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ORIGINAL ARTICLE

A decision-making framework for fire safety in engineered timber buildings: an IVIF-SWARA-based assessment

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Abstract

Timber structures have gained increasing popularity due to their environmental benefits and structural efficiency. However, this growing adoption also presents complex challenges, particularly in ensuring adequate fire safety. This study aims to identify and prioritize the most critical fire safety measures in mass timber construction. To achieve this objective, a decision-making framework based on an interval-valued intuitionistic fuzzy step-wise weight assessment ratio analysis (IVIF-SWARA) is employed to model experts' opinions under uncertainty. A three-level hierarchical structure with five main factors and twenty-five subfactors is devised based on the literature and expert consultations. IVIF-SWARA is applied to obtain weight vectors. The results indicate that the most critical factors are "fire compartments and insulation systems", "safe escape routes and evacuation planning", "cross-section optimization and load-bearing capacity", "fire resistance and protection of connection elements", and "early detection and warning systems". The proposed framework is designed to function as a reusable and adaptable tool for various timber building projects, supporting evidence-based resource allocation, strategic fire safety planning, and the continuous improvement of fire risk mitigation practices.

1 Introduction

Engineered wood products, such as cross-laminated timber panels, glue-laminated timber beams, and laminated veneer lumber, are modern composite materials designed to deliver high structural performance in construction. These materials support mass timber construction with prefabricated wood components for mid- and high-rise buildings. In recent years, numerous showcase projects, including the 18-story student residence in Vancouver and the 18-story Mjøsa Tower in Norway, have demonstrated the feasibility of tall timber buildings, and many more are planned worldwide. The growing interest in mass timber construction is driven by advantages such as sustainability and prefabrication efficiency. Historically, the use of timber in large buildings was restricted by strict fire safety regulations due to timber's combustibility. Building authorities are now gradually relaxing these restrictions as research and technology advance (Gernay and Ni 2020).

Fire safety remains one of the foremost challenges for buildings constructed with engineered wood products. Timber's combustibility raises concerns about the intensity and duration of fires in mass timber buildings (Gorska et al. 2021). Mass timber elements are large, dense, and contain few voids. As a result, they tend to char on the surface rather than burn through rapidly. This charring behavior provides a degree of inherent fire resistance (Mitchell et al. 2023). Because timber is inherently combustible and its fire behavior can involve continued charring and the potential for re-flashover, extensive research and careful design are essential to enhance the fire safety of mass timber buildings (Wiesner and Bisby 2019).

Building fire safety is an integrated set of strategies, systems, and practices designed to prevent fire ignition, limit fire growth, protect structural integrity, enable safe evacuation, and support firefighting efforts (Östman et al. 2017). The use of engineered timber requires careful integration within overall building design and management. As such, ensuring fire safety in mass timber construction calls for a holistic framework addressing structural, architectural, mechanical, electrical, and operational systems in a coordinated manner (Buchanan and Östman 2022). Failures in

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fire safety can result in long-term consequences, including human casualties, financial loss, and diminished public trust in timber construction. Establishing a comprehensive and evidence-based understanding of fire risks and the effectiveness of mitigation strategies is critical to ensuring safety in buildings (Koval et al. 2023).

Fire safety measures are critical in terms of their role in safeguarding human life, protecting assets, and ensuring the resilience of built environments. A comprehensive, building-scale perspective is essential, focusing on a structure's overall capacity to resist ignition, contain fire spread, facilitate safe evacuation, and maintain critical operational functions during and after fire events. Given the complexity of fire safety requirements, it is crucial to systematically prioritize measures based on their level of criticality. In this context, multicriteria decision-making (MCDM) methods offer a valuable framework for assigning appropriate weights to each safety intervention (Omidvari et al. 2020).

MCDM is a branch of operations research that addresses decision problems involving multiple, often conflicting, factors. It provides structured approaches to identify the most preferable options based on the objectives and preferences of decision-makers (Kumar et al. 2017). The MCDM process begins with problem definition. In the factor selection phase, key factors influencing the decision are identified. Feasible options or strategies are then listed for evaluation (Singer and Özşahin 2023). A crucial component of the MCDM process is the weighting of decision factors. Methods such as pairwise comparison, direct rating, or entropy techniques can be used to derive weights. The MCDM process concludes with analysis and final decision-making (Sampathkumar and Augustin 2024). Several MCDM methods are available for factor prioritization. The step-wise weight assessment ratio analysis (SWARA) is among the most popular methods used for this purpose (Debbarma et al. 2024).

SWARA is designed to determine the relative weights of factors based on expert judgment. The SWARA procedure begins by ranking factors in order of importance. Experts then assign a comparative importance ratio to each factor (starting from the second one) relative to the one above it. Using these ratios, recalculated coefficients are determined, and step-wise weights are calculated sequentially. Finally, weights are normalized to reflect the relative importance of each factor (Zandi et al. 2024). SWARA is simple and intuitive. It requires only basic comparative judgments rather than complex mathematical formulations or extensive pairwise comparisons (Ayoobi et al. 2024). SWARA allows for expert-driven prioritization. This makes it ideal in situations where qualitative insights and experience are more valuable than quantitative data (Bağcı and Kartal 2024). SWARA's step-wise approach makes it highly transparent and traceable. Since weights are derived through a clear, logical sequence of judgments, it becomes easier to explain and justify model results (Song et al. 2024).

In many MCDM problems, decision-makers are faced with evaluating options based on subjective judgments, qualitative assessments, or vague linguistic expressions. These types of assessments often cannot be expressed precisely with traditional numerical values or handled effectively using crisp mathematical models (Mardani et al. 2015). Fuzzy logic provides a powerful framework for incorporating uncertainty, ambiguity, and imprecision into the decision-making process in order to achieve more realistic and human-like evaluations (Karnavas et al. 2025). Unlike classical set theory, which strictly categorizes information into absolute sets, fuzzy set theory handles uncertainty and imprecision by representing data in terms of membership functions that range between 0 and 1. This allows for more flexible modeling of real-world problems. At the core of fuzzy logic lies the concept of fuzzy sets. In fuzzy sets, each element is associated with a membership function that determines the degree to which the element belongs to the set (Stanković and Petrović 2025). Fuzzy logic models verbal labels using fuzzy sets, thereby enabling machines or systems to interpret and act upon vague human inputs. The use of fuzzy sets in SWARA enables better modeling of human reasoning and improves the overall reliability of decision-making outcomes (Puška et al. 2023).

Building upon the foundation of fuzzy sets, more advanced models have been developed to capture greater levels of uncertainty and hesitation in decision-making processes. One such extension is the interval-valued intuitionistic fuzzy (IVIF) set. The IVIF set expands on traditional fuzzy sets by incorporating not only degrees of membership but also degrees of non-membership, both of which are expressed as intervals rather than precise values (Fu et al. 2022). The main advantage of the IVIF set is its enhanced ability to handle ambiguity, vagueness, and conflicting expert opinions. By allowing interval-based values, the IVIF set accommodates a range of possible judgments rather than forcing experts to commit to single values. The IVIF set provides greater flexibility and reliability in modeling linguistic terms and subjective evaluations (Alrasheedi et al. 2024). Hence, this study uses IVIF-SWARA for factor prioritization.

1.1 Objective of the study

The primary objective of this study is to identify, categorize, evaluate, and prioritize fire safety measures in mass timber construction. An IVIF-SWARA-based framework is employed as an analytical tool to assess the relative importance of the identified factors. The decision-making

framework is intended to be replicable and adaptable, allowing its application to different projects. Specifically, this study aims to:

- Identify and categorize the key fire safety measures in mass timber construction.
- Capture expert opinions under uncertainty using the IVIF set.
- Apply IVIF-SWARA to determine the relative importance of each factor.
- Support the development of fire safety strategies in mass timber construction by highlighting the most critical areas requiring attention from architects, engineers, contractors, and policymakers.
- Provide a methodological framework that can be replicated or adapted in similar MCDM contexts related to fire safety and building practices.

1.2 Motivation of the study

The motivation behind this study stems from the need to:

- Develop a structured framework for prioritizing fire safety measures in mass timber construction.
- Address the complexity and uncertainty involved in evaluating fire safety measures by incorporating IVIF logic.
- Provide actionable insights for architects, engineers, building regulators, and fire safety professionals to focus on the most critical aspects of fire safety.
- Contribute to the development of safer, more resilient timber structures.
- Bridge the gap between fire safety theory and practice by transforming expert knowledge into a quantifiable and applicable prioritization model.

It is also useful to briefly position the applied approach with respect to alternative MCDM methods commonly used in fuzzy decision-making environments. While AHP (analytic hierarchy process) provides a robust pairwise comparison structure, it typically requires a large number of comparisons, which can increase computational complexity and expert fatigue, particularly in problems involving a high number of factors. BWM (best-worst method) reduces the number of comparisons compared to AHP; however, it still relies on the accurate identification of best and worst factors and additional consistency checks. In contrast, SWARA offers a more streamlined and transparent weighting process based on step-wise expert judgments, resulting in lower computational burden and improved practicality. When combined with IVIF logic, the method effectively captures uncertainty while maintaining reliability, making it particularly suitable for complex fire safety decision-making contexts.

