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An Integrated Neutrosophic Group BWM-FMEA Approach for OHS Risk Assessment in Sustainable Construction Projects

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ABSTRACT

The expansion of the sustainable development concept in construction projects, coupled with the construction industry's high rates of safety accidents and job losses, underscores the critical need for effective Occupational Health and Safety (OHS) risk assessment in sustainable construction projects (SCPs). Poor safety performance, resulting from the lack of efficient and accurate risk assessment mechanisms, can reduce employee productivity and increase project cost and duration. Existing studies often overlook the integration of sustainability and health, safety, and environmental (HSE) dimensions with quantitative risk assessment under expert uncertainty. To address this gap, this research develops a hybrid Neutrosophic Group Best-Worst Method and Failure Modes and Effects Analysis (NG-BWM–NG-FMEA), incorporating expert weighting to quantify and prioritize OHS risks in Iran's SCPs. Thirteen experts participated via a focus group discussion. Key findings indicate that the top-ranked risks are: (1) insufficient employee safety skills due to inadequate training, (2) hazards from flawed design and site layout, and (3) occupational injuries and illnesses. The study proposes both reactive and preventive strategies to mitigate these and other prominent risks.

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1. Introduction

The construction industry involves collaboration among numerous specialized groups to complete complex tasks (Mohandes & Zhang, 2021). The construction phase is inherently dynamic, encompassing material handling, workforce management, equipment operation, and transportation. These activities not only generate significant environmental impacts but also pose critical occupational health and safety (OHS) challenges, particularly in large-scale projects. With the expansion of industrialized construction practices in developing countries, there is an urgent need for robust risk assessment and management strategies that integrate sustainability considerations with operational safety (Malik et al., 2019). Despite the increasing emphasis on sustainable construction, most existing studies primarily focus on economic and environmental dimensions, often neglecting the social and OHS aspects, particularly under uncertainty (Pangemanan et al., 2023; Chen & Reniers, 2020). Work-related accidents and illnesses remain prevalent, causing substantial financial losses, human suffering, and project delays globally (Dabbagh & Yousefi, 2019; Kim et al., 2019).

In Iran, the construction sector has witnessed significant growth in design and implementation in recent years. Statistics reveal that work-related accidents are the second leading cause of death in Iran, after traffic accidents, posing major health, social, and economic challenges. Improving occupational health and safety (OHS) in this high-risk industry remains a national priority. Lack of attention to safety measures and inadequate recognition of workplace risks, especially in large-scale construction projects, has led to irreparable harm and substantial costs for organizations (Ardeshir et al., 2018). Developing and implementing robust safety risk assessment methods is critical to minimizing financial and human costs in this sector. Risk assessment and management serve as foundational tools for identifying health, safety, and environmental (HSE) risks, enabling projects to pinpoint critical areas and classify them by risk levels. Researchers have increasingly focused on safety risk assessment in construction projects, recognizing its importance in improving worker safety (Mohandes & Zhang, 2021; (Gunduz & Laitinen, 2018; Karakhan & Gambatese, 2017; Bai & Zhao, 2021; Alipour-Bashary et al., 2021; El-Sayegh et al., 2021; Jeong et al., 2022).

While risk management is not a novel concept, recent research highlights its application in construction safety within the context of sustainable development. Previous studies have primarily categorized safety risks within HSE dimensions, neglecting other aspects. This study combines three sustainability dimensions (economic, social, and environmental) with HSE dimensions to provide a comprehensive framework for organizing safety risks in construction projects. This integration allows the evaluation of SCP risks not only from a sustainability perspective but also in terms of operational safety, workforce health, and project management effectiveness. The hybrid framework thus ensures a holistic approach to risk identification and prioritization in sustainable construction projects. Besides, Previous research on OHS risk assessment in construction projects has largely concentrated on descriptive risk categorization, lacking quantitative prioritization and comprehensive integration with sustainability principles. Furthermore, conventional methods often fail to accommodate expert judgment uncertainty, which is critical when addressing complex, multi-dimensional risks in sustainable construction projects (SCPs). To address these gaps, this study introduces a novel hybrid framework that integrates the three pillars of sustainability (economic, social, and environmental) with operational OHS/HSE dimensions (Health, Safety, Managerial & Structural) using Neutrosophic Group Best-Worst Method and Failure Modes and Effects Analysis (NG-BWM–NG-FMEA). This approach enables systematic weighting and prioritization of OHS risks while explicitly accounting for uncertainty in expert opinions. By combining sustainability and OHS dimensions with neutrosophic MCDM, the study provides a holistic and methodologically rigorous framework for risk assessment in SCPs, advancing both theoretical understanding and practical applications.

The subsequent sections of this study explore the theoretical foundations of OHS in SCPs and risk management approaches. Following this, the research methodology and proposed framework are detailed. Materials and methods used for data analysis are introduced, and the framework is validated through its implementation in managing OHS risks in Iran's SCPs, with findings discussed. The study concludes with final thoughts and recommendations. A dedicated section is subsequently devoted to the limitations of the study.

2. Methodology

The current research is applied in terms of purpose and descriptive-survey in terms of nature and strategy. The required data has been collected from 13 project managers and executive officials in Iran's SCPs, who were sampled by snowballing method, using a semi-structured interview protocol and two researcher-made questionnaires. In expert-based multi-criteria decision-making (MCDM) studies, the objective is not statistical generalization but the elicitation of informed judgments from highly experienced professionals. Accordingly, small expert panels (typically between 10–20 experts) are widely accepted. The snowball sampling approach was intentionally adopted to ensure the inclusion of domain experts with direct experience in sustainable construction projects and OHS management in Iran, where access to qualified experts is limited. The assessment of OHS risks in SCPs was done based on the group decision-making approach. Since the experts had different job position, experience, education, and age, their opinions had different degrees of importance. In order to obtain more accurate results in the evaluation, it is necessary to give weight to the opinions. Expert weighting has been applied to mitigate individual bias and enhance the reliability of group judgments. The weights of experts' opinions can be calculated as follows (Guo et al., 2021):

$$\mathrm{WE_k} = \frac{\mathrm{SE_k}}{\sum_{k=1}^{f} \mathrm{SE_k}} \qquad (1)$$

According to this equation, assume there are f experts in the committee, WE_k represents the weight of expert k's opinion and SE_k represents the score of expert k's opinion, which is calculated by summing the scores of job title, experience, and education of the Kth expert. In this regard, Table 1 showed a weighting scale to experts' opinions. In this equation $\sum_{k=1}^{f} \mathrm{WE_k} = 1$ and $0 < \mathrm{WE_k} \leq 1 \quad \forall\, k \in \{0, 1, \ldots, f\}$.

Table 1 A weighting scale to experts' opinions (Guo et al., 2021; Miri Lavasani et al., 2015)

Dimension	Category	Score	Dimension	Category	Score	Dimension	Category	Score
Job title/ organizational position	CEO and board members	5	Experience	More than 30 years	5	Education degree	Doctorate	5
	project manager	4		20 to 29	4		Master's degree	4
	Senior Engineer	3		10 t0 19	3		Bachelor's degree	3
	The expert	2		6 to 9	2		Associate's degree	2
	Technician	1		Less than 6 years	1		High school diploma	1

The validity of the semi-structured interview protocol and questionnaires was initially ensured through face validity, by consulting a panel of university professors and expert committee members, who confirmed the clarity, relevance, and structure of all items. Besides, content validity was qualitatively established by aligning each item with theoretical constructs from the literature and confirming comprehensive coverage of OHS risk dimensions in sustainable construction projects. Reliability was assessed using the Consistency Rate (CR) within the NG-BWM linear programming model, ensuring logical coherence in pairwise comparisons of criteria. CR is widely recognized in MCDM applications as an indicator of consistent expert judgments (Rezaei, 2016). Nevertheless, it primarily addresses consistency rather than traditional psychometric reliability. Overall, the combination of expert-reviewed and content validity and CR-based reliability provides a robust foundation for capturing OHS risks in sustainable construction projects while acknowledging methodological limitations.

In this research, the OHS risks in SCPs are evaluated and analyzed under the neutrosophic environment and the form of group decision-making. In this regard, after identifying the final risks, the developed Neutrosophic Group Failure Modes and Effect Analysis (NG-FMEA) method was used to measure the importance and determine the key risks while applying the Neutrosophic Group Best-Worst Multi-criteria (NG-BWM) method. The group decision-making approach will prevent the bias of the results and increase the accuracy of decision-making by obeying the collective wisdom. The problem of insufficient data and uncertainty in modeling play a significant role in many engineering and management problems (Ardeshir et al., 2018). Neutrosophic logic is adopted in this study as it offers a more comprehensive and realistic representation of uncertainty in OHS risk assessment compared to probabilistic and classical fuzzy approaches. Probabilistic methods require reliable historical data and well-defined probability distributions, which are rarely available in construction projects characterized by dynamic conditions and expert-based qualitative judgments (Aven, 2016). Classical fuzzy set theory models uncertainty through partial membership degrees and is effective in handling vagueness; however, it assumes that uncertainty can be fully captured by a single membership function, thereby overlooking indeterminacy arising from incomplete, conflicting, or unreliable information (Zadeh, 1965). In contrast, neutrosophic logic explicitly incorporates an independent indeterminacy component alongside truth and falsity degrees, allowing expert hesitation, disagreement, and information incompleteness to be modeled without forced precision (Smarandache, 1999).

