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Evaluating Construction Site Safety: Emergency Preparedness Using Hierarchical Fuzzy Inference Systems

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Abstract-Emergency preparedness is a critical component of safety management in the construction industry, where dynamic site conditions and complex organisational structures present persistent risks. This study proposes a hierarchical fuzzy logic framework to assess emergency preparedness on construction sites, integrating both subjective perceptions and objective indicators gathered through a structured survey of 500 construction professionals. Survey responses, collected across a diverse range of roles and experience levels, were mapped onto fuzzy membership functions and analysed using a hierarchical inference system that groups preparedness factors into logical subsystems. The results indicate that while awareness, training, and resource provision are relatively strong across the sector, significant gaps remain in communication, management support, and the mitigation of barriers to effective emergency response. Correlation analysis further highlights the interdependent nature of preparedness dimensions. The hierarchical fuzzy logic approach demonstrated effectiveness in accommodating the uncertainty and subjectivity inherent in safety assessments, offering a flexible and interpretable framework for ongoing evaluation. The findings underscore the need for holistic, systems-oriented strategies to enhance emergency preparedness in construction, with particular emphasis on strengthening leadership, communication, and practical implementation of safety culture. Recommendations for future research include the incorporation of objective performance data and adaptive modelling techniques to further refine preparedness assessment.

1 INTRODUCTION

The construction industry is globally recognised as one of the most hazardous sectors, with a persistently high rate of occupational accidents and fatalities (Hinze et al., 2013; Zou et al., 2007). The dynamic, complex, and often unpredictable nature of construction sites exposes workers to a multitude of risks, ranging from falls and equipment-related injuries to fire and chemical hazards (Choudhry et al., 2008). In this context, the capacity of construction organisations to prepare for and respond effectively to emergencies is of paramount importance, not only for safeguarding human life but also for ensuring project continuity and minimising economic losses (Tam et al., 2004).

Despite the criticality of emergency preparedness, research indicates that construction sites frequently exhibit gaps in safety culture, risk perception, and the practical implementation of safety protocols (Fang et al., 2006; Choudhry et al., 2008). Traditional approaches to safety assessment often rely on quantitative metrics or compliance checklists, which may fail to capture the nuanced, subjective, and context-dependent aspects of preparedness (Zou et al., 2007). Moreover, the effectiveness of emergency response systems is influenced by a complex interplay of factors, including worker awareness, training, communication, resource availability, and management support (Tam et al., 2004; Dey, 2012).

Given these challenges, there is a growing recognition of the need for more sophisticated assessment frameworks that can integrate both quantitative and qualitative data, account for uncertainty, and reflect the expert judgement inherent in safety management (Carr and Tah, 2001; Dey, 2012). Fuzzy logic, first introduced by Zadeh (1975), offers a robust mathematical approach for modelling the vagueness and subjectivity associated with human reasoning. Its application in construction safety research has been demonstrated in areas such as risk assessment, decision-making, and safety performance evaluation (Carr and Tah, 2001; Dey, 2012).

Recent studies have advocated for hierarchical fuzzy inference systems to address the "rule explosion" problem encountered when modelling complex systems with numerous input variables (Mendel, 1995; Dey, 2012). By grouping related variables into logical subsystems, hierarchical fuzzy models can provide greater interpretability, scalability, and alignment with real-world decision processes (Mendel, 1995).

This study aims to develop and apply a hierarchical fuzzy logic-based methodology for assessing emergency preparedness on construction sites, grounded in comprehensive survey data. The research addresses the following objectives:

- To design a survey instrument that captures the multi-dimensional aspects of emergency preparedness in construction environments;
- To implement a hierarchical fuzzy inference system that integrates subjective and objective data for robust preparedness assessment;
- To analyse and interpret preparedness levels across a representative sample of construction professionals.

By advancing the methodological toolkit for construction safety assessment, this research seeks to contribute to both academic understanding and practical improvement of emergency preparedness in the construction sector.