1.3 Value of the study

Previous studies have focused on fire performance and safety strategies in timber buildings (Barber and Gerard 2015; Chorlton and Gales 2019; Kincelova et al. 2020; Zang et al. 2023; Menzemer et al. 2025), none has provided a holistic, expert-driven, and uncertainty-aware methodology for comprehensively ranking fire safety measures. This study is the first of its kind in several key aspects.

- Application of IVIF-SWARA in this field: Although SWARA has been applied to various MCDM problems, integrating it with IVIF logic in the context of fire safety for timber buildings represents a novel contribution.
- Comprehensive structuring of fire safety measures: The study presents a hierarchical classification of fire safety considerations, organized into five main factors and twenty-five subfactors. This level of detail represents the most holistic framework to date.
- Timber-focused fire safety prioritization model: While many existing fire safety models are either generic or designed for steel and concrete buildings, this study focuses specifically on mass timber construction.
- Strategic guidance for policy and design: This research provides strategic value for policymakers, designers, and regulators by identifying which fire safety measures require the most urgent attention and investment. The prioritization outcomes can inform design procedures tailored to the growing use of timber in mid- and high-rise construction.

1.4 Organization of the study

This study is structured into four sections. Section 1 provides an overview of the research topic and outlines the study's objectives, motivation, and novelty. Section 2 explains the IVIF set and IVIF-SWARA. It also describes the proposed decision-making framework. Section 3 presents the application results of the model and provides comparative and sensitivity analyses. Finally, Sect. 4 highlights the main findings and proposes directions for future research.

2 Materials and methods

2.1 Interval-valued intuitionistic fuzzy set

In complex decision-making environments where uncertainty and hesitation are prevalent, traditional sets often fall short of capturing the full depth of human judgment. Building upon the concept of fuzzy sets, the intuitionistic fuzzy set has been introduced to more comprehensively model uncertainty and hesitation. In this set, each element is characterized by membership and non-membership degrees. The membership degree represents the extent to which an element belongs to a given set or satisfies a specific criterion, while the non-membership degree reflects the extent to which the element does not belong to the set (Singer and Özçelik 2024).

The IVIF set enhances the intuitionistic fuzzy model by representing both membership and non-membership degrees as intervals rather than exact values. This extension is particularly useful in situations where it is difficult or impossible to assign precise degrees due to varying sources of information, subjective judgments, or inherent vagueness (Zheng and Dong 2025). Any IVIF set is defined using Eq. (1). Figure 1 shows a graphical representation of the IVIF set (Verma and Chandra 2021).

$$\tilde{A} = \left\{ x, \left[\mu_{\tilde{A}}^{-}(x), \mu_{\tilde{A}}^{+}(x) \right], \left[v_{\tilde{A}}^{-}(x), v_{\tilde{A}}^{+}(x) \right] \middle| x \in X \right\} \tag{1}$$

where:

- x denotes the specific element being evaluated in the universe of discourse X,
- $[\mu_{\tilde{A}}^{-}(x), \mu_{\tilde{A}}^{+}(x)] \subseteq [0,1]$ is the interval-valued membership degree, where $-$ and $+$ indicate the lower and upper bounds, respectively,
- $[v_{\tilde{A}}^{-}(x), v_{\tilde{A}}^{+}(x)] \subseteq [0,1]$ is the interval-valued non-membership degree, and.
- $0 \le \mu_{\tilde{A}}^{+}(x) + v_{\tilde{A}}^{+}(x) \le 1$ for all $x \in X$.

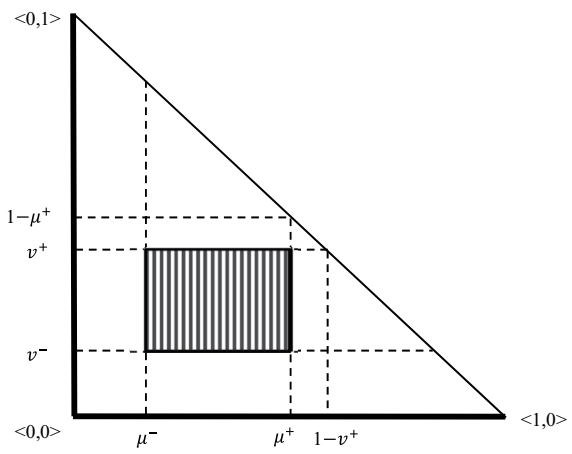

Fig. 1 Graphical representation of the IVIF set

The hesitation margin ($\pi_{\tilde{A}}(x)$), which reflects the lack of knowledge or indeterminacy, is represented by Eq. (2) (Wang et al. 2009).

$$\pi_{\tilde{A}}(x) = \left[1 - \mu_{\tilde{A}}^{+}(x) - v_{\tilde{A}}^{+}(x),\ 1 - \mu_{\tilde{A}}^{-}(x) - v_{\tilde{A}}^{-}(x) \right] \tag{2}$$

Some arithmetic operations with two IVIF numbers ($\tilde{A}$ and $\tilde{B}$) are elucidated below (Büyüközkan et al. 2018).

$$\tilde{A} \oplus \tilde{B} = \left(\left[\mu_{\tilde{A}}^{-} + \mu_{\tilde{B}}^{-} - \mu_{\tilde{A}}^{-}\mu_{\tilde{B}}^{-}, \mu_{\tilde{A}}^{+} + \mu_{\tilde{B}}^{+} - \mu_{\tilde{A}}^{+}\mu_{\tilde{B}}^{+} \right], \left[v_{\tilde{A}}^{-}v_{\tilde{B}}^{-}, v_{\tilde{A}}^{+}v_{\tilde{B}}^{+} \right] \right) \tag{3}$$

$$\tilde{A} \otimes \tilde{B} = \left(\left[\mu_{\tilde{A}}^{-}\mu_{\tilde{B}}^{-}, \mu_{\tilde{A}}^{+}\mu_{\tilde{B}}^{+} \right], \left[v_{\tilde{A}}^{-} + v_{\tilde{B}}^{-} - v_{\tilde{A}}^{-}v_{\tilde{B}}^{-}, v_{\tilde{A}}^{+} + v_{\tilde{B}}^{+} - v_{\tilde{A}}^{+}v_{\tilde{B}}^{+} \right] \right) \tag{4}$$

$$\lambda\tilde{A} = \left(\left[1 - \left(1 - \mu_{\tilde{A}}^{-}\right)^{\lambda}, 1 - \left(1 - \mu_{\tilde{A}}^{+}\right)^{\lambda} \right], \left[\left(v_{\tilde{A}}^{-}\right)^{\lambda}, \left(v_{\tilde{A}}^{+}\right)^{\lambda} \right] \right) \tag{5}$$

$$(\tilde{A})^{\lambda} = \left(\left[\left(\mu_{\tilde{A}}^{-}\right)^{\lambda}, \left(\mu_{\tilde{A}}^{+}\right)^{\lambda} \right], \left[1 - \left(1 - v_{\tilde{A}}^{-}\right)^{\lambda}, 1 - \left(1 - v_{\tilde{A}}^{+}\right)^{\lambda} \right] \right) \tag{6}$$

2.2 Interval-valued intuitionistic fuzzy step-wise weight assessment ratio analysis

SWARA is an expert-based MCDM method used to determine the relative weights of various factors. It is designed to help decision-makers prioritize and assign importance to factors when evaluating complex problems. The method begins by forming a group of experts to identify and list factors. These factors are then arranged in descending order of importance. Once the ranking is established, each expert assesses the relative importance of each factor in comparison to the one ranked immediately above it. This step-wise process continues sequentially from the most to the least important factor. In the next phase, a coefficient is calculated for each factor based on expert judgment regarding how much more important the current factor is compared to the previous one. Using this coefficient, a recalculated weight is derived for each factor. The final weights reflect the overall importance of each factor in the decision-making process (Keršulienė et al. 2010; Khoshsepehr and Alinejad 2025).

Traditional SWARA relies on precise numerical inputs from experts. However, such crisp values often fall short in capturing the inherent uncertainty and imprecision of real-world decision-making. Experts frequently struggle to express their preferences using exact values (Mohammadian et al. 2021). Fuzzy logic-based SWARA addresses this limitation by allowing experts to express their evaluations using linguistic variables, which are then converted

into fuzzy numbers. This enhancement enables SWARA to better accommodate the vagueness, uncertainty, and subjectivity of human judgment, resulting in more realistic and reliable assessments (Kundakci and Arman 2023). In this study, IVIF-SWARA is employed to address the problem at hand. The IVIF-SWARA procedure adopted in this research is detailed below.

Step 1: Constructing decision matrices.

Experts assess the significance of each factor using a weighting scale, and their individual evaluations are compiled into an initial decision matrix.

Step 2: Consolidating expert opinions.

