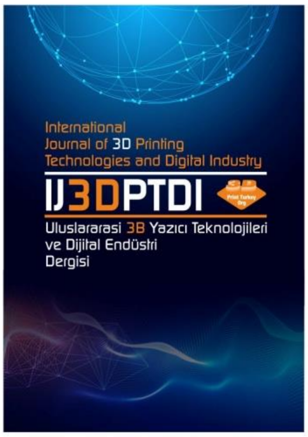

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A HYBRID LEARNING FRAMEWORK FOR POST-DISASTER DAMAGE ASSESSMENT AND SHELTER DECISION-MAKING: INCORPORATING 3D-PRINTED MODULAR ARCHITECTURE IN THE KAHRAMANMARAŞ, TÜRKİYE CONTEXT

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A HYBRID LEARNING FRAMEWORK FOR POST-DISASTER DAMAGE ASSESSMENT AND SHELTER DECISION-MAKING: INCORPORATING 3D-PRINTED MODULAR ARCHITECTURE IN THE KAHRAMANMARAŞ, TÜRKİYE CONTEXT

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ABSTRACT

The growing frequency and severity of natural disasters have highlighted the urgent need for adaptive, efficient, and sustainable temporary housing strategies. This study introduces a hybrid computational framework that integrates parametric design, Bayesian networks, fuzzy logic, and weakly supervised learning to enhance post-disaster temporary housing decisions. Using high-resolution aerial imagery from the 2023 Türkiye Earthquake dataset, the system extracts multi-layered spatial and structural features to classify damage levels and inform shelter typology. In addition to damage assessment and decision support, the framework incorporates fabrication-aware modules for 3D-printed modular architecture, enabling rapid, locally manufacturable shelter components tailored to site-specific needs. This integration improves deployment speed, supports modular adaptability, and aligns with Industry 4.0 principles for automated construction. The proposed SEHRNet-based architecture combines deep learning with probabilistic graphical models to accommodate both quantitative and qualitative uncertainty. A hybrid decision-making mechanism integrating TOPSIS, PROMETHEE, and Simulated Annealing enables evaluation of shelter alternatives under multiple constraints such as cost, modularity, climate compatibility, and cultural adaptability. A feedback loop based on Multi-Time-Step Rolling with MPC allows for real-time updates and adaptive planning. The results demonstrate improved decision accuracy and provide a fabrication-aware, computationally scalable solution for disaster-responsive shelter planning.

Keywords: Post-Disaster Architecture, 3D-Printed Modular Housing, Additive Manufacturing, Hybrid Learning Models, Decision Support Systems.

1. INTRODUCTION

In recent years, disasters have become more frequent and severe, causing unprecedented destruction of housing and mass displacement; between 2008 and 2018 alone, disasters displaced at least 265 million people globally [1-4]. This immense impact has underscored the urgent need for effective post-disaster shelter solutions, spurring the development of various temporary housing models to bridge the gap between initial emergency shelters and permanent reconstruction [5]. Meanwhile, Industry 4.0 applications (e.g., digital fabrication, Building Information Modeling, robotics) are increasingly being leveraged to expedite post-disaster construction, improving efficiency and reducing labor requirements [6-10]. In parallel, recent studies emphasize that incorporating disaster-affected communities in shelter design and decision-making leads to more culturally appropriate and widely accepted housing outcomes [11-14]. Furthermore, emerging parametric design and additive manufacturing frameworks allow for rapidly deployable, customizable, and sustainable post-disaster shelters tailored to local needs and conditions [15-19].

Although parametric design is often interpreted in the literature as a tool for digital form generation, this study expands its scope to include decision support models, systematic modularization, and reusability [17,20].

Nevertheless, there remain considerable theoretical and practical gaps in the application of parametric systems in post-disaster contexts. Many models remain confined to digital prototyping, ignoring key variables such as on-site applicability, resource optimization, and user feedback [8,21,22]. Furthermore, most existing algorithms lack the capacity to deliver the speed and flexibility required in post-disaster scenarios [9,23,24]. Studies conducted in Turkey indicate that modular systems often become obsolete in a short time due to cultural incompatibility, insufficient insulation, and inadequate infrastructure [13,14,25,26]. Therefore, there is a pressing need for hybrid design systems that can simultaneously integrate technical and socio-cultural parameters [19,27,28].