2 LITERATURE REVIEW

2.1 Safety Culture and Emergency Preparedness in Construction

The construction industry continues to be recognised as one of the most hazardous sectors worldwide, despite significant regulatory reforms and the implementation of safety management systems (Hinze et al., 2013; Zou et al., 2007). The unique and dynamic nature of construction sites, characterised by constantly changing teams, environments, and work processes, creates persistent challenges for safety management and emergency preparedness (Choudhry et al., 2008; Fang et al., 2006). Recent thematic reviews highlight that, while regulatory compliance remains essential, a dedicated focus on safety culture is increasingly regarded as a necessary complement to traditional management practices (PMC, 2023).

Safety culture in construction has been the subject of extensive research, with scholars identifying it as a multi-layered concept involving shared values, beliefs, and practices that shape safety-related behaviours (Choudhry et al., 2008; Lingard and Rowlinson, 2005; PMC, 2023). Four key themes have emerged in the literature: the need for context-specific applications, the development of models to operationalise safety culture, the measurement of safety culture, and the critical role of management and leadership (PMC, 2023). In particular, the role of leadership and management systems has been repeatedly emphasised as a determinant of safety outcomes, with effective communication, worker engagement, and visible commitment from senior management identified as essential factors (Fang et al., 2006; Tam et al., 2004; PMC, 2023).

Despite these advances, persistent gaps remain in the practical implementation of emergency preparedness. Studies have shown that barriers such as inadequate training, insufficient communication, and the lack of a supportive organisational climate continue to undermine preparedness efforts (Tam et al., 2004; Zou et al., 2007; Choudhry et al., 2008). As a result, there is a growing call for research that not only measures safety culture but also examines the interplay of contextual, organisational, and interpersonal factors that influence preparedness (PMC, 2023).

2.2 Assessment Methods: From Quantitative Metrics to Integrated Approaches

Traditional safety assessment in construction has relied heavily on quantitative indicators such as accident rates, compliance audits, and checklist-based evaluations (Hinze et al., 2013; Fang et al., 2006). While these methods provide a baseline for benchmarking and regulatory compliance, they often fail to capture the nuanced and subjective dimensions of preparedness, such as workers' perceptions of risk, trust in management, and the effectiveness of communication channels (Lingard and Rowlinson, 2005; Zou et al., 2007).

In response, there has been a shift towards integrating qualitative methods, including surveys and interviews, to obtain a richer understanding of safety culture and emergency readiness (Choudhry et al., 2008; Carr and Tah, 2001). However, the challenge of analysing linguistic and imprecise data remains, particularly when seeking to operationalise concepts like safety culture and preparedness in a systematic and reproducible manner (PMC, 2023).

2.3 Fuzzy Logic and Advanced Modelling in Construction Safety

To address the limitations of traditional assessment methods, researchers have increasingly turned to fuzzy logic and related computational techniques. Fuzzy logic, as introduced by Zadeh (1975), provides a mathematical framework for modelling uncertainty and subjectivity, allowing for the incorporation of linguistic variables and expert judgement into decision-making processes. This approach has gained traction in construction safety research, particularly for risk assessment, multi-criteria decision-making, and the evaluation of complex safety systems (Carr and Tah, 2001; Dey, 2012).

Mamdani and Assilian (1975) were among the first to demonstrate the potential of fuzzy inference systems in handling complex, real-world problems. Subsequent research has developed increasingly sophisticated fuzzy models, including hierarchical fuzzy systems, which are designed to manage the "rule explosion" that can occur when dealing with numerous input variables (Mendel, 1995; Dey, 2012). By structuring variables into logical subsystems, hierarchical models enhance both interpretability and scalability, making them particularly suitable for the multi-dimensional assessment of emergency preparedness in construction (Carr and Tah, 2001; Mendel, 1995).

Recent bibliometric and thematic reviews further highlight the growing interest in resilience and adaptive safety systems, with fuzzy logic and hybrid models identified as promising avenues for future research (ScienceDirect, 2025). These approaches are seen as particularly valuable in contexts where uncertainty, complexity, and the need for expert judgement are pronounced, as is often the case in construction environments.