Experts' individual judgments are combined by applying the IVIF hybrid geometric (IVIFHG) operator (Eq. (7) (Seker and Aydin 2022).

$$\begin{aligned}\mathrm{IVIFHG}\left(\tilde{A}_1, \tilde{A}_2, \ldots, \mathrm{n}\right) &= \sum_{j=1}^{\mathrm{n}} \vartheta_j \tilde{A}_{\mathrm{j}} \\ &= \left(\left[\prod_{j=1}^{\mathrm{n}} \left(\mu_j^-\right)^{\vartheta_j}, \prod_{j=1}^{\mathrm{n}} \left(\mu_j^+\right)^{\vartheta_j}\right]\right. \\ &\left., \left[1 - \prod_{j=1}^{\mathrm{n}} \left(1 - v_j^-\right)^{\vartheta_j}, 1 - \prod_{j=1}^{\mathrm{n}} \left(1 - v_j^+\right)^{\vartheta_j}\right]\right)\end{aligned} \tag{7}$$

Where $\tilde{A}_{\mathrm{j}}$ denotes the IVIF evaluation provided by the j-th expert, ϑ_j represents the weight of IVIF numbers, and n denotes the total number of experts.

Step 3: Obtaining score values (S_{j}).

IVIF values are transformed into score values by applying Eq. (8) (Xu et al. 2015; Rani et al. 2024).

$$S_{\mathrm{j}}\left(\tilde{A}\right) = \frac{\left(\frac{\mu_{\tilde{A}}^- - v_{\tilde{A}}^- + \mu_{\tilde{A}}^+ - v_{\tilde{A}}^+}{2} + 1\right)}{2} \tag{8}$$

Step 4: Ranking factors.

Factors are ranked in descending order according to their score values.

Step 5: Determining comparative importance (s_j).

The comparative importance of each factor j is determined by comparing it with the preceding factor j-1.

Table 1 IVIF evaluation scale

Linguistic term	IVIF number			
	μ^-	μ^+	v^-	v^+
Absolutely low importance (ALI)	0.10	0.25	0.65	0.75
Very low importance (VLI)	0.15	0.30	0.60	0.70
Low importance (LI)	0.20	0.35	0.55	0.65
Medium low importance (MLI)	0.25	0.40	0.50	0.60
Equal importance (EI)	0.50	0.50	0.50	0.50
Medium high importance (MHI)	0.50	0.60	0.25	0.40
High importance (HI)	0.55	0.65	0.20	0.35
Very high importance (VHI)	0.60	0.70	0.15	0.30
Absolutely high importance (AHI)	0.65	0.75	0.10	0.25

Step 6: Computing comparative coefficients (k_j).

Comparative coefficients are calculated using Eq. (9).

$$k_j = \begin{cases} 1 & j = 1 \\ s_j^* + 1 & j > 1 \end{cases} \tag{9}$$

Step 7: Calculating recalculated weights (q_j).

Recalculated weights are determined using Eq. (10).

$$q_j = \begin{cases} 1 & j = 1 \\ \frac{q_{j-1}}{k_j} & j > 1 \end{cases} \tag{10}$$

Step 8: Determining weight vectors (w_j).

The final weights (w_{j}) of factors are obtained using Eq. (11).

$$w_{\mathrm{j}} = \frac{q_{\mathrm{j}}}{\sum_{j=1}^{\mathrm{m}} \mathrm{q}_j} \tag{11}$$

The IVIF scale considered in the evaluation process is given in Table 1 (Dogan et al. 2020). A structured questionnaire is used as the primary data collection instrument to obtain expert evaluations. Participants receive an assessment form together with the linguistic rating scale shown in Table 1, which allows qualitative professional judgments to be represented using IVIF numbers. The form is structured to reflect the hierarchical organization of the decision problem, featuring distinct sections for each level of the factor tree. Within these sections, comparison tables are utilized. Factors are presented in a comparative layout that facilitates the step-wise ranking process. Experts select the most appropriate linguistic term from the scale for each factor to reflect its relative importance. The transformation from linguistic terms to IVIF numbers is performed by the researcher by systematically mapping each expert-selected label to the corresponding numerical intervals defined in the scale. This procedure provides quantitative inputs required for the IVIF-SWARA analysis.

2.3 Decision-making framework

Engineered timber structures present fire safety challenges due to the combustible nature of wood and the complexity of hybrid construction systems. This multifaceted issue requires a systematic evaluation and prioritization of numerous factors, each contributing differently to overall fire safety. To address this complexity and provide a structured decision-making pathway, this study proposes an IVIF-SWARA model to evaluate and rank fire safety measures under conditions of uncertainty. The decision-making framework considered in the study is illustrated in Fig. 2. This framework consists of the following key phases:

- Problem structuring: A comprehensive set of fire safety measures is identified through a literature review and consultations with experts.
- Expert-based IVIF-SWARA analysis: Expert evaluations are collected using IVIF scales to determine the relative importance of each fire safety measure.
- Factor prioritization: This phase produces a ranked list of fire safety priorities.
- Robustness analysis: The obtained results are evaluated through both sensitivity analysis and comparison with an alternative weighting method to demonstrate the consistency and reliability of the prioritization outcomes.

To clarify the computational flow, the following pseudocode outlines the implementation of IVIF-SWARA:

Inputs: n: number of factors (j = 1 to n), t: number of experts (h = 1 to t), Factor evaluations	
Output: Weights corresponding to each factor	
Begin	
// Step 1: Identify the factors to be evaluated	
For h = 1 to t do:	
// Step 2: Collect the evaluations from the experts and translate the verbal labels into IVIF numbers	Based on Table 1
// Step 3: Aggregate the expert evaluations	Using Equation (7)
End for	
For j = 1 to n do:	
// Step 4: Compute the score values for the factors	Using Equation (8)
// Step 5: Identify the importance of each factor based on the score values	
// Step 6: Compute the comparative coefficients	Using Equation (9)
// Step 7: Determine the recalculated weights	Using Equation (10)
// Step 8: Determine the final weights	Using Equation (11)
End for	
// Step 9: Rank the factors in descending order based on the weights	
End	

Expert evaluations form the foundation of this study's decision-making model. To ensure the reliability and depth of the collected input, experts are selected based on the following criteria: (i) possession of an advanced academic degree; (ii) a minimum of ten years of professional experience; (iii) contributions to scientific publications and technical reports; and (iv) prior experience with MCDM methods or similar analytical frameworks. A total of nine experts participate in the study. They are purposefully selected to represent a broad spectrum of perspectives and expertise. The expert panel includes structural engineers, fire safety consultants, architects, regulatory authorities, and academics. This interdisciplinary composition is essential to ensure a well-rounded and context-sensitive evaluation. Prior to the evaluation process, the experts are provided with a structured explanation of the assessment procedure and a shared understanding of the factor definitions.

Fire safety measures are labeled as factors in the study. Factors are determined through a two-stage process that combines a literature review and expert consultation. First, a review of academic publications takes place. This review forms the basis for a preliminary list of factors. The draft list is shared with the experts for critical evaluation. During this phase, each expert assesses the factors based on their relevance to fire safety applications, their completeness in addressing the problem, and their significance. The list is refined by clarifying factor definitions, merging overlapping elements, removing redundant factors, and adding new factors. As a result of this process, a decision tree with five main factors and twenty-five subfactors is established. The hierarchical structure of the factors is presented in Fig. 3. This structure is organized into three distinct levels: Level 1 represents the overall goal of the analysis; Level 2 includes the main fire safety factors; and Level 3 consists of the associated subfactors.

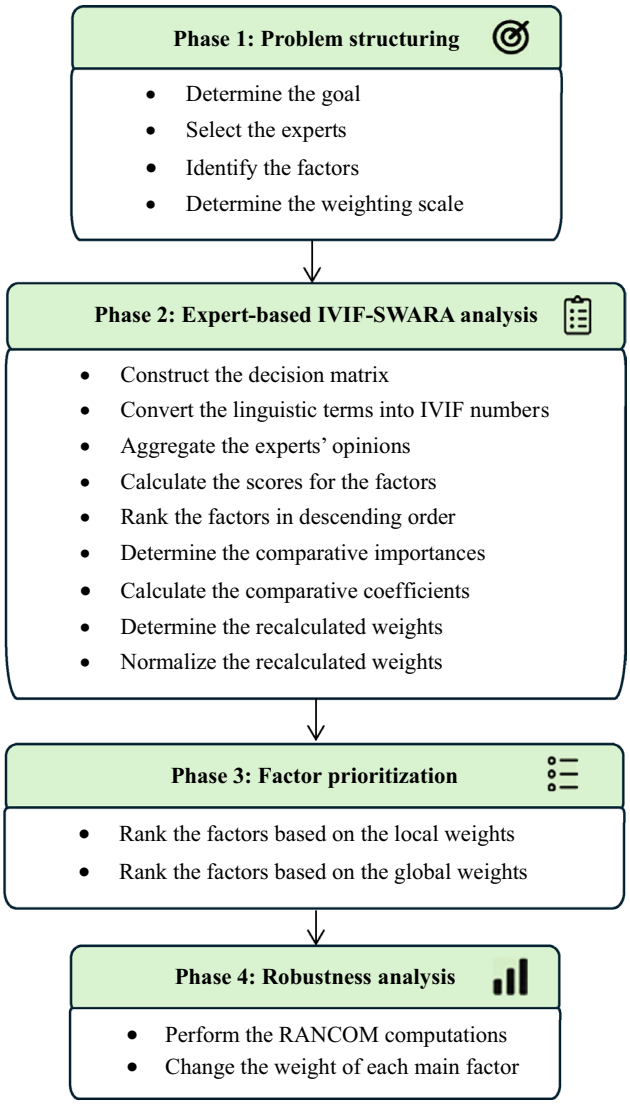

Fig. 2 Flowchart of the decision-making approach

3 Results and discussion

3.1 IVIF-SWARA results

The data required for the IVIF-SWARA analysis are gathered through structured interviews conducted with the selected experts. Each expert is provided with a detailed questionnaire designed to elicit their judgments on the importance of the factors. To ensure consistency and clarity in expert evaluations, the questionnaire incorporates a predefined set of linguistic variables representing different levels of importance. The linguistic evaluations collected from the experts are presented in Table 2.

