for construction safety risks in civil engineering was constructed. The weights of various indicators were accurately determined by AHP algorithm, and qualitative indicators were quantified by combining fuzzy algorithm. Entropy weight method was introduced to correct weight deviation, optimize membership function parameters, and improve the accuracy of model evaluation; A visualization system developed based on Python has achieved intelligent evaluation process and result visualization, solving the problems of low efficiency and cumbersome operation in traditional evaluations.

The example verification shows that the evaluation results of the model are highly consistent with the actual safety conditions on the engineering site, with an evaluation error controlled within 5%. It can accurately identify the main risk points and provide precise decision-making support for safety control, verifying the feasibility and practicality of the model. Meanwhile, this article objectively analyzes the shortcomings of the model and proposes improvement directions such as dynamic weight updating and membership function classification adaptation.

This study enriches the theory and methods of safety risk assessment in civil engineering construction, provides a new technological path for safety control in the construction industry, and helps to transform construction safety governance from passive response to active prevention and control. It has important theoretical value and practical significance for promoting high-quality development of the construction industry.

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