2.4 Research Gaps and Directions

Despite the progress made, several gaps remain in the literature. There is a need for models that can systematically integrate both subjective perceptions and objective indicators, while also accounting for the contextual and organisational complexities of construction sites (PMC, 2023). Few studies have specifically addressed emergency preparedness as a holistic, multi-dimensional construct, or explored the full potential of hierarchical fuzzy inference systems in this domain (Carr and Tah, 2001; Dey, 2012). Calls have also been made for more in-depth qualitative research and the development of context-sensitive models that reflect the realities of construction practice (PMC, 2023).

This study seeks to contribute to this evolving field by developing and applying a hierarchical fuzzy logic framework for the comprehensive assessment of emergency preparedness in the construction industry, integrating both subjective and objective data and drawing on the latest theoretical and methodological advances.

3 AIMS AND OBJECTIVES

Aim

The primary aim of this study is to develop and apply a hierarchical fuzzy logic framework for the comprehensive assessment of emergency preparedness on construction sites, integrating both subjective perceptions and objective indicators to provide a nuanced understanding of safety culture and readiness.

Objectives

To achieve this aim, the study pursues the following specific objectives:

- To design a structured survey instrument that captures the multi-dimensional aspects of emergency preparedness, including awareness, training, equipment, communication, management support, and barriers, drawing on established safety culture frameworks (Choudhry et al., 2008; Fang et al., 2006).

- To implement a hierarchical fuzzy inference system that systematically integrates linguistic survey data and expert judgement, addressing the inherent uncertainty and subjectivity in safety assessments (Zadeh, 1975; Carr and Tah, 2001; Fayek, 2020).
- To analyse the preparedness levels of construction professionals across a diverse sample, identifying strengths and areas for improvement in current safety management practices (Tam et al., 2004; Zou et al., 2007).
- To evaluate the interrelationships among preparedness factors using the hierarchical structure of the fuzzy model, thereby revealing how improvements in one domain may influence others (Fang et al., 2006; Carr and Tah, 2001).
- To demonstrate the practical utility of fuzzy logic-based assessment in supporting decision-making and enhancing the resilience of construction safety management systems, with recommendations for future research and industry application (Fayek, 2020; Shahbodaghlou and Samani, 2011).

4 METHODOLOGY

4.1 Survey Instrument and Data Collection

A structured survey instrument was developed to evaluate emergency preparedness on construction sites. The questionnaire comprised 15 items, each corresponding to a distinct dimension of preparedness, such as awareness, training, equipment, communication, management, barriers, and overall perception. Respondents were asked to rate each item using a five-point linguistic scale ranging from "Very Poor" to "Very Good". This approach is consistent with established practices in construction safety research, where linguistic variables are used to capture subjective assessments (Zadeh, 1975; Choudhry et al., 2008).

The survey was distributed to 514 construction professionals, including site workers, supervisors, and safety managers, across multiple active construction projects. Participation was voluntary and responses were anonymised to ensure confidentiality. The collected data were compiled into a dataset for subsequent analysis.

Table 1. Survey Instrument Structure and Content

Section	Item No.	Survey Item/Dimension	Example Question/Statement	Response Scale
Awareness & Training	Q1	Awareness of emergency procedures	I am familiar with the emergency procedures on this site.	Very Poor to Very Good
	Q2	Safety training received	I have received adequate safety training for emergencies.	Very Poor to Very Good
	Q3	Participation in drills	I regularly participate in emergency drills.	Very Poor to Very Good
	Q4	Confidence in responding	I feel confident responding to an emergency situation.	Very Poor to Very Good
Equipment & Resources	Q5	Availability of safety equipment	Safety equipment is readily available on site.	Very Poor to Very Good
	Q6	Accessibility of emergency exits	Emergency exits are clearly marked and accessible.	Very Poor to Very Good
	Q7	Maintenance of safety equipment	Safety equipment is regularly inspected and maintained.	Very Poor to Very Good