As linguistic expressions are not mathematically operable in their original form, the evaluations provided by the experts are first converted by the researchers into their corresponding IVIF numbers using the predefined scale in Table 1. This transformation allows the qualitative assessments to be processed quantitatively within the IVIF-SWARA framework. Following the conversion, the individual expert evaluations are aggregated to obtain a collective decision matrix. The aggregation is performed using Eq. (7) (Seker and Aydin 2022). The resulting aggregated IVIF weights for each factor are presented in Table 3.

The score values for each factor are derived from the aggregated IVIF evaluations provided in Table 3. It should be noted that the score values obtained in Step 3 of the IVIF-SWARA method represent the initial performance inputs. These scores are used as input data in the comparative evaluation stage, in which the final importance of each factor is determined using IVIF-SWARA. Thereafter, Steps 4 through 8 of the IVIF-SWARA methodology are implemented to obtain weight vectors. The results of the IVIF-SWARA-based prioritization process are presented in Tables 4, 5, 6, 7, 8 and 9. The ranking of the factors presented in these tables is established in descending order based on the score values. This sequence represents the preliminary importance hierarchy required for the SWARA comparative assessment. In the tables, the comparative coefficients (k_j) and the recalculated weights (q_j) are calculated using Eq. (9) and Eq. (10), respectively. The final weights of the factors are obtained by applying Eq. (11) to the values in the last column of each table.

The importance of the main factors is illustrated in Fig. 4. According to the results, the most important main factor is "passive fire protection and compartmentation applications". The second most important main factor is "fire-resistant structural design and reinforcement". "Managerial measures and regulatory compliance" receives the lowest weight among the main factors. This result suggests that procedural and regulatory efforts are perceived as supportive rather than primary mechanisms in the overall fire safety strategy.

The results of the IVIF-SWARA analysis for the subfactors within the "fire-resistant structural design and reinforcement" group are presented in Fig. 5. The most important subfactor is identified as "cross-section optimization and load-bearing capacity". This highlights the foundational role of structural design in maintaining the integrity of timber components under elevated temperatures. Proper dimensioning not only affects the charring rate and residual strength of wood but also determines how long a structural member can fulfill its intended function during fire exposure. Closely following is "fire resistance and protection of connection elements". Connection points are often the weakest links under fire conditions. Their protection through intumescent coatings, encapsulation, or design detailing is essential to prevent early failure and preserve structural continuity. "Isolation of concealed cavities and

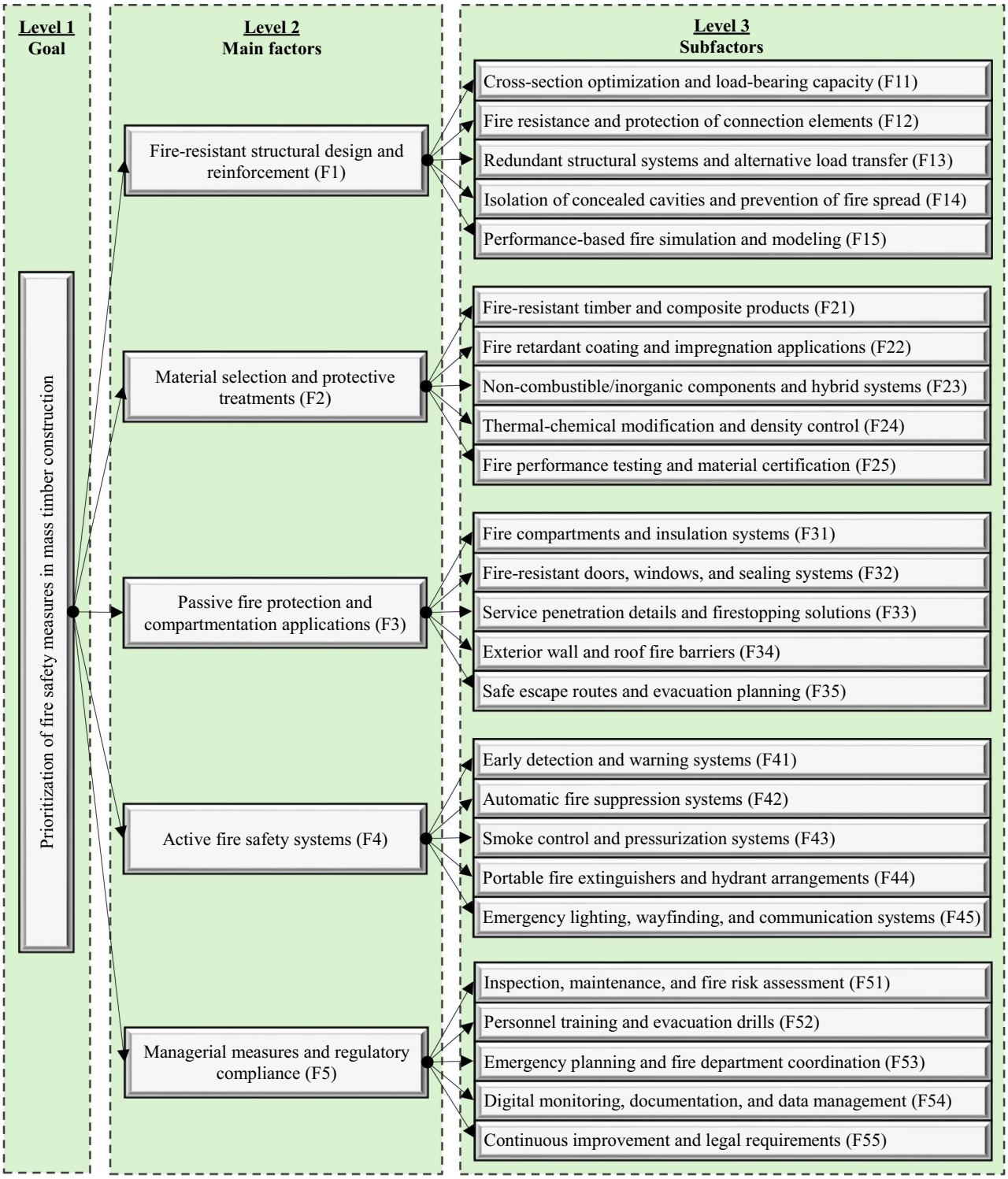

Fig. 3 Hierarchical structure of the factors

prevention of fire spread" is identified as the third most important subfactor. Hidden voids within walls, ceilings, or flooring systems can facilitate rapid fire propagation if not properly sealed or compartmentalized. In addition, fires in hidden cavities are often difficult to detect and suppress due to limited accessibility. Addressing these voids is crucial for delaying internal fire development and maintaining compartmental integrity. "Performance-based fire simulation and modeling" is ranked as the least important subfactor. While advanced modeling supports predictive analyses and