This research positions parametric architecture not merely as a tool for form generation but as a strategic system that guides decision-making processes [18]. The aim of this study is to develop a temporary housing model that integrates multi-variable data [29,30], adapts to user needs, synchronizes with the production process, and prioritizes reusability. The proposed model incorporates computational techniques such as Fuzzy Logic, Bayesian Networks, Weakly Supervised Learning, and Simulated Annealing—ultimately contributing to both short-term recovery and long-term transformation [31,32].

1.1. Motivation and Objective

The current models for post-disaster temporary housing reveal significant shortcomings in addressing user needs, environmental context, and long-term adaptability. The key challenges that motivate this research are as follows:

Inadequate understanding of user needs: Most existing temporary housing models fail to define the specific spatial, cultural, and functional needs of disaster-affected populations. This leads to mismatches between the provided solutions and real-life requirements.

Lack of contextual integration: Design processes frequently disregard contextual variables such as climate, geography, and sociocultural dynamics. This results in solutions that are not viable or comfortable in the specific disaster zone.

Insufficient data-driven decision-making: Post-disaster reconstruction efforts often lack multi-criteria decision-making frameworks, leading to ineffective resource allocation and suboptimal project prioritization.

Theoretical gap in parametric design: While parametric methods are widely acknowledged in theoretical discussions around disaster resilience, there is a scarcity of comprehensive, applied models that can translate theory into practice in the context of emergency architecture.

Deficiency in adaptive and modular systems: There is an evident research gap in flexible, modular, and data-driven systems that can accommodate evolving user needs and support long-term transformation beyond immediate shelter provision.

The primary objective of this research is to enhance the reconstruction process following a natural disaster through the use of Adhoc Architecture. The approach seeks to increase resilience, adaptability, and contextual relevance in post-disaster environments.

The specific objectives of the research are:
To implement an integrated approach to effectively handle the damage segmentation and data calibration processes.

To establish a robust training method for post-disaster reconstruction, aiming to eliminate the need for manual annotation.

To improve the decision-making efficiency and reduce uncertainty in reconstruction planning by considering both short-term needs and long-term recovery strategies.

To provide accurate multi-level damage classification using a novel method tailored to post-disaster architecture.

To enable real-time monitoring of disaster conditions, thereby improving the accuracy and responsiveness of the reconstruction process while reducing systemic demands.

In addition, the integration of 3D-printed construction techniques into the proposed model addresses the need for rapid, locally manufacturable, and cost-efficient shelter components in post-disaster settings.

1.2. Research Contribution

- A parametric temporary housing model integrating multiple data layers (climate, topography, user profile) and fabrication-aware modular components suitable for 3D printing is presented.

- A computational system based on weakly supervised learning is proposed, eliminating the need for manual intervention.

- A decision-support infrastructure is developed using Bayesian networks and fuzzy logic to manage uncertainty in post-disaster conditions.

- SEHRNet architecture enables spatial damage classification using high-resolution imagery, optimizing the decision-making process.

- Temporary housing decisions are evaluated through a multi-criteria framework combining TOPSIS-PROMETHEE with Simulated Annealing.

- A real-time monitoring and updating mechanism is established through a feedback loop employing Multi-Time-Step Rolling.

The framework aligns with additive manufacturing workflows, enabling the potential for on-site, digitally-driven shelter construction in line with Industry 4.0 principles.

1.3. Paper Organization

This article is structured to provide a comprehensive understanding of the proposed hybrid framework for post-disaster damage assessment and shelter planning. Section 2 delivers an extensive literature survey, highlighting the evolution of post-disaster housing strategies, the role of parametric and modular design in temporary shelter architecture, and recent advances in additive manufacturing and decision support systems. Section 3 articulates the research gap and formulates the core problem statement, offering a critical overview of existing limitations in modular post-disaster housing and establishing the theoretical and practical motivations for the proposed study. Section 4 introduces the proposed methodology, encompassing data acquisition, preprocessing, hybrid modeling techniques (Bayesian Networks, Fuzzy Logic, Weakly Supervised Learning), and decision-making algorithms such as TOPSIS-PROMETHEE with Simulated Annealing. This section also details the integration of fabrication-aware modules for 3D-printed construction. Section 5 presents the experimental implementation and evaluation of the proposed system, including simulation setup, performance benchmarking against baseline models, and statistical analyses. Visualizations such as ROC curves, confusion matrices, and feature importance graphs support the performance interpretation. Section 6 concludes the paper by summarizing the key findings, reflecting on the implications of the model in real-world disaster contexts, and proposing directions for future research, particularly toward scalable, adaptive, and AI-integrated post-disaster architectural systems.

