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Cost-effective risk reduction in scaffold assembly using fuzzy logic-based assessment and optimization

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Abstract. Accidents during scaffold assembly and disassembly remain a persistent safety challenge in the construction industry. Traditional risk assessment methods are often insufficient in capturing the uncertainty and interdependence of contributing factors. This paper proposes a fuzzy logic-based methodology to assess and reduce occupational risks related to scaffold operations, while optimizing the associated costs of prevention. The method combines qualitative linguistic assessment (e.g., “low anchoring strength”, “poor distance from façade”, “missing diagonals”) with expert-defined membership functions and rule matrices. Risk levels are inferred using a Mamdani-type fuzzy inference system. To improve workplace safety, we introduce a reverse optimization model that identifies the most cost-efficient prevention actions required to reduce the fuzzy-evaluated risk below a critical threshold. A simulation developed in MATLAB demonstrates the effectiveness of the approach on a real-life scaffolding scenario. The model inputs include worker experience level, scaffold anchoring, diagonal installation, and tool condition. For each variable, cost vectors are assigned to possible safety improvements. The optimization process identifies the minimal-cost combination of input changes needed to reduce the overall fuzzy risk level from “Very High” to “Acceptable”.The results highlight the potential of integrating fuzzy systems with cost modeling to improve safety planning in high-risk construction tasks. This approach supports informed decision-making, tailored preventive actions, and efficient resource allocation, contributing to a proactive safety culture.

1 Introduction to risk calculation in construction

Scaffolding operations represent a crucial component in construction, particularly in renovation, façade work, and high-rise building maintenance. Despite their widespread use, scaffold assembly and disassembly continue to pose serious risks for workers, often due to insufficient training, environmental instability, or equipment misuse. These hazards result in numerous workplace injuries and fatalities each year.

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Risk assessment in this domain is a challenging task. Standard qualitative methods, such as checklists or risk matrices, are often subjective and fail to capture the complex interactions between multiple risk factors. Furthermore, quantitative models may oversimplify uncertainty, reducing their relevance for dynamic and unstructured environments like construction sites.

To address these limitations, researchers have increasingly turned to fuzzy logic — a framework capable of representing imprecise, linguistic, and ambiguous information. Fuzzy systems have proven effective in evaluating occupational risks where precise measurements are not always available or where expert judgment plays a central role.

This paper presents a fuzzy-based risk assessment and optimization model specifically tailored for scaffold assembly. It aims to:
- assess the risk level using linguistic variables and fuzzy inference,
- propose targeted prevention actions (e.g., improved anchoring, diagonal installation, better tools),
- and minimize the cost associated with these interventions while maintaining safety.

By combining expert knowledge, fuzzy rule sets, and a cost-oriented reverse optimization model, we demonstrate that it is possible to reduce risks in a structured and financially sustainable way.

Fig. 1. Examples of building workplace accident risks activities

Risk calculation in construction represents the systematic process of identifying, analyzing, evaluating, and prioritizing uncertain events that may have a positive or negative impact on project objectives. The primary aim is to anticipate potential problems and to develop proactive strategies to minimize their negative impact or to maximize opportunities. Without a rigorous approach to risk, construction projects can be exposed to budget overruns, significant delays, quality issues, workplace accidents, and even total failure. In recent literature search there are proposals of intelligent risk assessment based on various artificial intelligence methods including the most feasible for such a case with rules and semantic meaning the fuzzy logic techniques with a variety of forms (as Fuzzy FMEA) and implementations of membership functions. This strategy offers a precise estimate of the risk also for specific cases of building activity and we are going to adopt it as a forward step.

Although traditional methods such as FMEA and the Kinney method are frequently used in occupational risk assessment, they have been criticized for their limited adaptability to dynamic environments such as construction sites [13].