Table 2 Expert evaluations of the factors using linguistic terms

Factor	Expert-1	Expert-2	Expert-3	Expert-4	Expert-5	Expert-6	Expert-7	Expert-8	Expert-9
F1. Fire-resistant structural design and reinforcement	VHI	AHI	AHI	VHI	VHI	VHI	VHI	VHI	VHI
F2. Material selection and protective treatments	MHI	HI	VHI	VHI	HI	HI	HI	VHI	HI
F3. Passive fire protection and compartmentation applications	AHI	VHI	VHI	VHI	AHI	AHI	VHI	VHI	AHI
F4. Active fire safety systems	HI	MHI	HI	VHI	HI	AHI	HI	VHI	HI
F5. Managerial measures and regulatory compliance	EI	EI	MHI	HI	MHI	HI	EI	MHI	EI
F11. Cross-section optimization and load-bearing capacity	HI	VHI	VHI	VHI	HI	VHI	HI	HI	VHI
F12. Fire resistance and protection of connection elements	VHI	HI	HI	HI	HI	AHI	HI	VHI	HI
F13. Redundant structural systems and alternative load transfer	MHI	MHI	AHI	MHI	MHI	HI	MHI	MHI	MHI
F14. Isolation of concealed cavities and prevention of fire spread	AHI	EI	MHI	HI	VHI	HI	VHI	HI	VHI
F15. Performance-based fire simulation and modeling	MLI	MLI	EI	EI	MHI	MHI	EI	EI	MHI
F21. Fire-resistant timber and composite products	VHI	VHI	VHI	VHI	VHI	VHI	VHI	VHI	VHI
F22. Fire retardant coating and impregnation applications	HI	HI	AHI	HI	HI	VHI	HI	HI	HI
F23. Non-combustible/inorganic components and hybrid systems	MHI	MHI	HI	MHI	MHI	HI	MHI	HI	MHI
F24. Thermal-chemical modification and density control	MLI	MLI	MHI	EI	EI	MHI	EI	EI	EI
F25. Fire performance testing and material certification	EI	EI	HI	HI	HI	VHI	VHI	MHI	HI
F31. Fire compartments and insulation systems	AHI	AHI	AHI	VHI	VHI	AHI	AHI	AHI	AHI
F32. Fire-resistant doors, windows, and sealing systems	VHI	HI	VHI	HI	HI	VHI	VHI	VHI	VHI
F33. Service penetration details and firestopping solutions	HI	MHI	HI	MHI	MHI	HI	HI	MHI	HI
F34. Exterior wall and roof fire barriers	EI	MLI	MHI	MHI	HI	MHI	MHI	MHI	MHI
F35. Safe escape routes and evacuation planning	MHI	VHI	AHI	VHI	AHI	AHI	VHI	AHI	VHI
F41. Early detection and warning systems	AHI	VHI	AHI	VHI	VHI	AHI	AHI	AHI	AHI
F42. Automatic fire suppression systems	VHI	HI	VHI	VHI	AHI	VHI	HI	AHI	VHI
F43. Smoke control and pressurization systems	HI	MHI	HI	HI	HI	HI	MHI	MHI	HI
F44. Portable fire extinguishers and hydrant arrangements	EI	EI	MHI	MHI	MHI	HI	MHI	EI	MHI
F45. Emergency lighting, wayfinding, and communication systems	MHI	MHI	AHI	HI	MHI	VHI	MHI	HI	HI
F51. Inspection, maintenance, and fire risk assessment	VHI	HI	AHI	HI	HI	HI	HI	HI	HI
F52. Personnel training and evacuation drills	MHI	MHI	VHI	HI	MHI	HI	HI	VHI	VHI
F53. Emergency planning and fire department coordination	HI	MHI	AHI	HI	VHI	VHI	MHI	VHI	HI
F54. Digital monitoring, documentation, and data management	MLI	MLI	MHI	EI	MHI	MHI	MLI	MLI	EI
F55. Continuous improvement and legal requirements	EI	EI	HI	MHI	HI	HI	EI	MHI	MHI

Table 3 Aggregated weights for the factors

Factor	μ^-	μ^+	v^-	v^+
F1. Fire-resistant structural design and reinforcement	0.61	0.71	0.14	0.29
F2. Material selection and protective treatments	0.56	0.66	0.19	0.34
F3. Passive fire protection and compartmentation applications	0.62	0.72	0.13	0.28
F4. Active fire safety systems	0.57	0.67	0.18	0.33
F5. Managerial measures and regulatory compliance	0.51	0.56	0.36	0.44
F11. Cross-section optimization and load-bearing capacity	0.58	0.68	0.17	0.32
F12. Fire resistance and protection of connection elements	0.57	0.67	0.18	0.33
F13. Redundant structural systems and alternative load transfer	0.52	0.62	0.23	0.38
F14. Isolation of concealed cavities and prevention of fire spread	0.56	0.65	0.22	0.35
F15. Performance-based fire simulation and modeling	0.43	0.51	0.43	0.49
F21. Fire-resistant timber and composite products	0.60	0.70	0.15	0.30
F22. Fire retardant coating and impregnation applications	0.57	0.67	0.18	0.33
F23. Non-combustible/inorganic components and hybrid systems	0.52	0.62	0.23	0.38
F24. Thermal-chemical modification and density control	0.43	0.50	0.45	0.50
F25. Fire performance testing and material certification	0.54	0.62	0.27	0.38
F31. Fire compartments and insulation systems	0.64	0.74	0.11	0.26
F32. Fire-resistant doors, windows, and sealing systems	0.58	0.68	0.17	0.32
F33. Service penetration details and firestopping solutions	0.53	0.63	0.22	0.37
F34. Exterior wall and roof fire barriers	0.47	0.57	0.31	0.43
F35. Safe escape routes and evacuation planning	0.61	0.71	0.14	0.29
F41. Early detection and warning systems	0.63	0.73	0.12	0.27
F42. Automatic fire suppression systems	0.60	0.70	0.15	0.30
F43. Smoke control and pressurization systems	0.53	0.63	0.22	0.37
F44. Portable fire extinguishers and hydrant arrangements	0.51	0.57	0.34	0.43
F45. Emergency lighting, wayfinding, and communication systems	0.54	0.64	0.21	0.36
F51. Inspection, maintenance, and fire risk assessment	0.57	0.67	0.18	0.33
F52. Personnel training and evacuation drills	0.55	0.65	0.20	0.35
F53. Emergency planning and fire department coordination	0.56	0.67	0.18	0.33
F54. Digital monitoring, documentation, and data management	0.37	0.48	0.43	0.52
F55. Continuous improvement and legal requirements	0.52	0.58	0.33	0.42

Table 4 IVIF-SWARA analysis for the main factors

Main factor	Score	s_j	k_j	q_j
F3. Passive fire protection and compartmentation applications	0.734	-	1.000	1.000
F1. Fire-resistant structural design and reinforcement	0.723	0.011	1.011	0.989
F4. Active fire safety systems	0.678	0.045	1.045	0.946
F2. Material selection and protective treatments	0.673	0.005	1.005	0.941
F5. Managerial measures and regulatory compliance	0.568	0.105	1.105	0.852

Table 5 IVIF-SWARA analysis for the "fire-resistant structural design and reinforcement" group

Subfactor	Score	s_j	k_j	q_j
F11. Cross-section optimization and load-bearing capacity	0.690	-	1.000	1.000
F12. Fire resistance and protection of connection elements	0.684	0.006	1.006	0.994
F14. Isolation of concealed cavities and prevention of fire spread	0.662	0.022	1.022	0.973
F13. Redundant structural systems and alternative load transfer	0.633	0.029	1.029	0.945
F15. Performance-based fire simulation and modeling	0.503	0.130	1.130	0.837

Table 6 IVIF-SWARA analysis for the "material selection and protective treatments" group

Subfactor	Score	s_j	k_j	q_j
F21. Fire-resistant timber and composite products	0.713	-	1.000	1.000
F22. Fire retardant coating and impregnation applications	0.678	0.034	1.034	0.967
F23. Non-combustible/inorganic components and hybrid systems	0.629	0.050	1.050	0.921
F25. Fire performance testing and material certification	0.626	0.003	1.003	0.919
F24. Thermal-chemical modification and density control	0.492	0.134	1.134	0.810

Table 7 IVIF-SWARA analysis for the "passive fire protection and compartmentation applications" group

Subfactor	Score	s_j	k_j	q_j
F31. Fire compartments and insulation systems	0.751	-	1.000	1.000
F35. Safe escape routes and evacuation planning	0.722	0.029	1.029	0.972
F32. Fire-resistant doors, windows, and sealing systems	0.695	0.027	1.027	0.947
F33. Service penetration details and firestopping solutions	0.640	0.056	1.056	0.897
F34. Exterior wall and roof fire barriers	0.573	0.067	1.067	0.841

design optimization, its relative importance is perceived as supplementary compared to physical design measures.

The IVIF-SWARA analysis for the "material selection and protective treatments" group reveals the weights of

Table 8 IVIF-SWARA analysis for the "active fire safety systems" group

Subfactor	Score	s_j	k_j	q_j
F41. Early detection and warning systems	0.745	-	1.000	1.000
F42. Automatic fire suppression systems	0.712	0.034	1.034	0.967
F45. Emergency lighting, wayfinding, and communication systems	0.655	0.057	1.057	0.916
F43. Smoke control and pressurization systems	0.645	0.010	1.010	0.907
F44. Portable fire extinguishers and hydrant arrangements	0.576	0.069	1.069	0.848

Table 9 IVIF-SWARA analysis for the "managerial measures and regulatory compliance" group

Subfactor	Score	s_j	k_j	q_j
F51. Inspection, maintenance, and fire risk assessment	0.678	-	1.000	1.000
F53. Emergency planning and fire department coordination	0.678	0.001	1.001	0.999
F52. Personnel training and evacuation drills	0.661	0.016	1.016	0.983
F55. Continuous improvement and legal requirements	0.586	0.075	1.075	0.915
F54. Digital monitoring, documentation, and data management	0.476	0.111	1.111	0.823

the subfactors within this group, as shown in Fig. 6. The top-ranked subfactor is "fire-resistant timber and composite products". Engineered wood products significantly contribute to a building's ability to resist fire. Composite configurations offer enhanced structural and thermal stability during fire exposure. The next most important subfactor is "fire retardant coating and impregnation applications". Surface treatments and impregnation techniques extend ignition time and reduce flame spread. These applications are particularly critical in retrofitting and exposed wood design scenarios. "Non-combustible/inorganic components and hybrid systems" is considered moderately significant. Incorporating materials such as gypsum boards, cementitious panels, or mineral wool as part of a hybrid timber system can effectively delay heat penetration and improve compartmentation. These components act as thermal buffers, slowing the temperature rise in timber members and enhancing overall system performance during fire events. The least prioritized subfactor is "thermal-chemical modification and density control". Although such modifications can influence the ignition characteristics, charring behavior, and thermal degradation processes of timber, their contribution to overall fire safety is generally indirect and material-specific when compared to system-level protective strategies.