To implement the mentioned hybrid method, GAMS 24.1.2 mathematical programming software and advanced functions of Excel software were used. In order to achieve the research objectives, the proposed methodological framework is presented in five main phases in Figure 1.

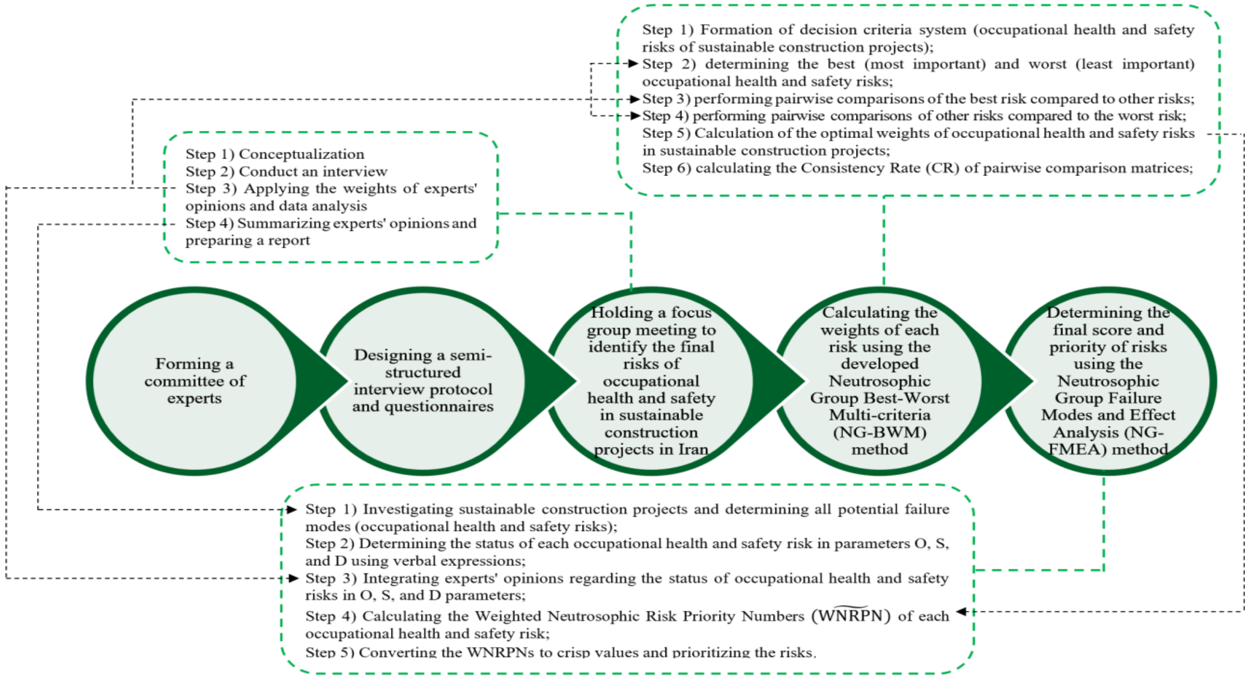

Figure 1 The proposed methodological framework

2.1 NG-BWM method

Rezaei (2016) proposed the Best-Worst Multi-criteria decision-making method. This efficient weighting method requires fewer comparative data, ensures more stable comparisons, and delivers more dependable outcomes. Despite the capabilities of the BWM, it uses crisp values to evaluate comparisons that cannot determine the weights in an uncertain and unknown space. Considering the shortcomings of this method in the face of the uncertainty in expert judgments, in the current research, this method has been developed in the form of a group decision-making approach and under neutrosophic space while applying weight to expert opinions. The NG-BWM method inherits the prominent features of the classic Best-Worst method and can obtain the risk weights with neutrosophic numbers instead of crisp ones. $\tilde{n} = \langle (n_1, n_2, n_3); \alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}} \rangle$ is a single-valued neutrosophic number where n_1, n_2, and n_3 represent the low, middle, and high values of the neutrosophic number, respectively, and $\alpha_{\tilde{n}}$, $\beta_{\tilde{n}}$, and $\theta_{\tilde{n}}$ represent Truth, Indeterminacy, and Falsehood memberships, respectively. These three membership functions are introduced as follows:

- Truth membership $(T_{\tilde{n}}(x))$

$$= \begin{cases} \alpha_{\tilde{n}}\left(\frac{x-n_1}{n_2-n_1}\right) & (n_1 \leq x \leq n_2) \\ \alpha_{\tilde{n}} & (x = n_2) \\ \alpha_{\tilde{n}}\left(\frac{n_3-x}{n_3-n_2}\right) & (n_2 \leq x \leq n_3) \\ 0 & \text{Otherwise} \end{cases} \tag{2}$$

- Indeterminacy membership $(I_{\tilde{n}}(x))$

$$= \begin{cases} \frac{(n_2-x+\beta_{\tilde{n}}(x-n_1))}{(n_2-n_1)} & (n_1 \leq x \leq n_2) \\ \beta_{\tilde{n}} & (x = n_2) \\ \frac{(x-n_2+\beta_{\tilde{n}}(n_3-x))}{(n_3-n_2)} & (n_2 \leq x \leq n_3) \\ 1 & \text{Otherwise} \end{cases} \tag{3}$$

- Falsehood membership $(F_{\tilde{n}}(x))$

$$= \begin{cases} \frac{(n_2-x+\theta_{\tilde{n}}(x-n_1))}{(n_2-n_1)} & (n_1 \leq x \leq n_2) \\ \theta_{\tilde{n}} & (x = n_2) \\ \frac{(x-n_2+\theta_{\tilde{n}}(n_3-x))}{(n_3-n_2)} & (n_2 \leq x \leq n_3) \\ 1 & \text{Otherwise} \end{cases} \tag{4}$$

In these proposed membership functions, the values $\alpha_{\tilde{n}}$, $\beta_{\tilde{n}}$, and $\theta_{\tilde{n}}$ represent the maximum degree of Truth membership, the minimum degree of Indeterminacy membership, and the minimum degree of Falsehood membership, respectively.

The NG-BWM method consists of 6 steps as follows:

Step 1) Formation of decision criteria system (OHS risks in SCPs)

At this step, a set of risks (N) should be created for decision making and analysis.

$$N = \{R_1, R_2, \dots, R_n\} \tag{5}$$

Suppose there are n OHS risks in Iran's SCPs, and the results of pairwise comparisons of these n risks are collected by experts based on verbal variables. After collecting the questionnaires, it is necessary to convert the linguistic judgments of the decision-makers into the corresponding single-valued neutrosophic numbers using Table 2. In this regard, the neutrosophic pairwise comparison matrix is obtained as follows:

$$\tilde{A} = \begin{array}{c|cccc} & R_1 & R_2 & \cdots & R_n \\ \hline R_1 & \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ R_2 & \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ R_n & \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{nn} \end{array} \tag{6}$$

In this matrix, $\tilde{a}_{ij}$ represents the neutrosophic preference of risk i over risk j, which is a single-valued triangular neutrosophic number.

Table 2 Verbal expressions and the corresponding single-valued triangle neutrosophic numbers to explain the priority degree of a pair of risks (Yucesan et al., 2021)

Saaty Scale	Corresponding linguistic expression	Neutrosophic triangular scale	Reciprocal neutrosophic triangular scale
1	Equally Important (EI)	$\langle(1,1,1);\ 0.5,0.5,0.5\rangle$	$\langle(1,1,1);\ 0.5,0.5,0.5\rangle$
2	Sporadic values between EI and SI	$\langle(1,2,3);\ 0.4,0.65,0.6\rangle$	$\langle(0.33,0.5,1);\ 0.4,0.65,0.6\rangle$
3	Slightly Important (SI)	$\langle(2,3,4);\ 0.3,0.75,0.7\rangle$	$\langle(0.25,0.33,0.5);\ 0.3,0.75,0.7\rangle$
4	Sporadic values between SI and STI	$\langle(3,4,5);\ 0.6,0.35,0.4\rangle$	$\langle(0.2,0.25,0.33);\ 0.6,0.35,0.4\rangle$
5	Strongly Important (STI)	$\langle(4,5,6);\ 0.8,0.15,0.2\rangle$	$\langle(0.17,0.2,0.25);\ 0.8,0.15,0.2\rangle$
6	Sporadic values between STI and VSI	$\langle(5,6,7);\ 0.7,0.25,0.3\rangle$	$\langle(0.14,0.17,0.2);\ 0.7,0.25,0.3\rangle$
7	Very Strongly Important (VSI)	$\langle(6,7,8);\ 0.9,0.1,0.1\rangle$	$\langle(0.13,0.14,0.17);\ 0.9,0.1,0.1\rangle$
8	Sporadic values between VTI and AI	$\langle(7,8,9);\ 0.85,0.1,0.15\rangle$	$\langle(0.11,0.13,0.14);\ 0.85,0.1,0.15\rangle$
9	Absolutely Important (AI)	$\langle(9,9,9);\ 1,0,0\rangle$	$\langle(0.11,0.11,0.11);\ 1,0,0\rangle$

Step 2) Determining the most critical OHS risk (denoted as CB) and the least critical OHS risk (denoted as CW)

At this stage, decision-makers (experts) must identify the most critical OHS risk (denoted as CB) and the least critical OHS risk (denoted as CW) based on the decision criteria system.