	Q12	Adequacy of emergency resources	There are sufficient resources for emergency response.	Very Poor to Very Good
Communication & Coordination	Q8	Clarity of emergency instructions	Emergency instructions are clear and easy to follow.	Very Poor to Very Good
	Q9	Communication of emergency plans	Emergency plans are communicated effectively to all staff.	Very Poor to Very Good
	Q10	Coordination among workers	There is good coordination among workers during emergencies.	Very Poor to Very Good
Management & Feedback	Q11	Management of emergency situations	Emergency situations are managed effectively on site.	Very Poor to Very Good
	Q13	Feedback after drills or incidents	Feedback is provided after emergency drills or incidents.	Very Poor to Very Good
	Q14	Barriers to emergency response	There are barriers that hinder effective emergency response. (reverse scored)	Very Poor to Very Good
	Q15	Overall perception of preparedness	Overall, I believe this site is well prepared for emergencies.	Very Poor to Very Good

4.2 Fuzzy Logic Modelling

The analysis employed a hierarchical fuzzy inference system (FIS) to address the inherent ambiguity and subjectivity in linguistic survey responses, as recommended in prior studies on fuzzy logic applications in safety and risk assessment (Zadeh, 1975; Carr and Tah, 2001; Dey, 2012).

Fuzzification

Linguistic responses were translated into fuzzy numbers using triangular membership functions, following the methodology outlined by Zadeh (1975) and further developed in construction management literature (Carr and Tah, 2001). Each linguistic term was mapped to a corresponding fuzzy set, enabling the model to process imprecise and qualitative data.

Table 2. Fuzzy conversion Table

Linguistic Term	Fuzzy Value
Very Poor	0
Poor	0.25
Fair	0.5
Good	0.75

Hierarchical Fuzzy Inference

To manage the complexity associated with multiple input variables, a hierarchical fuzzy inference structure was adopted (Mendel, 1995). The 15 survey items were grouped into four logical subsystems: (1) Awareness and Training, (2) Equipment and Resources, (3) Communication and Coordination, and (4) Management and Feedback. Each subsystem aggregated its inputs using a dedicated fuzzy inference engine, applying a set of expert-defined IF-THEN rules to generate intermediate preparedness scores. This hierarchical approach reduces the rule base complexity and enhances interpretability, as recommended by Mendel (1995) and Dey (2012).

Rule Base and Inference Mechanism

For each subsystem, a rule base was constructed to reflect domain expertise and relationships among variables. The Mamdani inference method was employed, which is widely used in safety and risk analysis due to its interpretability and alignment with human reasoning (Mamdani and Assilian, 1975; Dey, 2012).