The weights calculated for the "passive fire protection and compartmentation applications" group are presented in Fig. 7. The most important subfactor emerges as "fire compartments and insulation systems". This underscores the critical role of compartmentation in preventing both horizontal and vertical fire spread within buildings. Properly designed and insulated compartments can effectively localize fire. Closely following in importance is "safe escape routes and evacuation planning". The layout and integrity of escape pathways directly influence occupant safety during fire emergencies. Ranked third is "fire-resistant doors, windows, and sealing systems". Openings in fire compartments represent potential weak points; if inadequately protected, they can compromise the effectiveness of the entire fire separation strategy. "Service penetration details and fire-stopping solutions" is ranked fourth. These elements ensure the continuity of fire-resistive barriers at points where electrical, mechanical, or plumbing systems intersect compartments. "Exterior wall and roof fire barriers" receives the lowest weight.

The weight distribution of the "active fire safety systems" group can be seen in Fig. 8. The highest-ranked subfactor within this group is "early detection and warning

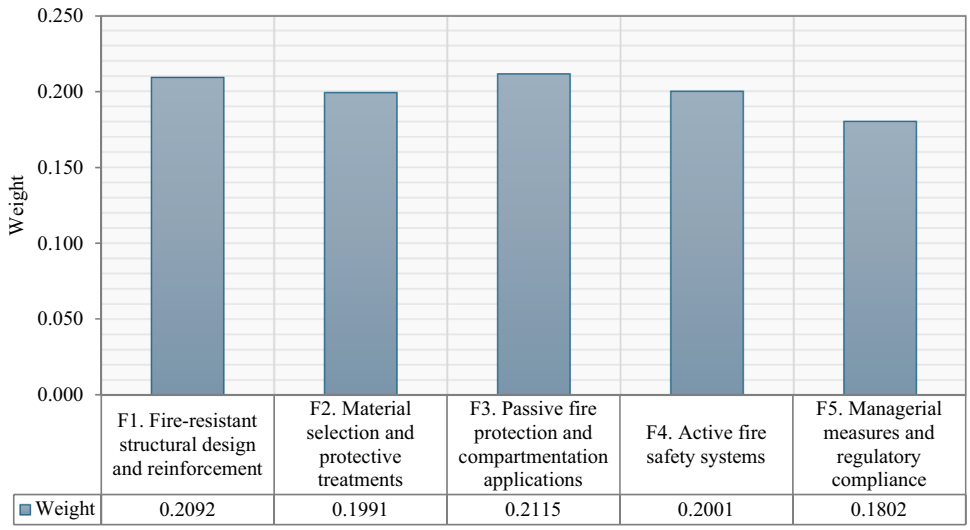

Fig. 4 Model results for the main factors

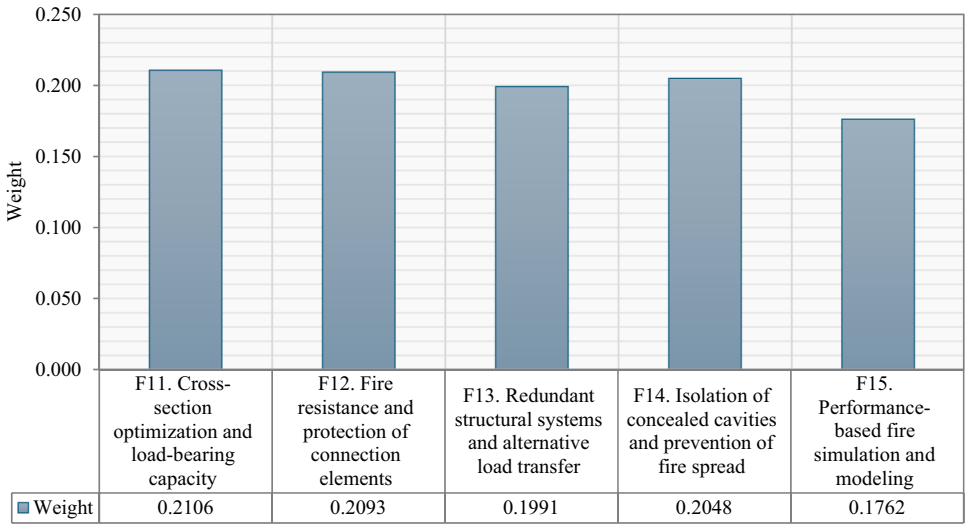

Fig. 5 Model results for the "fire-resistant structural design and reinforcement" group

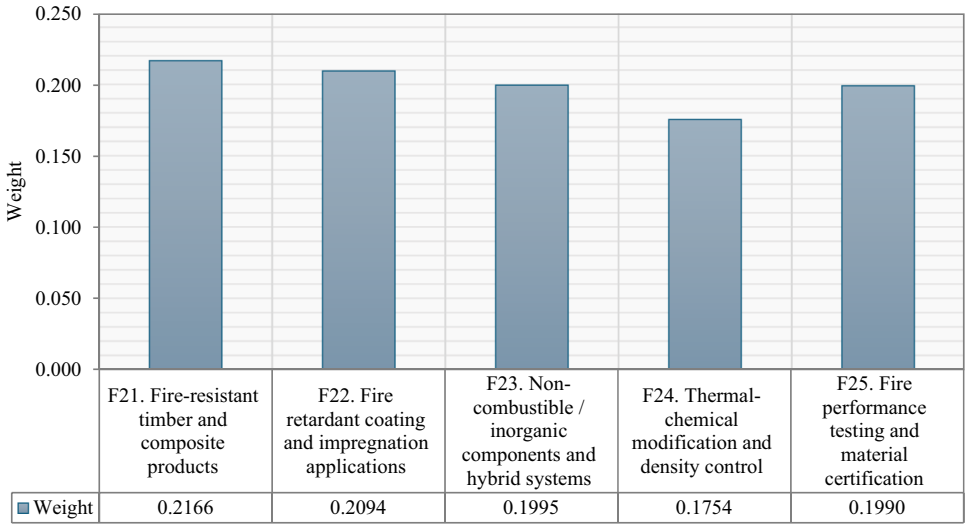

Fig. 6 Model results for the "material selection and protective treatments" group

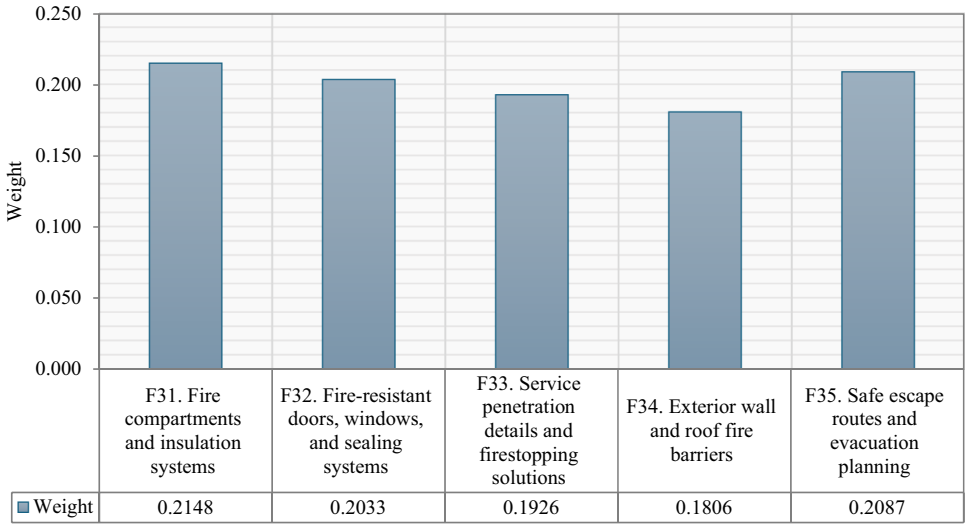

Fig. 7 Model results for the "passive fire protection and compartmentation applications" group