Step 3) Performing pairwise comparisons of the best risk compared to other risks

According to Table 2, the decision makers determine their opinions regarding the degree of preference of the best risk over others. The resulting vector is shown as $\tilde{A}_B^k = \{\tilde{a}_{B1}^k, \tilde{a}_{B2}^k, \dots, \tilde{a}_{Bn}^k\}$, where $\tilde{a}_{Bj}^k$ is the preference of the best risk B over risk j by expert k. It is clear that $\tilde{a}_{BB} = \{(1,1,1);\ 0.5,0.5,0.5\}$.

After collecting the expert opinions and applying their weights, the vector of cumulative pairwise comparisons for the best risk compared to other risks is obtained based on the weighted average of the expert opinions using the following equations:

$$\tilde{A}_B = \{\tilde{a}_{B1}, \tilde{a}_{B2}, \dots, \tilde{a}_{Bn}\} \tag{7}$$

$$\tilde{a}_{Bj} = \frac{\sum_{k=1}^{f} WE_k * \tilde{a}_{Bj}^k}{\sum_{k=1}^{f} WE_k} = \langle(n_1, n_2, n_3);\ \alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}}\rangle \tag{8}$$

The vector of pairwise comparisons of the best risk compared to other risks (i.e. $\tilde{a}_{Bj}$) is transformed to deterministic value as follows:

$$S(\tilde{a}_{Bj}) = \frac{1}{8}[n_1 + n_2 + n_3] \times (2 + \alpha_{\tilde{n}} - \beta_{\tilde{n}} - \theta_{\tilde{n}}) = a_{Bj} \tag{9}$$

Step 4) Performing pairwise comparisons of other risks compared to the worst risk

In this step, similarly, other risks are compared with the worst one, and after collecting the expert opinions and applying their weights, the vector of cumulative pairwise comparisons for the risks compared to the worst risks is obtained based on the weighted average of the expert opinions and transformed to deterministic values (a_{jw}).

Step 5) Calculation of the optimal weights of OHS risks in SCPs

At this stage, the optimal weights of risks $(W_1^*, W_2^*, \dots, W_n^*)$ and ξ^* are calculated to determine the consistency of the results. To determine the optimal weight of each risk, $\frac{W_B}{W_j} = a_{Bj}$ and $\frac{W_j}{W_W} = a_{jW}$ are formed. Then, to satisfy these conditions for all risks, a solution must be found so that the expressions $\left|\frac{W_B}{W_j} - a_{Bj}\right|$ and $\left|\frac{W_j}{W_W} - a_{jW}\right|$ maximize for all the risks that are minimized. Considering the non-negativity of the weights of the risks and as a result the sum of the weights, the linear form of the mathematical model for calculating the optimal weights can be formulated as Equation (10):

$$\begin{aligned} &\min \xi \\ &\text{S.t.} \\ &|W_B - a_{Bj} W_j| \le \xi * W_j \quad \text{for all j,} \\ &|W_j - a_{jw} W_w| \le \xi * W_w \quad \text{for all j,} \\ &\textstyle\sum_j W_j = 1 \\ &W_j \ge 0, \quad \text{for all j,} \end{aligned} \tag{10}$$

By solving the above model, the optimal values $(W_1^*, W_2^*, \dots, W_n^*)$ and ξ^* are obtained.

Step 6) calculating the Consistency Rate (CR) of pairwise comparison matrices;

To measure the compatibility of experts' opinions, which is equivalent to the reliability of the questionnaire, the Consistency Rate (CR) is calculated. CR is calculated using ξ*. The larger the value of ξ* indicates the higher the consistency rate. Since $a_{Bj} \times a_{jW} = a_{BW}$ and $a_{BW} \in \{1,2,\dots,9\}$, the maximum value of ξ can be obtained. CR is calculated through the values of consistency indices corresponding to a_{BW} in Table 3 and Equation (11).

Table 3 The value of consistency indices in the BWM method (Rezaei, 2016)

a_{BW}	1	2	3	4	5	6	7	8	9
consistency index	0	0/44	1	1/63	2.3	3	3/73	4/47	5/23

$$CR = \frac{\xi^*}{\text{consistency index}} \tag{11}$$

The closer the consistency rate values are to zero, the more consistent the results are.

2.2. Neutrosophic Group Fault Modes and Effects Analysis (NG-FMEA)

FMEA is a tool to identify and assess potential failure modes and associated risks in systems, processes, or products (Haktanir & Kahraman, 2021). Unlike other risk assessment tools, the core philosophy of FMEA emphasizes proactively dealing with problems, rather than finding solutions after failures or risks occur. This method calculates the Risk Priority Numbers (RPNs) for each risk by multiplying three indicators of Occurrence (O), Severity (S), and Detectability (D) to show the criticality level of risks. (Kumru & Kumru, 2013). Many experts and researchers have criticized deterministic RPNs due to their shortcomings. Recently various extensions of fuzzy sets, such as triangular, trapezoidal, intuitionistic, type-2 interval, hesitant, Pythagorean, and Orthopair fuzzy sets have been integrated with the FMEA approach (Xue & Deng, 2020; Lo et al., 2020; Fang et al., 2020). Given the ability of multi-criteria decision-making techniques to guide decision-makers toward accurate evaluations and the strength of FMEA in organizing and assessing risks, combining these approaches in a hybrid framework can yield more precise and dependable outcomes. Given the comprehensiveness of neutrosophic theory by simultaneously considering three membership functions of $(T_{\tilde{n}}(x))$, $(I_{\tilde{n}}(x))$, and $(F_{\tilde{n}}(x))$ in the face of decision-making uncertainty, implementing the proposed combined approach to risk analysis in a neutrosophic environment can yield more reliable results.

In this research, the proposed Failure Modes and Effect Analysis method developed by single-valued triangular Neutrosophic numbers consists of 5 steps as follows:

Step 1) Investigating SCPs and determining all potential failure modes (OHS risks)

At this step, the output of the focus group meeting will be used and the list of risks and the causes of each risk in different dimensions will be explained.

Step 2) Determining the status of each OHS risk in parameters O, S, and D using verbal expressions

Assume that there are n risks (R_j; j= 1,…, n), that must be evaluated and scored by the expert committee members consisting of f members (k=1,…,f). Besides, $\tilde{X}^O_{jk} = \langle (l^O_{jk}, m^O_{jk}, u^O_{jk});\ \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle$, $\tilde{X}^S_{jk} = \langle (l^S_{jk}, m^S_{jk}, u^S_{jk});\ \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle$, and $\tilde{X}^D_{jk} = \langle (l^D_{jk}, m^D_{jk}, u^D_{jk});\ \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle$ respectively express the kth expert's opinion about the status of O, S and D parameters for the jth OHS risk. By distributing the questionnaire among the expert committee members, their views are collected in the form of single-valued triangular Neutrosophic numbers (Table 4).