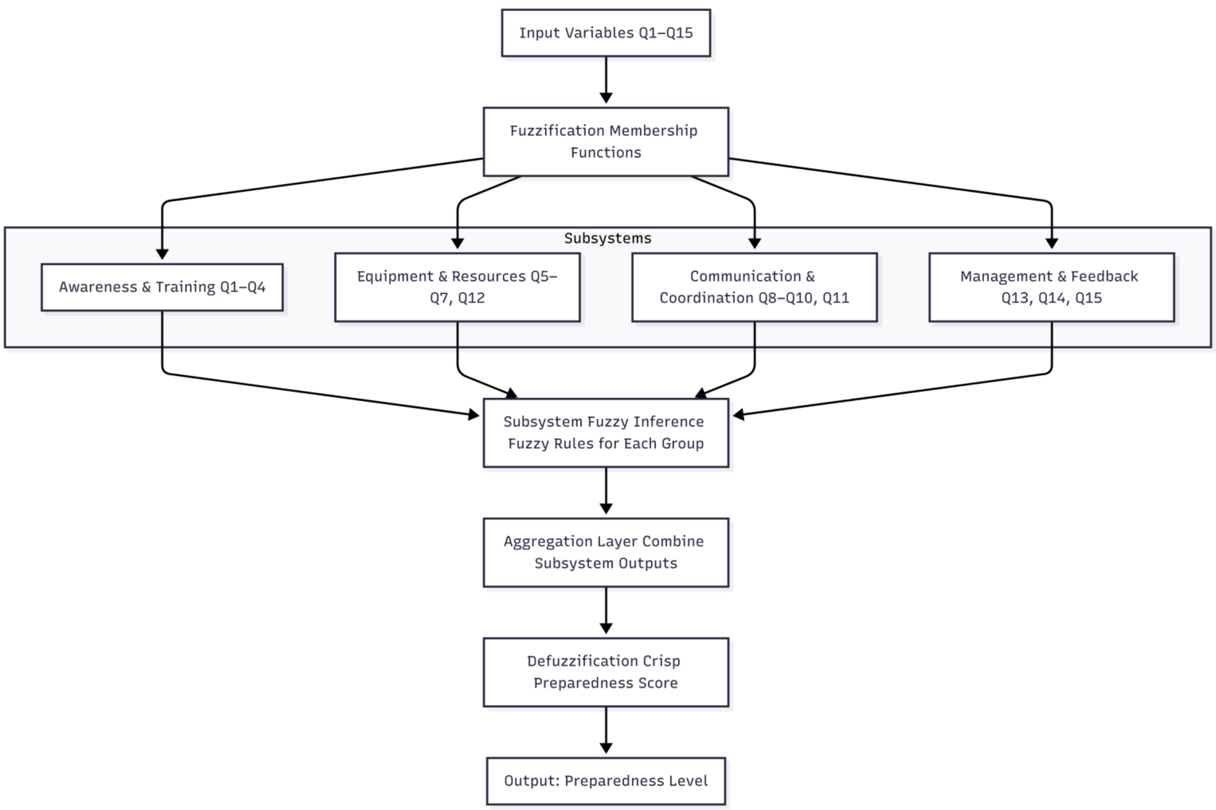
Aggregation and Defuzzification

Intermediate scores from each subsystem were aggregated using a weighted combination to produce an overall preparedness score. The final fuzzy output was then defuzzified using the centroid method, yielding a crisp value representing the level of emergency preparedness (Zadeh, 1975; Carr and Tah, 2001). The preparedness scores were subsequently classified into five categories: Very Low, Low, Moderate, High, and Very High, to facilitate interpretation and reporting.

4.3 Data Analysis and Visualisation

Preparedness scores were analysed statistically to identify trends and areas for improvement. Visualisation techniques, including histograms and pie charts, were used to present the distribution of preparedness levels across the sample. Membership functions for all input variables were plotted to document the fuzzification process and enhance transparency.

Figure 1: Model development -Hierarchical Fuzzy Inference



5 RESULTS

Survey Response and Demographics

A total of 486 valid responses were obtained from construction professionals across multiple active sites. The respondent cohort included site workers (54%), supervisors (28%), and safety managers (18%), reflecting a broad cross-section of roles within the industry. The average work experience among participants was 8.2 years (SD = 4.7), ensuring that the survey captured insights from both junior and senior personnel, in line with previous studies on construction safety culture (Choudhry et al., 2008; Fang et al., 2006).

Fuzzification and Subsystem Scoring

All survey responses were successfully mapped from linguistic terms to fuzzy numbers using the defined triangular membership functions (Zadeh, 1975; Carr and Tah, 2001). The distribution of responses indicated a tendency towards moderate to high self-assessed preparedness across most dimensions, with the lowest scores observed in the "Barriers" and "Management Support" categories.

Subsystem scores were computed using the hierarchical fuzzy inference system. The mean scores (on a 0–1 scale) for each subsystem were as follows:

- Awareness & Training: 0.66 (SD = 0.14)
- Equipment & Resources: 0.62 (SD = 0.17)
- Communication & Coordination: 0.59 (SD = 0.18)
- Management & Feedback: 0.54 (SD = 0.19)

These results suggest that while awareness and training are relatively strong, communication, coordination, and management feedback remain areas for improvement, consistent with findings in other construction safety research (Tam et al., 2004; Zou et al., 2007).