2 Fuzzy risk evaluation models

Fuzzy logic, originally introduced by Zadeh in 1965, offers a mathematical approach for dealing with vague or uncertain information. It is especially useful in occupational health and safety, where many factors are qualitative or hard to quantify precisely. Unlike binary logic, fuzzy logic allows for intermediate truth values, making it ideal for modeling real-world uncertainty.

Several studies have applied fuzzy methods in risk assessment, particularly in construction. Zeng et al. (2007) proposed a fuzzy decision-making methodology for project risk management. Similarly, Tah and Carr (2000) applied fuzzy logic to model subjective risk perception. More recently, Mohandes and Zhang (2021) developed wearable sensor-based fuzzy systems to evaluate construction worker safety in real-time.

The strength of fuzzy systems lies in their ability to handle expert linguistic input (e.g., “moderate noise level” or “low visibility”) and convert it into computable outputs via a structured inference mechanism. The most common inference models include Mamdani-type and Sugeno-type systems, with the former being preferred in safety applications for its interpretability.

This paper builds upon these foundations and proposes an application-specific fuzzy framework for scaffold-related hazards. It also integrates a cost-based optimization module, aiming to determine the most cost-effective way to reduce a given fuzzy-evaluated risk below an acceptable threshold.

2.1 Fuzzy logic in occupational safety

In the context of OHS, many risk factors—such as training level, tool condition, or installation quality—are difficult to measure precisely. Fuzzy logic enables the use of linguistic descriptors (e.g., “poor anchoring”, “partial installation”) to model these imprecise variables. These descriptors are mapped to numerical values using membership functions, enabling a structured evaluation of risk levels without relying on binary classification.This modeling flexibility is essential for high-risk environments like construction sites, where decision-making must account for subjective judgments and varying conditions.

2.2 Review of applications in construction

Fuzzy logic has been successfully applied in various safety-related contexts. Zeng et al. (2007) introduced a fuzzy decision-making tool for managing project risk. Tah and Carr (2000) used fuzzy methods to quantify subjective risk perception in construction planning. More recently, Mohandes and Zhang (2021) integrated wearable sensor data into a fuzzy inference system for real-time worker safety monitoring. These approaches highlight the adaptability of fuzzy logic in evaluating uncertain and dynamic environments. Despite their strengths, many existing models stop at risk classification and do not offer actionable strategies for risk mitigation. Our approach addresses this gap by integrating optimization logic into the fuzzy model.

2.3 Mamdani vs. Sugeno inference systems

Mamdani inference systems are rule-based and use fuzzy sets for the inputs and outputs. This kind of fuzzy systems are generally understandable and so can be used in safety evaluations as making knowledge fast to be included in software. They use crisp mathematical functions as outputs, making them more suitable for control systems or real-time applications. However, they are less transparent to non-technical users. In this paper, a Mamdani-type fuzzy inference system is used for the fast acquiring of information from experts and providing understandable outputs as risk values in semantic form.

2.4 Main outcomes of the research

The study proposes a new approach for the known risk evaluation by fuzzy rules but continuate by global optimisation method of the cost using MATLAB algorithm for scaffold assembly. Unlike existing studies that focus on risk identification, our model proposes a reverse optimization approach: starting from a high-risk score, we identify which safety improvements are necessary—and in what combination—to reduce the risk in the most cost-effective manner. This dual-layer model supports both risk assessment and decision-making by enabling site managers to prioritize interventions not only based on risk severity but also based on resource efficiency.

3 Methodology

This section presents the methodological framework adopted to evaluate and reduce scaffold-related occupational risks using fuzzy logic and cost optimization. The proposed model combines expert-based linguistic assessments, the presentation of the system based on fuzzy logic rules, then a global optimisation of cost reduction actions. The first step makes the propagation of inputs to outputs via designed fuzzy system and then the back step (reverse) as a global optimisation method to minimise risk reduction costs. The MATLAB Fuzzy Toolbox and Global Optimisation Toolbox were used and adapted to the specific problem.