Table 4 Verbal expressions and the corresponding single-valued triangular Neutrosophic numbers in determining the status of OHS risks (Ayber & Erginel, 2019)

Corresponding single-valued triangular Neutrosophic numbers	**Verbal expressions**		
	Detectability (D)	**Severity (S)**	**Occurrence (O)**
⟨(4/6; 5/5; 8/6); 0/4; 0/7; 0/2⟩	Essentially High (EH)	Low (L)	Low (L)
⟨(4/7; 6/9; 8/5); 0/7; 0/2; 0/6⟩	Fairly High (FH)	Not Low (NL)	Not Low (NL)
⟨(6/2; 7/6; 8/2); 0/4; 0/1; 0/3⟩	More or Less High (MLH)	Very Low (VL)	Very Low (VL)
⟨(7/1; 7/7; 8/3); 0/5; 0/2; 0/3⟩	Completely High (CH)	Completely Low (CL)	Completely Low (CL)
⟨(5/8; 6/9; 8/5); 0/6; 0/2; 0/3⟩	Very High (VH)	More or Less Low (MLL)	More or Less Low (MLL)
⟨(5/5; 6/2; 7/3); 0/8; 0/1; 0/2⟩	Not High (NH)	Fairly Low (FL)	Fairly Low (FL)
⟨(5/3; 6/7; 9/9); 0/3; 0/5; 0/2⟩	High (H)	Essentially Low (EL)	Essentially Low (EL)
⟨(6/2; 8/9; 9/1); 0/6; 0/3; 0/5⟩	Essentially Low (EL)	High (H)	High (H)
⟨(4/4; 5/9; 7/2); 0/7; 0/2; 0/3⟩	Fairly Low (FL)	Not High (NH)	Not High (NH)
⟨(6/6; 8/8; 10); 0/6; 0/2; 0/2⟩	More or Less Low (MLL)	Very High (VH)	Very High (VH)
⟨(6/3; 7/5; 8/9); 0/7; 0/4; 0/6⟩	Completely Low (CL)	Completely High (CH)	Completely High (CH)
⟨(5/3; 7/3; 8/7); 0/7; 0/2; 0/8⟩	Very Low (VL)	More or Less High (MLH)	More or Less High (MLH)
⟨(6/5; 6/9; 8/5); 0/6; 0/8; 0/1⟩	Not Low (NL)	Fairly High (FH)	Fairly High (FH)
⟨(7/5; 7/9; 8/5); 0/8; 0/5; 0/4⟩	Low (L)	Essentially High (EH)	Essentially High (EH)

Step 3) Integrating experts' opinions regarding the status of OHS risks in O, S, and D parameters

After distributing and collecting the questionnaire, the resulting values are integrated using Equation 12.

$$\tilde{X}^O_j = \frac{\sum_{k=1}^{f} WE_k * \tilde{X}^O_{jk}}{\sum_{k=1}^{f} WE_k} = \langle (l^O_j, m^O_j, u^O_j);\ \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle \quad ; \quad j = 1, \dots, n$$

$$\tilde{X}^S_j = \frac{\sum_{k=1}^{f} WE_k * \tilde{X}^S_{jk}}{\sum_{k=1}^{f} WE_k} = \langle (l^S_j, m^S_j, u^S_j);\ \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle \quad ; \quad j = 1, \dots, n \tag{12}$$

$$\tilde{X}^D_j = \frac{\sum_{k=1}^{f} WE_k * \tilde{X}^D_{jk}}{\sum_{k=1}^{f} WE_k} = \langle (l^D_j, m^D_j, u^D_j);\ \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle \quad ; \quad j = 1, \dots, n$$

According to the equation above, WE_k represents the weight of the kth expert's opinion and $\tilde{X}^O_j$, $\tilde{X}^S_j$, and $\tilde{X}^D_j$respectively represent the values of the occurrence, severity, and detectability of OHS risks in the form of single triangular Neutrosophic numbers.

Step 4) Calculating the Weighted Neutrosophic Risk Priority Numbers $(\widetilde{WNRPN})$ of each OHS risk

According to the risk weights calculated by the NG-BWM method, in this step, by multiplying the weights in the single-valued neutrosophic triangular values of the risk status in O, S, and D parameters, the weighted risk value is obtained (Equation 13).

$$\begin{aligned}
\tilde{X}_j^{O*} &= W_j^*.\tilde{X}_j^O = \langle (W_j.l_j^O, W_j.m_j^O, W_j.u_j^O); \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle = \langle (l_j^{O*}, m_i^{O*}, u_i^{O*}); \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle \quad ; j = 1, \dots, n \\
\tilde{X}_j^{S*} &= W_j^*.\tilde{X}_j^S = \langle (W_j.l_j^S, W_j.m_j^S, W_j.u_j^S); \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle = \langle (l_j^{S*}, m_i^{S*}, u_i^{S*}); \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle \quad ; j = 1, \dots, n \\
\tilde{X}_j^{D*} &= W_j^*.\tilde{X}_j^D = \langle (W_j.l_j^D, W_j.m_j^D, W_j.u_j^D); \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle = \langle (l_j^{D*}, m_i^{D*}, u_i^{D*}); \alpha_{\tilde{x}}, \beta_{\tilde{x}}, \theta_{\tilde{x}} \rangle \quad ; j = 1, \dots, n
\end{aligned} \tag{13}$$

$$(\widetilde{WNRPN}) = \tilde{X}_j^{O*} * \tilde{X}_j^{S*} * \tilde{X}_j^{D*} \tag{14}$$

According to the above relationships, $\tilde{X}_j^{O*}$, $\tilde{X}_j^{S*}$, and $\tilde{X}_j^{D*}$ respectively show the integrated weighted values of the occurrence, severity, and detectability of risks in the form of single-valued triangular Neutrosophic numbers.

Step 5) Converting the WNRPNs to crisp values and prioritizing the risks

According to the obtained Neutrosophic scores for each OHS risk in SCPs, at this step, to compare and prioritize the risks, the deterministic form of Neutrosophic scores are calculated using Equation 9

3. Data Analysis

After negotiating with a number of Iran's construction companies, that adhered to the principles and requirements of sustainable development, 13 project managers and executive officers formed the expert committee of the current research. According to the demographic characteristics of these committee members, the weight of the experts' opinions was determined using Equation (1) as shown in Table 5.

Table 5 Weight of opinions of expert committee members

Expert ID	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13
Weight of comments	0.0957	0.0783	0.0783	0.0348	0.0957	0.0870	0.0957	0.0609	0.0696	0.0609	0.0957	0.0870	0.0609

By conducting in-depth library studies, the common OHS risks in SCPs were summarized into six dimensions: economic, environmental, social, health, safety, and managerial and structural. While sustainability traditionally emphasizes the three pillars of economic, social, and environmental factors (Elkington, 1997; Silvius & Schipper, 2019), occupational health and safety (OHS) represent critical operational dimensions that transcend general social considerations. Health captures the physical and mental well-being of workers, while Safety addresses risks, hazards, and preventive measures in construction operations. Treating Health and Safety as separate dimensions allows a more precise identification, measurement, and prioritization of operational risks in sustainable construction projects. In order to screen and localize these risks, the focus group meeting was held with the committee members and the semi-structured interview protocol was distributed among them. After holding a focus group meeting and calculating the weighted average of the opinions about the acceptance of each risk, while applying the weights of each expert's opinion and setting the adoption limit of 0.5 as a contract, it was observed that out of 66 candidate risks, 43 risks were screened for Iran's sustainable construction industry and included in the final list. It was also observed that the two risks "insufficient employee safety skills due to inadequate specialized safety training" and "unpredictable weather conditions" with a cumulative weighted acceptance level of 0.904 and 0.53 as the best (most important) and worst, respectively. The (least important) risks were determined by experts. Besides, the opinions of other experts regarding risks outside of the announced risks were put to an oral survey. A consensus was formed on two risks: "the existence of a work culture that conflicts with safety in organizational strategies" and "risks caused by neglecting the safety in the initial and detailed phases of the project". These risks were also placed in the managerial and structural dimension. In this way, the final theoretical framework, including 45 OHS risks, was constructed for Iran's SCPs (Table 6).

Table 6 Final OHS risks in Iran's SCPs

Dimensions	Risks	References
Economic	stress and not focusing on assigned tasks due to not paying employees' salaries on time rect selection of personnel in high-risk jobs due to lack of allocation of funds for periodical ; and at the beginning of employment (R21); Lack of health certificate for all machinery and ue to lack of budget allocation (R31); Lack of standard personal equipment due to lack of ıtion (R41); Failure to recruit supervisors, experts and HSE officers in accordance with the project due to insufficient budget (R51)	(Mohandes S R, Zhang et al., 2021; Gunduz & Laitinen, 2018; Alipour-Bashary et al., 2021; Jeong et al., 2022; Belayutham et al., 2016; Rosenbaum et al., 2014; Zhou et al., 2018; Murè et al., 2017; Rowlinson & Jia, 2015; Yan et al., 2019; Sui et al.,
Environmental	Unexpected natural events (floods, earthquakes, lightning, etc.) (R12); Unpredictable weather conditions (R22); Unfavorable condition of soil and geology (R32); Adverse environmental effects on other surrounding structures and buildings (R42); Release of environmental pollutants (R52)	
Social	insufficient employee safety skills due to inadequate specialized safety training (R13); Neglect and non-implementation of the 20th topic of the National Building Regulations regarding making the workshop safe (R23); Neglect and non-implementation of safety culture plans (R33); Overlooking and failing to adequately plan for emergency maneuvers (R43); Ignoring the formation of a quick response team in the project (R53);	