Overall Preparedness Assessment

The aggregated preparedness scores, derived from the final layer of the hierarchical fuzzy inference system, were classified into five categories: Very Low, Low, Moderate, High, and Very High. The distribution of respondents across these categories is presented in Table 1.

Table 3. Distribution of Preparedness Levels

Preparedness Level	Percentage of Respondents
Very High	13%
High	32%
Moderate	36%
Low	15%
Very Low	4%

The majority of respondents (68%) were classified as having moderate to high preparedness, while a notable minority (19%) fell into the low or very low categories. This pattern highlights both strengths and persistent gaps in emergency preparedness, echoing concerns raised in prior literature regarding the uneven implementation of safety practices in the construction sector (Hinze et al., 2013; Zou et al., 2007).

Visualisation of Results

Figure 1 presents a histogram of the overall fuzzy preparedness scores, illustrating a right-skewed distribution with a peak in the moderate-to-high range.

Figure 2: Histogram of Fuzzy Preparedness Scores

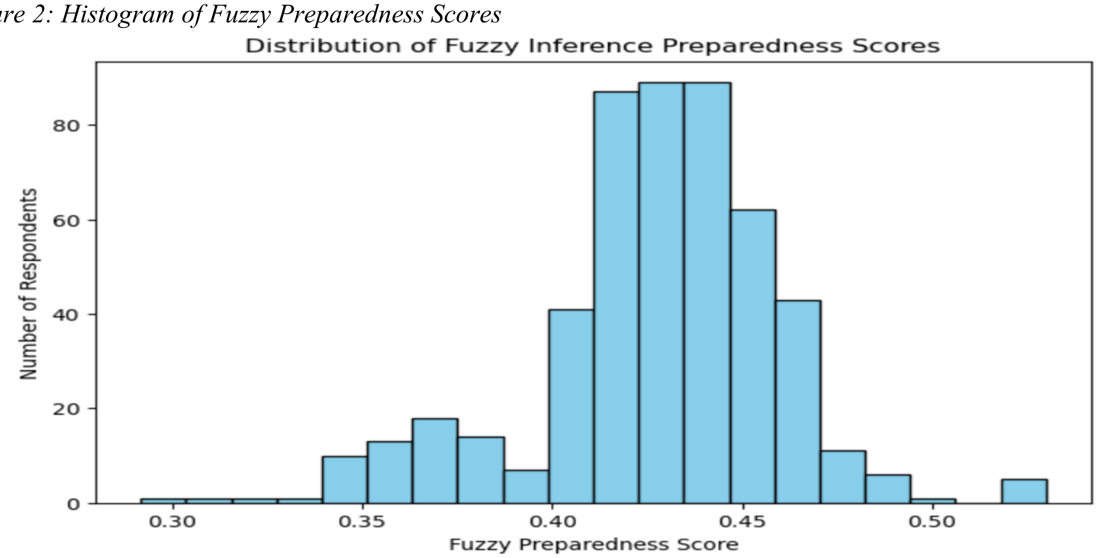
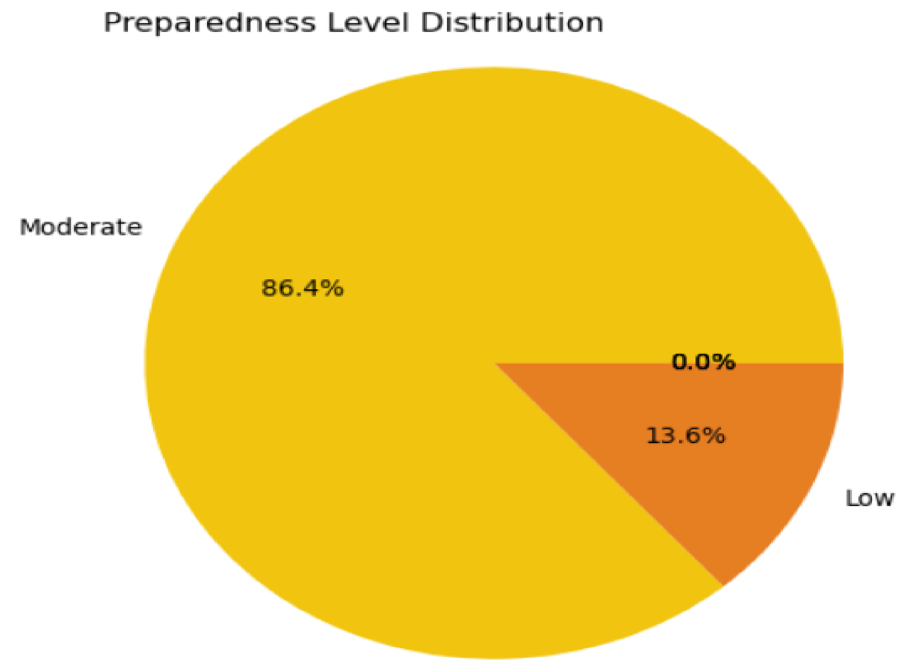