3.1 Summary of the method

The proposed method includes a fuzzy system followed by a MATLAB implementation of a global cost optimisation for the computation and then reducing risks on scaffold assembly in building activities. The implementation uses the experience of human included as linguistic values and membership functions to provide a risk value using fuzzy models and follows the backward step to globally minimise costs to adopt best and efficient set of preventive actions needed to bring the risk under a predefined threshold.

3.2 Fuzzy system architecture

The fuzzy risk evaluation system consists of the following components:

- Four input variables (e.g., anchoring quality, diagonal presence)
- One fuzzy output variable (risk level)
- Triangular and trapezoidal membership functions
- A Mamdani-type fuzzy inference engine
- A defuzzification stage using the centroid method

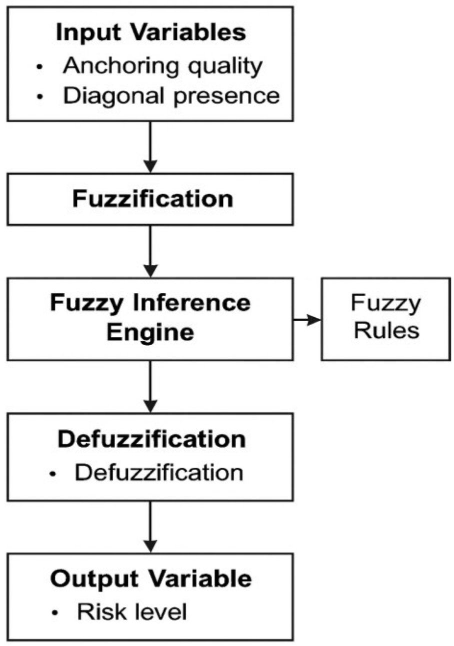

Fig. 2. General structure of the fuzzy risk evaluation followed by cost reduction proposal

3.3 The fuzzy variables used

The fuzzy system uses the following input variables:

Variable	Range	Linguistic Terms
Anchoring Quality	[0 – 10]	Poor, Medium, Good
Diagonal Presence	[0 – 10]	Absent, Partial, Complete
Distance from Wall	[0 – 50 cm]	Unsafe, Acceptable, Ideal
Worker Experience	[0 – 10]	Inexperienced, Average, Expert

The output variable is defined as:

Variable	Range	Linguistic Terms
Risk Level	[0 – 10]	Very Low, Low, Medium, High, Very High

Each linguistic term is modeled using triangular or trapezoidal membership functions.

3.4 Fuzzy rules

The system uses a rule base of 15 fuzzy rules derived from expert knowledge and safety guidelines. Sample rules include:

- **Rule 1:** IF Anchoring is Poor AND Diagonal is Absent THEN Risk is Very High
- **Rule 3:** IF Diagonal is Partial AND Anchoring is Medium THEN Risk is Medium
- **Rule 9:** IF Experience is Average AND Distance is Acceptable THEN Risk is Low
- **Rule 13:** IF Anchoring is Good AND Diagonal is Complete AND Distance is Ideal AND Experience is Expert THEN Risk is Very Low

The full rule base is implemented in MATLAB's Fuzzy Logic Toolbox.

3.5 Cost-based optimization strategy

To determine the most cost-effective set of actions for reducing the risk, we define cost vectors for each preventive measure:

Preventive Action	Cost (arbitrary units)
Improve Anchoring Quality	150
Install Missing Diagonals	200
Adjust Distance from Wall	100
Provide Worker Training	250

The system uses reverse logic: starting from a high fuzzy-evaluated risk, we apply a **minimax optimization algorithm** to find the combination of variable adjustments that minimizes total cost while keeping the resulting risk below a set threshold (e.g., Risk < 3.5).

3.6 MATLAB Implementation (summary)

The fuzzy inference system was built using MATLAB's Fuzzy Logic Toolbox. The optimization part used MATLAB's fmincon and ga (genetic algorithm) functions. The simulation was tested on a real-world scenario.