	Workforces with insufficient knowledge, experience, and skills (R63)	2020; Gürcanli & Müngen, 2009; Raviv et al., 2017; Tong et al., 2018; Pinto, 2014; Zhang & Mohandes, 2020; Fung et al., 2010; Liang et al., 2020; Interview)
Health	Confusion and mental disorders caused by exposure to sound and vibrations (R14); Repeated pressure injuries to different parts of the body due to continuous incorrect movements (R24); Excessive fatigue from long work or night work (R34); Heat stroke due to working in very hot weather (R44); Increased blood pressure due to continuous work in hot weather (R54); occupational injuries and illnesses (R64); Mortality caused by occupational hazards (R74)	
Safety	Falling from a height (R15); Explosion and fire (R25); Risk of electrocution and electric shock (R35); Falling objects from a height (R45); Welding and cutting hazards (R55); Debris fall (R65); Dangers of drilling and excavating (R75); Dangers of installing structures (R85); Accident of machinery with workers (R95); Surface and underground water leakage (R105); Neglecting and not allocating time to secure all the workplaces before starting construction operations (R115); Risks from improper use of tools and equipment (R125); Slip and slide (R135); Risks of working with slippery and sharp equipment (R145); hazards stemming from flawed design and site layout (R155); Insufficient work space (R165); Excessive noise pollution (R175)	
Managerial and structural	Ambiguity and lack of transparency of OHS management processes (R16); Inadequacy and ineffectiveness of OHS management personnel (R26); Poor management and insufficient supervision (R36); The existence of a work culture that conflicts with safety in organizational strategies (R46); Risks caused by neglecting the safety in the initial and detailed phases of the project (R56)	

After determining the best (most important) and worst (least important) risks, a survey was conducted to specify the preference of the best risk over other risks and the preference of other risks over the worst one, and the frequency of experts' opinions was collected. After forming the neutrosophic pairwise comparison matrices and applying the weights of experts, the weighted neutrosophic pairwise comparison matrices were obtained. By calculating the arithmetic mean of experts' opinions, the cumulative weighted neutrosophic pairwise comparison matrix was obtained in Table 7.

Table 7 Cumulative weighted neutrosophic pairwise comparison matrices

Dimensions	Risks	The best risk (insufficient employee safety skills due to inadequate specialized safety training (R13))	The worst risk (unpredictable weather conditions (R22))
Economic	R11	<(1.6095,2.61,3.6105); 0.3, 0.75, 0.7)>	<(2.0358,3.0363,4.0368); 0.3, 0.75, 0.7)>
	R21	<(1.0962,2.0967,3.0972); 0.3, 0.75, 0.7)>	<(2.5839,3.5844,4.5849); 0.3, 0.75, 0.7)>
	R31	<(1.4616,2.4621,3.4626); 0.3, 0.75, 0.7)>	<(1.5486,2.5491,3.5496); 0.3, 0.75, 0.7)>
	R41	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(2.5839,3.5844,4.5849); 0.3, 0.75, 0.7)>
	R51	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(2.2533,3.2538,4.2543); 0.3, 0.75, 0.7)>
Environmental	R12	<(1.6443,2.6448,3.6453); 0.3, 0.75, 0.7)>	<(1.0353,2.0358,3.0363); 0.3, 0.75, 0.7)>
	R22	<(8.8131,8.9088,9.0045); 0.85, 0.1, 0.15)>	<(1.0005,1.0005,1.0005); 0.5, 0.5, 0.5)>
	R32	<(1.5834,2.5839,3.5844); 0.3, 0.75, 0.7)>	<(1.3572,2.3577,3.3582); 0.3, 0.75, 0.7)>
	R42	<(2.1663,3.1668,4.1673); 0.3, 0.75, 0.7)>	<(1.0614,2.0619,3.0624); 0.3, 0.75, 0.7)>
	R52	<(1.5399,2.5404,3.5409); 0.3, 0.75, 0.7)>	<(1.1397,2.1402,3.1407); 0.3, 0.75, 0.7)>
Social	R13	<(1.0005,1.0005,1.0005); 0.5, 0.5, 0.5)>	<(8.8131,8.9088,9.0045); 0.85, 0.1, 0.15)>
	R23	<(1.1571,2.1576,3.1581); 0.3, 0.75, 0.7)>	<(2.4534,3.4539,4.4544); 0.3, 0.75, 0.7)>
	R33	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(1.3485,2.349,3.3495); 0.3, 0.75, 0.7)>
	R43	<(1.0614,2.0619,3.0624); 0.3, 0.75, 0.7)>	<(5.0112,5.9508,6.8904); 0.3, 0.75, 0.7)>
	R53	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(1.2963,2.2968,3.2973); 0.3, 0.75, 0.7)>
	R63	<(1.2267,2.2272,3.2277); 0.3, 0.75, 0.7)>	<(1.9401,2.9406,3.9411); 0.3, 0.75, 0.7)>
Health	R14	<(1.4964,2.4969,3.4974); 0.3, 0.75, 0.7)>	<(1.3137,2.3142,3.3147); 0.3, 0.75, 0.7)>
	R24	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(1.4268,2.4273,3.4278); 0.3, 0.75, 0.7)>
	R34	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(2.2968,3.2973,4.2978); 0.3, 0.75, 0.7)>
	R44	<(1.2528,2.2533,3.2538); 0.3, 0.75, 0.7)>	<(1.5399,2.5404,3.5409); 0.3, 0.75, 0.7)>
	R54	<(1.2354,2.2359,3.2364); 0.3, 0.75, 0.7)>	<(1.7487,2.7492,3.7497); 0.3, 0.75, 0.7)>
	R64	<(1.9227,2.9232,3.9237); 0.3, 0.75, 0.7)>	<(6.003,6.8469,7.6908); 0.4, 0.65, 0.6)>
	R74	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(2.6796,3.6801,4.6806); 0.3, 0.75, 0.7)>

Safety	R15	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(2.436,3.4365,4.437); 0.3, 0.75, 0.7)>
	R25	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(1.7661,2.7666,3.7671); 0.3, 0.75, 0.7)>
	R35	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(1.305,2.3055,3.306); 0.3, 0.75, 0.7)>
	R45	<(1.2963,2.2968,3.2973); 0.3, 0.75, 0.7)>	<(1.2093,2.2098,3.2103); 0.3, 0.75, 0.7)>
	R55	<(1.2876,2.2881,3.2886); 0.3, 0.75, 0.7)>	<(1.2702,2.2707,3.2712); 0.3, 0.75, 0.7)>
	R65	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(2.7057,3.7062,4.7067); 0.3, 0.75, 0.7)>
	R75	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(2.5404,3.5409,4.5414); 0.3, 0.75, 0.7)>
	R85	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(1.6617,2.6622,3.6627); 0.3, 0.75, 0.7)>
	R95	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(2.5317,3.5322,4.5327); 0.3, 0.75, 0.7)>
	R105	<(1.6095,2.61,3.6105); 0.3, 0.75, 0.7)>	<(1.1484,2.1489,3.1494); 0.3, 0.75, 0.7)>
	R115	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(2.523,3.5235,4.524); 0.3, 0.75, 0.7)>
	R125	<(1.4268,2.4273,3.4278); 0.3, 0.75, 0.7)>	<(1.7922,2.7927,3.7932); 0.3, 0.75, 0.7)>
	R135	<(1.74,2.7405,3.741); 0.3, 0.75, 0.7)>	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>
	R145	<(1.3572,2.3577,3.3582); 0.3, 0.75, 0.7)>	<(1.827,2.8275,3.828); 0.3, 0.75, 0.7)>
	R155	<(1.0614,2.0619,3.0624); 0.3, 0.75, 0.7)>	<(5.6115,6.5337,7.4559); 0.4, 0.65, 0.6)>
	R165	<(1.5399,2.5404,3.5409); 0.3, 0.75, 0.7)>	<(1.1745,2.175,3.1755); 0.3, 0.75, 0.7)>
	R175	<(1.4181,2.4186,3.4191); 0.3, 0.75, 0.7)>	<(1.6617,2.6622,3.6627); 0.3, 0.75, 0.7)>
Managerial and Structural	R16	<(1.0788,2.0793,3.0798); 0.3, 0.75, 0.7)>	<(1.827,2.8275,3.828); 0.3, 0.75, 0.7)>
	R26	<(1.1919,2.1924,3.1929); 0.3, 0.75, 0.7)>	<(4.7067,5.7072,6.7077); 0.4, 0.65, 0.6)>
	R36	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(2.3229,3.3234,4.3239); 0.3, 0.75, 0.7)>
	R46	<(1.2963,2.2968,3.2973); 0.3, 0.75, 0.7)>	<(1.2789,2.2794,3.2799); 0.3, 0.75, 0.7)>
	R56	<(1.0005,2.001,3.0015); 0.4, 0.65, 0.6)>	<(2.3577,3.3582,4.3587); 0.3, 0.75, 0.7)>

By transforming the results to deterministic values and placing them in the linear programming model, the expanded model consisting of 45 variables and 89 constraints was entered into the GAMS software. By solving the model, the optimal value of each risk weight vector and the objective function were obtained as Figure 2. According to Table 3, in which the consistency index (CI) for $a_{BW} = 8$, the value is 4.5 and for $a_{BW} = 9$, the value is 5.2. By solving the equation of the line resulting from the values of a_{BW} and consistency index, for $a_{BW} = 8.7$, the consistency index value was 4.88.