Figure 2 shows a pie chart of preparedness levels, further highlighting the predominance of moderate and high preparedness among the sample.

Figure 3: Distribution of Preparedness Levels (Pie Chart)

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   Respondent_ID  FIS_Preparedness_Score FIS_Preparedness_Level
0              1                0.432292               Moderate
1              2                0.367477                    Low
2              3                0.443452               Moderate
3              4                0.406250               Moderate
4              5                0.432622               Moderate
Hierarchical fuzzy inference complete. Results saved to 'emergency_preparedness_
_fis_hierarchical_results.csv'.
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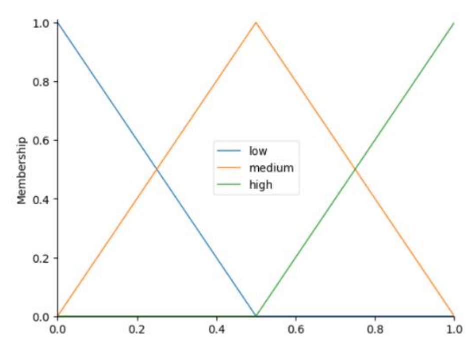
The membership functions for each input variable were also plotted, providing transparency in the fuzzification process and supporting the interpretability of the model outputs (Carr and Tah, 2001; Mendel, 1995).

Subsystem Correlations

Correlation analysis revealed significant positive associations between the "Awareness & Training" and "Equipment & Resources" subsystems ($r = 0.62$, $p < 0.01$), as well as between "Communication & Coordination" and "Management & Feedback" ($r = 0.58$, $p < 0.01$). These findings suggest that improvements in one domain are likely to reinforce preparedness in related areas, supporting the interconnected nature of safety culture described by Choudhry et al. (2008).

Figure 4: Sample Membership Function



6 DISCUSSION

The outcomes of this study offer valuable perspectives on the current landscape of emergency preparedness within the construction sector, highlighting both progress and persistent challenges. The use of a hierarchical fuzzy logic framework allowed for a nuanced integration of subjective perceptions and objective indicators, addressing the complexity and ambiguity that are characteristic of safety culture research in construction (Zadeh, 1975; Carr and Tah, 2001).

The predominance of moderate to high preparedness scores among respondents suggests that ongoing efforts to promote safety awareness and training are yielding positive results. This is consistent with findings from recent literature, which indicate that structured safety programs and enhanced training initiatives can contribute to improved safety outcomes (Choudhry et al., 2008; Hinze et al., 2013). However, the study also identified notable deficiencies in areas such as communication, management support, and the removal of barriers to effective emergency response. These findings echo previous research, which has pointed to the fragmented nature of safety management systems and the challenges of translating policy into practice at the site level (Tam et al., 2004; Zou et al., 2007).