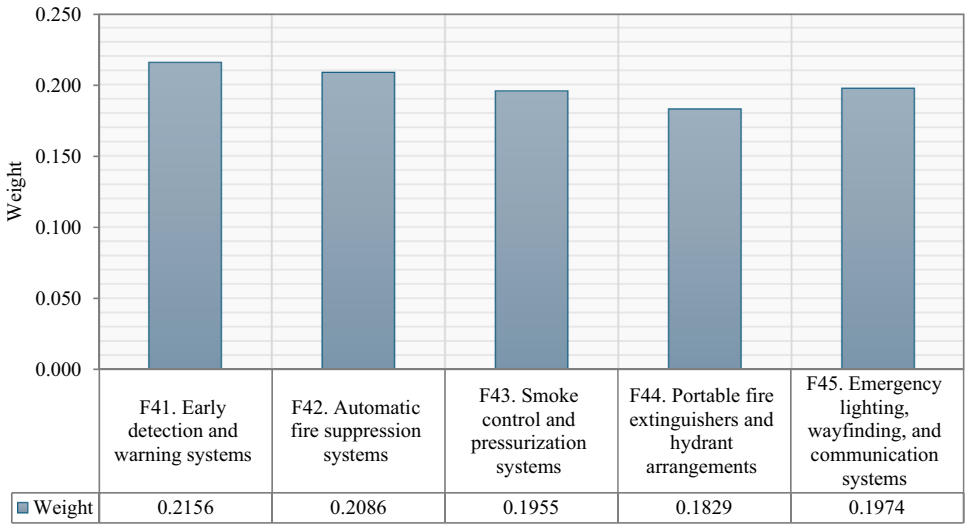

Fig. 8 Model results for the "active fire safety systems" group

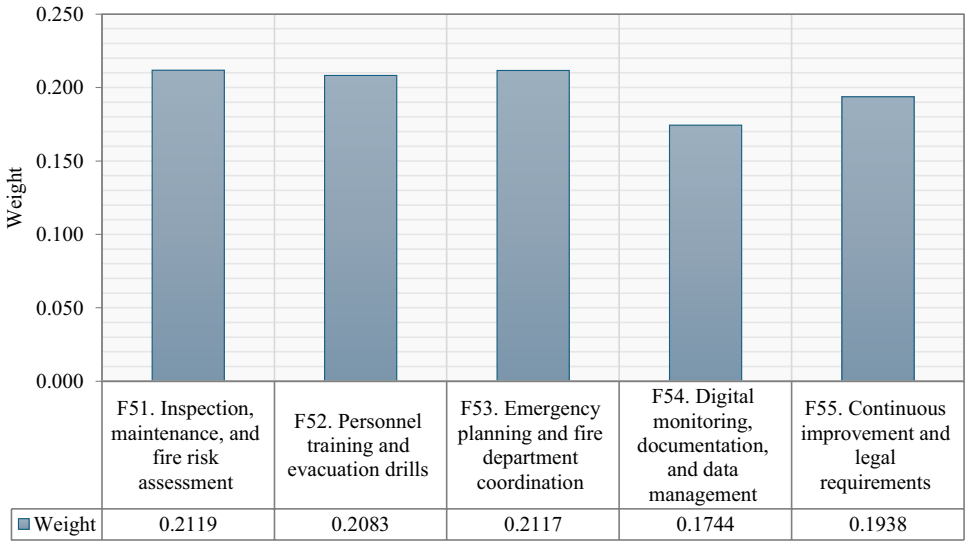

Fig. 9 Model results for the "managerial measures and regulatory compliance" group

systems". The timely identification of fire incidents plays an important role in minimizing both human and structural losses. In buildings with combustible elements, rapid detection becomes even more critical to initiate suppression measures and evacuation procedures before a fire escalates. Advanced smoke and heat detectors are viewed as essential in providing occupants and emergency responders with valuable lead time. "Automatic fire suppression systems" follows closely. These systems, such as sprinklers or mist systems, are designed to control or extinguish fires automatically upon activation. "Emergency lighting, wayfinding, and communication systems" is identified as the third most important subfactor. In fire scenarios where visibility is compromised, these systems enhance situational awareness and reduce panic. They are especially critical in large or complex buildings where unfamiliar layouts can hinder egress during emergencies. "Smoke control and pressurization systems" is nearly equally valued. These systems help manage smoke movement and maintain tenable conditions in escape routes such as stairwells and corridors. The least important subfactor is "portable fire extinguishers and hydrant arrangements". In complex timber structures, where fire development can be rapid and visibility conditions may deteriorate quickly, reliance on manual firefighting measures may be perceived as less reliable in the early stages of fire growth. For this reason, the experts may regard portable extinguishing and hydrant systems as essential supportive measures, yet secondary to automated and integrated fire safety systems in terms of overall risk reduction at the building scale.

Figure 9 shows the weights calculated for the subfactors of "managerial measures and regulatory compliance". The most important subfactor is "inspection, maintenance, and fire risk assessment". Regular inspections and maintenance ensure that fire protection systems remain operational and effective over time. Fire risk assessments allow for the

identification and mitigation of vulnerabilities. The second most important subfactor is "emergency planning and fire department coordination". Effective collaboration with local fire services, combined with scenario-specific emergency plans, enables faster, more informed responses. On the other hand, clear communication and joint preparedness can significantly impact the success of emergency operations. It should be noted that the weights of these two leading factors are very close, suggesting that they represent similarly critical priorities in fire safety design rather than distinctly separated levels of importance. "Personnel training and evacuation drills" is the third most important subfactor. Even the most advanced safety systems can fail if occupants are unprepared or unaware of correct response protocols. Frequent evacuation drills and fire safety training ensure that building users and staff can respond calmly and efficiently. The lowest-ranked subfactor is "digital monitoring, documentation, and data management". Although digital tools can significantly aid in record-keeping, system monitoring, and regulatory audits, the experts appear to prioritize more action-driven managerial functions.

The local weight of each subfactor is multiplied by the corresponding weight of its main factor. This step is fundamental to establishing a universal priority list that transcends individual categories, allowing for a direct comparison between all subfactors within the entire system. While local weights reflect the priority within a specific cluster, global weights represent the absolute contribution of each factor to the overall objective. The global weights of the subfactors are obtained as presented in Fig. 10. The observed similarity between local and global rankings is interpreted as a validation of the internal consistency of the expert evaluations.

According to Fig. 10, the five most important factors are "fire compartments and insulation systems", "safe escape routes and evacuation planning", "cross-section optimization and load-bearing capacity", "fire resistance and protection of connection elements", and "early detection and warning systems". These factors share a strong common characteristic. They directly influence life safety and



Fig. 10 Global importance of the factors

structural stability during the early and most critical stages of fire development. These factors operate at the building-system level and contribute either to controlling fire spread, maintaining structural integrity under thermal exposure, or enabling timely evacuation and intervention. Their high ranking indicates that the experts prioritize measures that provide immediate, system-wide risk reduction rather than localized or secondary protections. The lowest-ranked factors are "thermal-chemical modification and density control", "continuous improvement and legal requirements", and "digital monitoring, documentation, and data management". These factors are categorized as secondary preventive measures due to their indirect influence on immediate fire outcomes. While material enhancements and administrative protocols are recognized for their long-term contributions to fire safety, they are perceived by the expert panel as less critical than active suppression and life safety systems.

The proposed IVIF-SWARA-based framework offers a practical methodology for evaluating the fire safety performance of engineered timber buildings. The identified factors can be organized into an evaluation checklist. Decision-makers may apply the framework through a systematic multi-step procedure: (i) building inspectors or fire safety consultants assess individual buildings by assigning performance scores to each factor; (ii) the IVIF-SWARA-derived weights are then applied to these scores to account for the relative criticality of each element; and (iii) a composite fire safety performance index is calculated for each building. This index enables the objective comparison and ranking of multiple buildings, supporting data-driven decision-making for risk mitigation. The weighted scores obtained from IVIF-SWARA can also serve as inputs to MCDM ranking methods, such as TOPSIS, to systematically rank buildings from best to worst fire safety performance. Regulatory authorities may adopt the proposed framework as a transparent and replicable tool for performance-based evaluations, compliance monitoring, and the identification of buildings requiring urgent intervention. This structured approach ensures that critical fire safety measures receive appropriate attention during both the design and operational phases.

3.2 Comparative analysis

Conducting a comparative analysis is essential in MCDM studies, as it enhances the validity of model results by providing cross-methodological verification (Pramanik et al. 2021). In this study, a comparison is carried out between IVIF-SWARA and RANCOM (Więckowski et al. 2023) to assess the consistency of the factor prioritization outcomes. The primary aim of this comparison is to evaluate whether the ranking of the factors remains stable across different analytical models. Figure 11 illustrates the comparative results derived from the methods. The findings demonstrate a high degree of agreement between IVIF-SWARA and RANCOM, particularly in identifying the top five most critical factors. While the average weights obtained from SWARA and RANCOM are found to be consistent, notable differences are observed in the statistical dispersion of the results. RANCOM exhibits more pronounced peaks and valleys, whereas a narrower range and smaller standard deviations