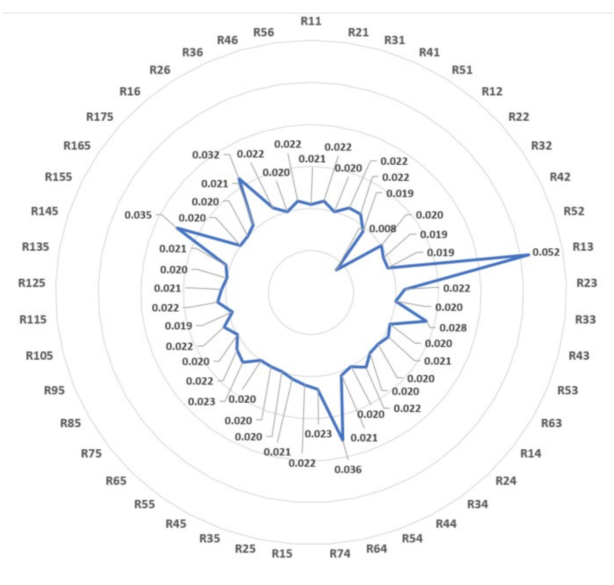

Figure 2 The optimal weights of OHS risks in Iran's SCPs

According to the results of solving the linear programming model of the best-worst method, five risks such as " insufficient employee safety skills due to inadequate specialized safety training (R13)", "occupational injuries and illnesses (R64)", "hazards stemming from flawed design and site layout (R155)", "Inadequacy and ineffectiveness of OHS management personnel (R26)", and " Overlooking and failing to adequately plan for emergency maneuvers (R43)" respectively with weights of 0.052, 0.036, 0.035, 0.032, and 0.028 had the most weight. Besides, by solving the linear programming model in GAMS software, the optimal value of the objective function ($\bar{\xi}^*$) was 1.89, and according to the equation (11), the Consistency Rate of the pairwise comparison matrices for this problem was 0.38. According to the threshold limit determined by Liang et al. (2020), the consistency of experts' judgments was suitable and the reliability of the questionnaire was confirmed.

Since relying merely on the NG-BWM method and focusing on the results of pairwise comparisons of risks cannot alone be a suitable basis for determining key and priority risks, it is necessary to specify the status of each OHS risk in three parameters of O, S, and D and risks are scored and ranked. Therefore, by distributing the questionnaire among the experts and collecting their opinions regarding the status of each risk in the three parameters, while applying their opinion weights, the weighted average of opinions was calculated (see Table 8). Then the $\widehat{WNRPN}$ were obtained by multiplying the corresponding weights for each risk, which were calculated by the NG-BWM method, in the values of the risk factors (O, S, D) and multiplying these factors together. In order to compare and prioritize OHS risks in Iran's SCPs, the $\widehat{WNRPN}$ were transformed to crisp values using Equation (9) (see Table 9). Based on the obtained results, higher OHS risk scores indicate a higher level of criticality for sustainable construction projects in

Iran. In order to classify the identified risks within a risk matrix according to their scores, by convention, risks with scores greater than or equal to 0.002 were categorized as high-criticality risks. Furthermore, risks with scores greater than or equal to 0.001 and less than 0.002 were classified as medium-criticality risks, while risks with scores lower than 0.001 were classified as low-criticality risks (Figure 3).

Given the dependence of the obtained results on the experts' subjective judgments, a sensitivity analysis was conducted to examine the robustness of the results. To this end, experts' perspectives were analyzed according to their levels of risk tolerance by applying the α-cut approach to determine the status of each OHS risk across the three criteria of O, S, and D at five α levels (α = 0, 0.25, 0.5, 0.75, and 1). The results of the sensitivity analysis for the final weighted neutrosophic RPN (WNRPN) of each risk at the five α-cut levels are illustrated in Figure 4.

Table 8 The neutrosophic weighted average of experts' judgments regarding the status of each risk under the O, S, and D parameters

Dimensions	Risks	Risk Weights	$\tilde{X}_j^O$	$\tilde{X}_j^S$	$\tilde{X}_j^D$
Economic	R11	0/021	<(6/34,8/63,9/27); 0/6, 0/8, 0/5)>	<(6/22,8/04,8/91); 0/6, 0/8, 0/8)>	<(5/54,6/71,8/5); 0/3, 0/8, 0/8)>
	R21	0/022	<(5/98,7/47,8/58); 0/4, 0/8, 0/8)>	<(5/84,7/44,8/45); 0/6, 0/5, 0/6)>	<(5/97,7/81,9/58); 0/3, 0/8, 0/6)>
	⋮	⋮	⋮	⋮	⋮
	R51	0/022	<(6/54,7/93,9/11); 0/6, 0/8, 0/6)>	<(5/94,7/59,8/76); 0/6, 0/5, 0/8)>	<(6/04,7/77,8/69); 0/6, 0/8, 0/5)>
Environmental	R12	0/019	<(5/71,7/14,8/31); 0/4, 0/4, 0/6)>	<(5/44,7/52,8/38); 0/6, 0/4, 0/8)>	<(6/51,7/51,8/35); 0/3, 0/5, 0/3)>
	R22	0/008	<(5/61,6/6,8/03); 0/3, 0/5, 0/8)>	<(6/15,8/29,9); 0/6, 0/4, 0/8)>	<(5/17,6/36,7/66); 0/3, 0/7, 0/3)>
	⋮	⋮	⋮	⋮	⋮
	R52	0/019	<(5/44,6/91,8/4); 0/3, 0/5, 0/6)>	<(5/91,7/79,9/25); 0/3, 0/5, 0/6)>	<(5/64,7/27,8/35); 0/3, 0/7, 0/5)>
Social	R13	0/052	<(5/21,6/76,8/73); 0/4, 0/7, 0/5)>	<(5/26,6/86,8/85); 0/4, 0/7, 0/8)>	<(5/49,6/61,8/46); 0/4, 0/7, 0/8)>
	R23	0/022	<(6/07,8/23,8/94); 0/6, 0/8, 0/8)>	<(6/36,7/99,8/93); 0/6, 0/8, 0/6)>	<(6/21,8/58,9/35); 0/6, 0/3, 0/8)>
	⋮	⋮	⋮	⋮	⋮
	R63	0/021	<(6,8/31,9/1); 0/6, 0/4, 0/8)>	<(6/09,7/4,8/77); 0/4, 0/8, 0/6)>	<(5/94,8/18,8/93); 0/6, 0/4, 0/8)>
Health	R14	0/020	<(5/54,7/21,8/71); 0/3, 0/5, 0/8)>	<(5/7,7/03,8/17); 0/4, 0/8, 0/6)>	<(5/88,8/09,8/91); 0/6, 0/3, 0/8)>
	R24	0/020	<(6/11,8/43,9/23); 0/6, 0/4, 0/8)>	<(5/52,7/39,8/34); 0/6, 0/8, 0/6)>	<(5/6,7/72,8/58); 0/6, 0/4, 0/8)>
	⋮	⋮	⋮	⋮	⋮
	R74	0/023	<(5/27,6/63,8/48); 0/4, 0/7, 0/6)>	<(6/61,7/56,8/45); 0/6, 0/5, 0/6)>	<(5/04,6/69,8/56); 0/4, 0/7, 0/8)>
Safety	R15	0/022	<(5/34,6/54,7/82); 0/6, 0/4, 0/8)>	<(6/66,8/07,8/99); 0/6, 0/8, 0/6)>	<(5/46,7/44,8/25); 0/6, 0/4, 0/8)>
	R25	0/021	<(5/89,7/31,8/25); 0/6, 0/5, 0/8)>	<(6/4,7/97,9/01); 0/6, 0/8, 0/6)>	<(5/59,6/85,8/15); 0/3, 0/5, 0/8)>
	⋮	⋮	⋮	⋮	⋮
	R175	0/020	<(5/75,7/17,8/62); 0/4, 0/8, 0/8)>	<(5/72,6/93,8/06); 0/4, 0/7, 0/5)>	<(6/65,8/45,9/24); 0/6, 0/5, 0/8)>
Managerial and Structural	R16	0/021	<(6/1,7/77,8/89); 0/6, 0/5, 0/6)>	<(6/36,8/28,9/24); 0/6, 0/8, 0/6)>	<(5/94,7/31,8/47); 0/3, 0/7, 0/6)>
	R26	0/032	<(5/69,7/22,8/49); 0/4, 0/8, 0/8)>	<(5/96,7/27,8/99); 0/3, 0/8, 0/8)>	<(5/18,6/95,8/22); 0/4, 0/7, 0/5)>
	⋮	⋮	⋮	⋮	⋮
	R56	0/022	<(6/52,8/09,8/9); 0/6, 0/8, 0/6)>	<(6/35,8/05,8/94); 0/6, 0/8, 0/6)>	<(5/67,7/11,8/25); 0/4, 0/7, 0/6)>