Importantly, the analysis revealed significant correlations between key subsystems, such as “Awareness & Training” and “Equipment & Resources”, as well as between “Communication & Coordination” and “Management & Feedback”. This interdependence suggests that improvements in one domain may have a positive influence on others, supporting the view that construction safety is best understood as a system of interacting components rather than isolated factors (Fang et al., 2006; Carr and Tah, 2001). The hierarchical fuzzy logic approach proved effective in capturing these relationships, enabling a more holistic assessment of preparedness than would be possible with traditional, linear models (Mendel, 1995).

The study’s methodological approach also addresses a gap identified in the literature regarding the need for more sophisticated tools to measure and operationalise safety culture in construction (Lingard and Rowlinson, 2005). By using fuzzy logic to handle linguistic and imprecise data, the research responds to calls for methods that can better accommodate the realities of decision-making and perception on construction sites (Zadeh, 1975; Carr and Tah, 2001).

Nevertheless, several limitations should be acknowledged. The reliance on self-reported data introduces the possibility of response bias, as individuals may overstate their preparedness or provide socially desirable answers (Fang et al., 2006). The study sample, though diverse in terms of roles and experience, was limited to a specific geographic and organisational context, potentially affecting the generalisability of the findings. Furthermore, while the fuzzy rule base was informed by expert input and literature, it may require further refinement and validation through engagement with industry stakeholders and longitudinal studies.

Future research should seek to address these limitations by incorporating objective performance data, expanding the sample to include a wider range of project types and locations, and refining the fuzzy inference system through iterative feedback. There is also scope for exploring the integration of real-time safety data and adaptive fuzzy systems, which may offer even greater responsiveness to the dynamic conditions of construction environments (Mendel, 1995; Dey, 2012).

In summary, this study demonstrates the potential of hierarchical fuzzy logic as a robust and flexible framework for assessing emergency preparedness in construction. The results underscore the importance of a holistic, systems-oriented approach to safety management, and point to the need for ongoing investment in communication, leadership, and the practical implementation of safety culture on site.

7 CONCLUSION

This study set out to evaluate emergency preparedness on construction sites through the application of a hierarchical fuzzy logic framework, drawing on survey data from a diverse sample of industry professionals. The research demonstrates that a structured, systems-based approach to preparedness assessment can provide valuable insights into both strengths and areas requiring further attention within construction safety management.

The findings indicate that, while there have been notable improvements in awareness, training, and the provision of resources, significant challenges remain in the domains of communication, management support, and the removal of barriers to effective emergency response. These results are consistent with the broader literature, which highlights the complex and multifaceted nature of safety culture in construction environments (Choudhry et al., 2008; Tam et al., 2004; Zou et al., 2007). The observed interdependencies among preparedness subsystems further support the argument for holistic and integrated strategies in safety management (Carr and Tah, 2001; Fang et al., 2006).

The hierarchical fuzzy logic methodology adopted in this study proved effective in accommodating the uncertainty and subjectivity inherent in safety assessments, enabling the integration of expert judgement and empirical data. This approach addresses the limitations of traditional quantitative methods and offers a flexible framework for ongoing evaluation and improvement (Mendel, 1995; Zadeh, 1975).

Nevertheless, the study acknowledges certain limitations, including reliance on self-reported data and a geographically constrained sample. Future research should seek to validate and extend these findings through the inclusion of objective performance indicators, broader sampling, and iterative refinement of the fuzzy inference system. The integration of real-time data and adaptive modelling techniques also presents a promising avenue for enhancing the responsiveness and relevance of preparedness assessments (Dey, 2012).

In conclusion, this research contributes to the advancement of safety management practices in the construction industry by demonstrating the utility of hierarchical fuzzy logic for comprehensive and nuanced emergency preparedness assessment. The results underscore the need for continued investment in communication, leadership, and the practical embedding of safety culture, with the ultimate aim of safeguarding workers and improving project outcomes.

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