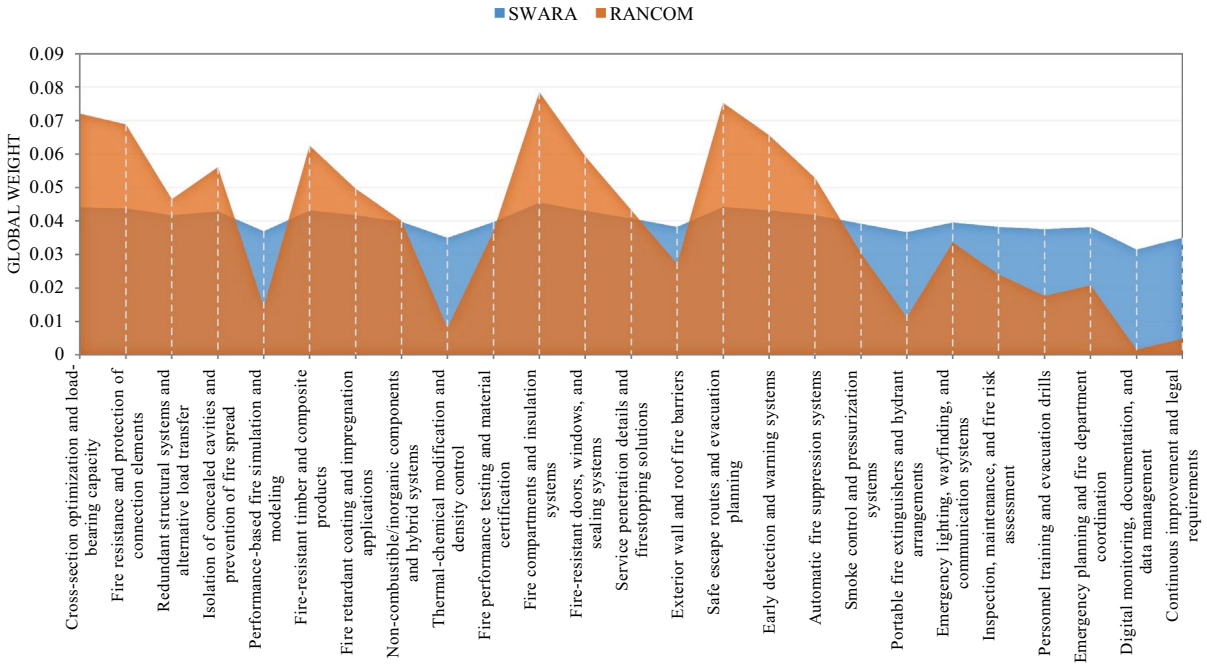

Fig. 11 Cross-method validation of the prioritized factors

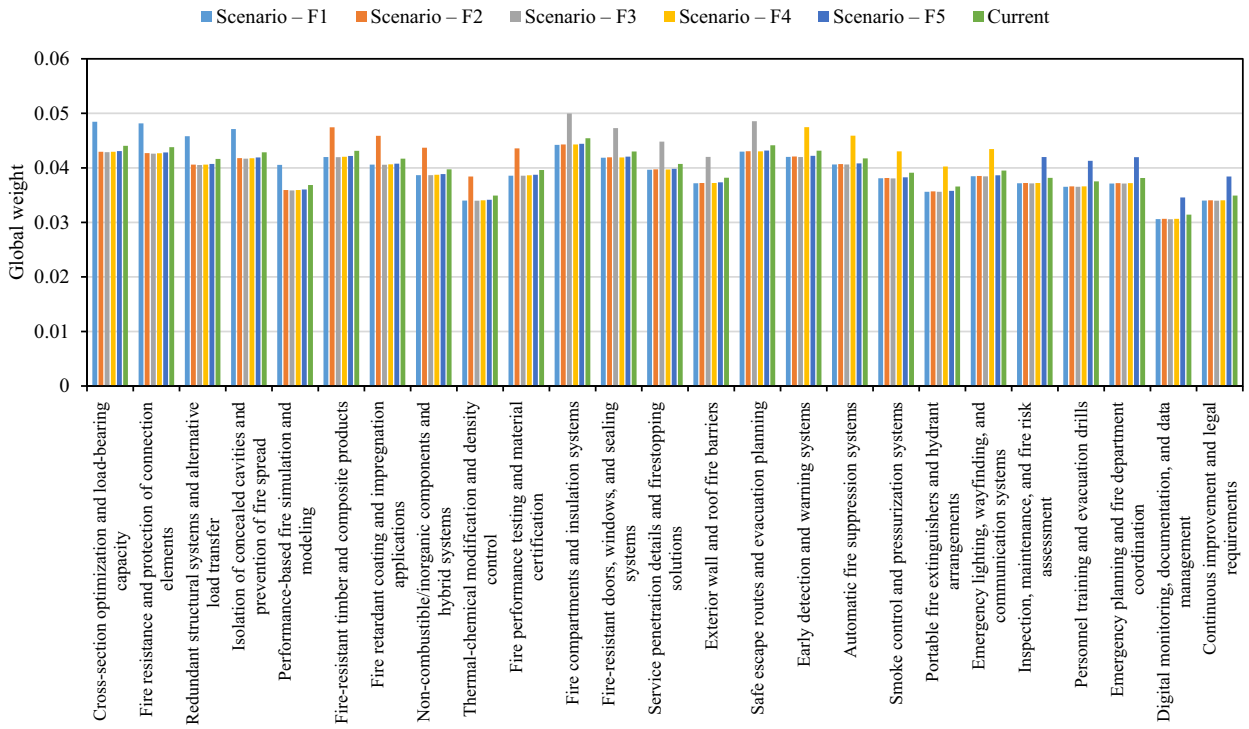

Fig. 12 Sensitivity analysis results

are produced by SWARA. This discrepancy is attributed to the inherent evaluation logic of each method. By balancing divergences in expert judgments, the SWARA framework provides a more homogeneous and stable representation of the decision-making process. Although slight variations exist in the weight assignments, the methods produce a similar ordering of priorities. This alignment reinforces the credibility of the results and supports the methodological soundness of the proposed model.

3.3 Sensitivity analysis

Sensitivity analysis is a critical step in any decision-making framework involving expert judgment and multicriteria assessment, as it evaluates the stability of model results against potential variations in input parameters. In particular, it examines how changes in the weights of factors influence the final prioritization of decision elements. This type of analysis is essential for understanding the reliability of model outputs and for validating whether the decision-making process is sensitive to minor perturbations in expert-provided data (Więckowski and Sałabun 2023; Demir et al. 2024). In this study, sensitivity analysis is employed to assess the stability of the factor prioritization results derived from IVIF-SWARA. This analysis is conducted by systematically increasing the weight of each main factor by 10%, while proportionally adjusting the weights of the remaining factors to maintain the total sum of weights as 1. This process is repeated for all the main factors identified in the factor prioritization phase, resulting in five distinct scenarios. For each scenario, the factors are re-ranked based on the adjusted weights, and the new prioritization is compared with the original ranking obtained from IVIF-SWARA. The obtained results are given in Fig. 12.

The results reveal that “fire compartments and insulation systems”, “safe escape routes and evacuation planning”, “cross-section optimization and load-bearing capacity”, “fire resistance and protection of connection elements”, and “early detection and warning systems” consistently rank among the top priorities across all the scenarios. This indicates that these factors maintain a high level of importance regardless of the weighting scheme, thereby confirming the stability and reliability of the model. Overall, the results suggest that the decision-making framework is both stable and adaptable, yielding robust outcomes under varying preference structures.

4 Conclusion

This study identifies, categorizes, evaluates, and prioritizes fire safety measures in engineered timber buildings through the application of the IVIF-SWARA decision-making model. The results demonstrate that the objective is successfully achieved. By integrating a comprehensive fire safety factor structure with IVIF-SWARA, the proposed

framework systematically translates expert knowledge into a transparent and quantifiable prioritization scheme. Based on the global weights, the most critical factors are identified as follows:

1. "Fire compartments and insulation systems".
2. "Safe escape routes and evacuation planning".
3. "Cross-section optimization and load-bearing capacity".
4. "Fire resistance and protection of connection elements".
5. "Early detection and warning systems".

The consistency of the ranking results, together with the comparative and sensitivity analyses, indicates that the framework is suitable for determining the most critical fire design considerations in timber buildings. The findings present a roadmap for designers, engineers, and policy-makers seeking to enhance fire resilience in modern timber structures.

The findings of this study offer several critical implications for decision-makers involved in the planning, design, and regulation of fire-safe timber buildings. The prioritization results enable construction firms, developers, and safety officers to allocate resources more effectively, ensuring that the most critical fire safety measures receive adequate attention. Additionally, the integration of expert judgment and fuzzy modeling allows for informed decision-making even under conditions of uncertainty, making this framework particularly valuable in complex or innovative timber projects. The results also support regulatory bodies in performance-based safety assessments tailored to the unique properties of engineered timber systems.

While this study presents a comprehensive and structured prioritization of fire safety measures in engineered timber buildings, several limitations should be acknowledged. First, the proposed model relies heavily on expert judgment which, although essential for capturing specialized knowledge in complex and innovative fire safety domains, may reflect the professional backgrounds and experiences of the expert panel. Therefore, the prioritization results can be interpreted within the context of the experts involved. The prioritization outcomes may be influenced by prevailing technical practices and regulatory frameworks. By integrating local expert panels and contextual building traditions, the model can be recalibrated for diverse geographical and regulatory environments. Future studies may also extend the framework by exploring causal relationships among the decision elements using dynamic or network-based modeling approaches. Applying alternative MCDM methods could provide different analytical perspectives.

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Data availability Data are available by contacting the authors.

Declarations

Conflict of interest The authors declare no competing interests.

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