Table 9 Final score and priority of OHS risks in Iran's SCPs

Dimensions	Risks	$\widetilde{WNRPN}$	WNRPN (Score)	Final Priority
Economic	R11	<(0/002,0/0043,0/0065); 0/3, 0/8, 0/8)>	0/0011	28
	R21	<(0/0022,0/0046,0/0074); 0/3, 0/8, 0/8)>	0/0012	23
	R31	<(0/002,0/0043,0/0058); 0/6, 0/8, 0/6)>	0/0018	10
	R41	<(0/0026,0/0046,0/0068); 0/6, 0/8, 0/8)>	0/0017	13
	R51	<(0/0025,0/005,0/0074); 0/6, 0/8, 0/8)>	0/0019	9
Environmental	R12	<(0/0014,0/0028,0/004); 0/3, 0/5, 0/8)>	0/0010	33
	R22	<(0/0001,0/0002,0/0003); 0/3, 0/7, 0/8)>	0/0001	45
	R32	<(0/0012,0/0026,0/005); 0/3, 0/8, 0/8)>	0/0008	43
	R42	<(0/0013,0/0021,0/0041); 0/3, 0/7, 0/8)>	0/0007	44
	R52	<(0/0012,0/0027,0/0045); 0/3, 0/7, 0/6)>	0/0010	29
Social	R13	<(0/0211,0/043,0/0919); 0/4, 0/7, 0/8)>	0/0176	1
	R23	<(0/0026,0/006,0/0079); 0/6, 0/8, 0/8)>	0/0021	7
	R33	<(0/0016,0/0038,0/0056); 0/3, 0/8, 0/8)>	0/0010	36
	R43	<(0/0053,0/011,0/0165); 0/3, 0/7, 0/6)>	0/0041	4
	R53	<(0/0019,0/0038,0/0061); 0/3, 0/8, 0/8)>	0/0010	30
	R63	<(0/002,0/0047,0/0066); 0/4, 0/8, 0/8)>	0/0013	20
Health	R14	<(0/0015,0/0033,0/0051); 0/3, 0/8, 0/8)>	0/0009	39
	R24	<(0/0015,0/0038,0/0053); 0/6, 0/8, 0/8)>	0/0013	19
	R34	<(0/0025,0/0046,0/0076); 0/3, 0/8, 0/6)>	0/0017	14
	R44	<(0/0018,0/004,0/0059); 0/3, 0/8, 0/8)>	0/0010	32
	R54	<(0/0018,0/0038,0/0055); 0/3, 0/8, 0/8)>	0/0010	35
	R64	<(0/0091,0/0178,0/0311); 0/3, 0/8, 0/8)>	0/0051	3
	R74	<(0/0021,0/0041,0/0075); 0/4, 0/7, 0/8)>	0/0015	17
Safety	R15	<(0/0021,0/0042,0/0062); 0/6, 0/8, 0/8)>	0/0016	16
	R25	<(0/002,0/0037,0/0056); 0/3, 0/8, 0/8)>	0/0010	34
	R35	<(0/0014,0/0034,0/0051); 0/3, 0/8, 0/8)>	0/0009	38
	R45	<(0/0017,0/0036,0/005); 0/6, 0/8, 0/8)>	0/0013	22
	R55	<(0/0014,0/0032,0/0048); 0/6, 0/8, 0/8)>	0/0012	25
	R65	<(0/0023,0/0047,0/0068); 0/5, 0/8, 0/8)>	0/0016	15
	R75	<(0/0023,0/0055,0/007); 0/6, 0/5, 0/8)>	0/0024	6
	R85	<(0/0016,0/0035,0/0052); 0/6, 0/8, 0/8)>	0/0013	21
	R95	<(0/0022,0/0039,0/0058); 0/4, 0/8, 0/8)>	0/0012	24
	R105	<(0/001,0/002,0/0035); 0/3, 0/7, 0/6)>	0/0008	42
	R115	<(0/0024,0/0051,0/0075); 0/6, 0/8, 0/8)>	0/0019	8
	R125	<(0/002,0/0043,0/0066); 0/3, 0/8, 0/8)>	0/0011	27
	R135	<(0/0014,0/0029,0/0056); 0/3, 0/8, 0/8)>	0/0009	37
	R145	<(0/002,0/0045,0/0066); 0/3, 0/8, 0/8)>	0/0011	26
	R155	<(0/0095,0/0208,0/0324); 0/3, 0/8, 0/8)>	0/0055	2
	R165	<(0/0015,0/0032,0/0049); 0/3, 0/8, 0/8)>	0/0008	41
	R175	<(0/0017,0/0034,0/0051); 0/4, 0/8, 0/8)>	0/0010	31
Managerial and Structural	R16	<(0/0021,0/0044,0/0064); 0/3, 0/8, 0/6)>	0/0015	18
	R26	<(0/0058,0/0119,0/0206); 0/3, 0/8, 0/8)>	0/0033	5
	R36	<(0/0024,0/0056,0/0078); 0/3, 0/8, 0/6)>	0/0018	12
	R46	<(0/0015,0/0032,0/0049); 0/3, 0/8, 0/8)>	0/0008	40
	R56	<(0/0025,0/0049,0/007); 0/4, 0/8, 0/6)>	0/0018	11

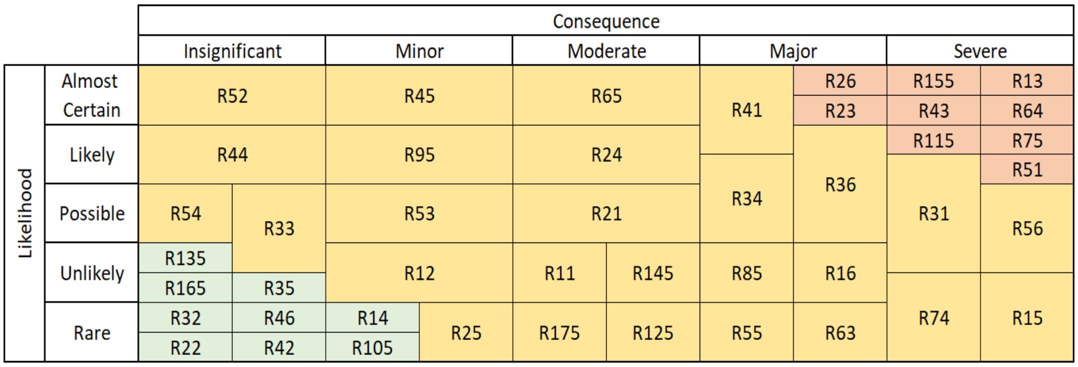

Figure 3 Risk Matrix

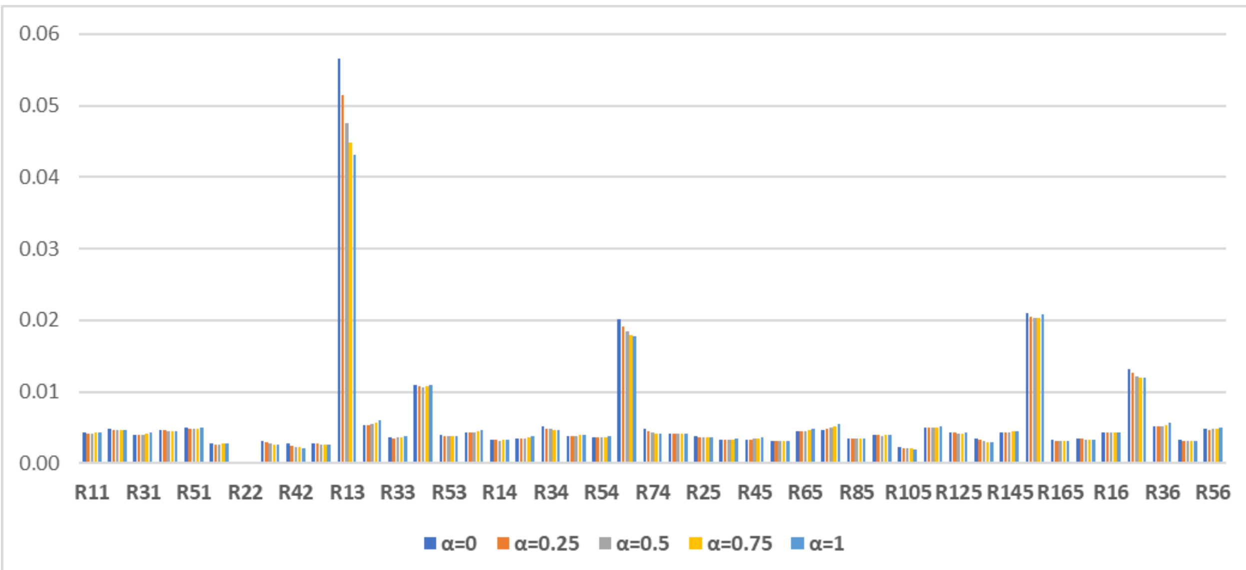

Figure 4 The optimal weights of OHS risks in Iran's SCPs

The results of the sensitivity analysis indicate that as the value of α varies from 0 to 1 (representing a transition from maximum neutrosophic uncertainty to a fully crisp state), the RPN values of most risks undergo gradual and well-controlled changes, reflecting the robustness and stability of the model against variations in the decision makers' confidence levels. For a substantial proportion of the risks, the changes in RPN values are minimal and their rankings remain nearly unchanged. Overall, this analysis confirms that while the proposed model demonstrates overall stability, it is also capable of identifying risks that are sensitive to uncertainty, thereby enabling more informed managerial decision-making across different levels of risk tolerance.