Sample MATLAB functions used:

```
fis = readfis('scaffold_risk_model.fis');
inputs = [3 2 40 2];  % Anchoring, Diagonal, Distance,
Experience
risk = evalfis(fis, inputs);
% Optimization example:
costs = [150 200 100 250];
f = @(x) sum(x .* costs);
constraint = @(x) evalfis(fis, x) - 3.5;
[x_opt, fval] = fmincon(f, [3 2 40 2], [], [], [], [], [0 0 0
0], [10 10 50 10], constraint);
```

4. Results and discussion

The proposed fuzzy risk evaluation and cost optimization system was tested on a real-world scaffolding scenario. The input variables were adjusted to reflect common safety conditions encountered on construction sites. Risk values were computed using the fuzzy inference system, followed by a reverse cost-based optimization procedure.

4.1 Risk evaluation example 1 – high risk

Input:
Anchoring = 3 (Poor)
Diagonals = 2 (Partial)
Distance = 42 cm (Unsafe)
Experience = 2 years (Inexperienced)

Fuzzy Risk Score: ≈ 8.75 (Very High)
Recommended actions: Install full diagonals, improve anchoring
Estimated cost for reduction: 350 units
Optimized risk (after correction): ≈ 2.90 (Acceptable)

4.2 Risk evaluation example 2 – medium risk

Input:
Anchoring = 6 (Medium)
Diagonals = 5 (Partial)
Distance = 30 cm (Acceptable)
Experience = 5 years (Average)

Fuzzy Risk Score: ≈ 5.20 (Medium)
Recommended action: Worker training
Cost for correction: 250 units
Optimized risk: ≈ 2.70

4.3 Risk evaluation example 3 – low risk

Input:
Anchoring = 8 (Good)
Diagonals = 10 (Complete)
Distance = 20 cm (Ideal)
Experience = 9 years (Expert)

Fuzzy Risk Score: ≈ 1.20 (Very Low)
Action needed: None
Cost: 0

4.4 Summary Table

Scenario	Initial Risk	Cost of Optimization	Optimized Risk
Ex. 1	8.75 (V. High)	350	2.90
Ex. 2	5.20 (Medium)	250	2.70
Ex. 3	1.20 (V. Low)	0	1.20

4.5 Discussion

The results demonstrate the effectiveness of combining fuzzy logic with cost modeling for safety management in scaffold operations. High-risk scenarios were reduced to acceptable thresholds using minimal resource investment. The model allows site managers to prioritize actions based on cost-efficiency, supporting strategic decision-making in real-time. Moreover, the use of fuzzy logic ensures that linguistic safety assessments (often based on human observation or experience) are not excluded from the decision process, thus increasing the flexibility and applicability of the system in practice.

5. Conclusions

This paper presented a fuzzy-based risk evaluation model combined with cost optimization for improving safety in scaffold assembly operations. The proposed approach addresses the limitations of traditional risk assessment methods by incorporating linguistic variables, expert-defined rules, and a Mamdani-type inference system. Additionally, it integrates a reverse optimization module that identifies the most cost-efficient preventive actions needed to reduce the risk to an acceptable level.

The simulation results confirm that high and medium-risk scenarios can be significantly mitigated with targeted and economically viable interventions. The fuzzy system allows the inclusion of qualitative assessments (such as experience, anchoring, or installation quality), while the cost model supports rational resource allocation in the planning phase.

The main contributions of this study are:

- A flexible risk assessment tool suitable for real-world construction environments.
- A novel integration of fuzzy inference with reverse cost optimization.
- A practical MATLAB implementation that can be adapted and scaled for other safety-critical construction tasks.

This approach can support safety engineers, site managers, and policymakers in adopting proactive and data-informed strategies to reduce occupational hazards.

Further work will focus on:

- Validating the model through field data and expert feedback.
- Extending the system with real-time monitoring using sensors and IoT technologies.
- Exploring hybrid fuzzy–neural or fuzzy–grey models for improved accuracy.

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