4. Discussion

The effects and consequences of non-observance of safety and the occurrence of accidents are very costly and sometimes irreparable for the interested groups. An accident in a construction project causes significant economic and social damage to the individual and the society. Preventing accidents in construction projects preserves the financial and human resources, which are among the main economic production factors. It also prevents the pressures and mental discomforts of the injured workers, their families and the society. From a safety governance perspective, these risks underscore the need for clear policies, accountability mechanisms, and continuous monitoring at both organizational and project levels. Effective governance ensures that safety procedures are systematically implemented, deviations are promptly corrected, and lessons learned from incidents are institutionalized.

The study identified "insufficient employee safety skills due to inadequate specialized safety training" as the highest-ranked OHS risk in Iran's SCPs. This finding highlights the critical role of workforce competency development as a governance strategy, linking training programs directly to organizational safety culture and overall project performance. Project managers and HSE professionals must implement structured, continuous training programs and competency assessments to foster a proactive safety culture, rather than relying solely on compliance-based approaches. The second-ranked risk, "hazards stemming from flawed design and site layout," emphasizes the importance of design-stage risk management. Integrating ergonomic principles, standard layouts, and the 5S methodology from the early design phase ensures that operational safety is embedded into the project architecture, reducing the likelihood of accidents before construction begins. This proactive approach aligns safety considerations with sustainable construction goals, as safer designs contribute to both human welfare and resource efficiency. The third-ranked risk, "occupational injuries and illnesses," illustrates the interplay between organizational safety culture and individual well-being. Maintaining employees' physical and mental health through incentive systems, health insurance, and regular check-ups reinforces a culture that values safety as integral to project success. A strong safety culture encourages employees to adhere to standards voluntarily, report hazards promptly, and participate actively in continuous improvement initiatives. Additional risks, such as "overlooking emergency maneuvers" and "ineffectiveness of OHS management personnel," reflect gaps in proactive management and operational governance. Proactive strategies, including scenario-based emergency drills and continuous monitoring of HSE personnel performance, are crucial to anticipate, mitigate, and manage potential incidents efficiently. Such measures enhance organizational resilience and align operational practices with the strategic goals of sustainable construction projects.

Practical and policy implications of these findings are multifaceted. For project managers, the results emphasize the integration of training, design optimization, and safety monitoring into routine project workflows to enhance workforce competence and reduce accidents. HSE professionals can leverage the neutrosophic MCDM approach to prioritize interventions based on quantified uncertainties, ensuring that resources are allocated to the most critical risks. Regulators and policymakers are encouraged to consider these findings when formulating standards, compliance checks, and incentive programs, promoting an ecosystem where safety, sustainability, and efficiency are aligned. In sum, this study translates methodological outcomes into actionable safety strategies by demonstrating how a neutrosophic-based hybrid assessment framework can inform decisions that strengthen governance, optimize design-stage safety measures, and cultivate a robust organizational safety culture. This holistic perspective ensures that OHS risk management is not just reactive but embedded within the strategic and operational fabric of sustainable construction projects.

The findings of this study align with and extend the international literature on OHS risks in construction projects. For example, Soltanzadeh et al. (2022) identified multiple health, safety, and environmental (HSE) risks across the nine areas of project management knowledge and emphasized the importance of comprehensive risk assessment techniques that integrate sustainability considerations, particularly the need for structured methodologies to quantify risk severity and probability in construction contexts. Their fuzzy Analytic Hierarchy Process (FAHP)-based assessment also highlighted training and hazard identification challenges, corroborating the prominence of insufficient safety skills, similar to our highest-ranked risk. Similarly, Zhang and Mohandes (2020) developed a holistic risk management framework for sustainable (green) building construction projects, where critical OHS risks, especially those related to fall hazards and design-stage risk factors, were identified as priorities. Their hybrid Z-numbers framework demonstrated that design and hazard control measures are integral to reducing accident rates, reinforcing our finding on the significance of design and site layout in safety performance. Moreover, broader reviews on OHS management in sustainable construction have emphasized the benefits of systematic OHS management systems to support worker well-being and reduce workplace harm. Kineber et al. (2023) found that effective implementation of OHSMSs enhances sustainability outcomes by continuously improving safety performance, supporting training initiatives, and aligning risk management with organizational practices, aspects reflected in our study's emphasis on workforce training and safety culture development. In general, these international studies support our results that training deficiencies, design-related hazards, and organizational safety practices are recurrent priorities in construction OHS research, illustrating that risks identified in Iran's sustainable construction context resonate with global evidence while supporting the need for context-specific, robust prioritization frameworks.

5. Conclusion and Recommendations

The lack of a continuous plan to manage OHS risks has overshadowed the realization of the functional goals of these projects from the perspective of time, cost, quality, and sustainability. This research aimed to identify and quantitatively analyze safety risks in Iran's SCPs. In this regard, the three aspects of sustainable development (economic, social, and environmental) were combined with HSE dimensions, and a framework including 45 occupational and safety risks of SCPs risks was extracted through library studies and a survey of experts in a focus group meeting.
Then, While using triangulated Neutrosophic numbers and applying weight to experts' views, a hybrid approach comprising the NG-BWM and NG-FMEA was used to determine the most key OHS risks in Iran's SCPs. This approach allowed the analyst to make a comprehensive quantitative assessment of these risks and prioritize them more precisely by combining the advantages and capabilities of both methods. The individual application of each one could not bring the analyst to this goal.

The reports of occupational accidents and their personal and social consequences indicate the importance of training and its role in improving workers' attitudes to safety issues. Managers and team members of SCPs can prevent occupational accidents and their consequences and achieve economic prosperity and sustainable development by adopting proper safety and health actions and basic engineering design through a coherent training program. The variety of executive activities and the type and nature of risks and potentially damaging factors in construction projects have made the need to use comprehensive approaches to safety, health, and environment management one of the priorities of organizations engaged in this field. Since project-oriented organizations' financial and non-financial funds are limited in dealing with OHS risks in construction projects, the weighting and prioritization of candidate risks in this research could guide project managers and other decision-makers. They can use this information to mobilize resources and optimal use of tangible and intangible capacities to deal with critical risks, risks that dealing with can bring more benefits to organizations and prevent unwanted costs from being imposed on the project and organization. Determining the high-priority risks provides a chance for the policymakers of the organizations to act scientifically in the design and formulation of the OHS risk management plan in the projects and to adopt and analyze the appropriate preventive strategies before such risks occur.

The risks selected in this research were related to social, safety, health, social, managerial, and structural dimensions, respectively. Therefore, it can be argued that the occurrence of safety risks in SCPs is not only caused by individual carelessness and the occurrence of unexpected accidents but can also originate from social, managerial and structural, and health areas. Therefore, the one-dimensional attention to OHS risks in SCPs and the absence of a structured and holistic perspective on this matter prevents managers and decision-makers from accurately identifying and assessing the root causes of risks, as well as from implementing effective preventive strategies. Despite the determination of the mentioned risks as the most important OHS risks of Iran's SCPs, this ranking does not indicate the unimportance of other risks, but each of them has its relative importance in accordance with the score obtained. In order to complete and develop the current study, future studies should concentrate on the following areas:

- Development of a model to evaluate the performance of OHS risk management in SCPs and analysing the gap between the current and desired situation.
- Conducting a system dynamic approach to study high-ranked OHS risks while adopting different scenarios;
- Design and develop an efficient control and response plan to deal with OHS risks.
- Due to the fact that OHS risks in construction projects do not act as independent islands and have cause-and-effect relations, future research should model these relationships and consider them in their analysis.

6. Limitations of the Study

Despite the contributions of this study, several limitations should be acknowledged. First, the empirical analysis is based on the judgments of a relatively small panel of experts (N = 13), selected through a non-random snowball sampling technique. This sampling approach was adopted due to the highly specialized nature of the research problem, which required experts with simultaneous knowledge of sustainable construction projects and occupational health and safety management. Nevertheless, the use of snowball sampling may introduce selection bias and restrict the statistical generalizability of the findings. Second, although the study does not aim at statistical inference but rather at structured expert-based risk prioritization within a neutrosophic group decision-making framework, the limited size of the expert pool may still influence the robustness of the results. To mitigate this issue, expert opinions were systematically weighted based on professional position, experience, and educational background, and uncertainty was explicitly modeled using single-valued triangular neutrosophic numbers and α-cut–based sensitivity analysis.

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Conflicts of Interests

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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