1.4. Related Works and Contextual Background

Recent studies have increasingly explored the integration of digital fabrication and modular systems into post-disaster architecture. Salta et al. [15] demonstrated the potential of generative design combined with 3D printing to enable mass customization of emergency shelters, while Kantaros et al. [9] discussed the scalability of additive manufacturing for rapid deployment in smart city disaster management. Nekooie and Toghraie [22] emphasized the long-term adaptability of modular systems for emergency sheltering, highlighting their potential for reuse and transformation into permanent housing. These works collectively indicate that combining modular adaptability with fabrication-aware design offers a promising pathway for resilient and context-specific shelter systems. Building on these insights, the present study positions 3D-printed modular architecture not as a stand-alone solution, but as an integrated component within a hybrid decision-support framework, enhancing both the technical and contextual responsiveness of post-disaster shelter planning.

2. LITERATURE SURVEY

Post-disaster sheltering in architectural literature is structured into distinct phases, including emergency shelter, temporary shelter, transitional housing, and permanent housing. While emergency shelters refer to immediate accommodations for several days, temporary shelters include tents and collective centers intended for weeks. Transitional housing refers to structures such as prefabricated or rented units that support relatively normalized life for a period ranging from six months to three years. Permanent housing, as the final phase, involves either the repair of original residences or the construction of new ones. Recent literature emphasizes the fluidity between these stages and the necessity for context-sensitive and adaptive design strategies [19,32]. In line with this structure, early foundational work by Quarantelli [2] and UNDRO [3] remains significant, having shaped the conceptual understanding of transitional stages. These foundational insights continue to influence contemporary adaptive sheltering models.

In Turkey, large-scale transitional housing efforts became prominent especially after the 1999 and 2011 earthquakes. Container settlements were deployed rapidly but often suffered from poor climatic performance and lack of spatial adequacy. Subsequent standards were revised to improve insulation, spatial layout, and cultural compatibility [33]. Scholars have highlighted that temporary housing, if culturally and climatically insensitive, may fail not only in providing shelter but also in supporting psychological recovery [34]. These issues reemerged after the 2023 Kahramanmaraş Earthquake, where container settlements were again rapidly deployed. While speed of deployment was critical, evaluations revealed repeating deficiencies in thermal performance and spatial flexibility, prompting renewed debates around modular adaptability and cultural fit [35]. Earlier experiences such as the 1999 Marmara Earthquake and subsequent studies by Johnson [13] and Arslan & Cosgun [14] underline the long-term social implications and material lifecycle of such transitional settlements. The importance of modularity and reuse was further explored through the Design for Disassembly (DfD) concept [28], now finding relevance in sustainable post-disaster strategies.

Parametric architecture, as a computational design methodology using rule-based variations, presents a promising alternative for disaster contexts. The standardized nature of post-disaster components such as containers and prefabricated panels supports algorithmic design strategies. Recent applications of parametric design demonstrate its adaptability to local needs, terrain, and climate through modular, data-driven solutions. These systems have shown promise in rapidly generating shelter layouts, especially when integrated with digital fabrication technologies such as CNC and 3D printing [8]. In the 2023 Kahramanmaraş response, container settlements were organized according to modular layout principles, with attention to spatial efficiency, accessibility, and family-based zoning. The official technical report [4] highlights that the settlement designs aimed to preserve social cohesion, reduce intra-camp movement, and maintain privacy. One generative planning system that has gained renewed interest in Türkiye after the 2023 earthquakes is the C-PoDS model, originally developed for optimizing container-based shelter layouts.

Parametric tools have also been applied in optimizing modular housing for thermal comfort and energy efficiency. For instance, simulation-based optimization strategies have been proposed to enhance thermal comfort in lightweight modular structures used in post-disaster environments [30]. Such integration lays the groundwork for fabrication-aware design strategies, particularly within 3D printing applications [9].

Transformability in modular systems is another dimension of current research. Modular shelters designed to be disassembled and reassembled have proven effective in enhancing long-term flexibility and reusability [22]. Recent studies emphasize the importance of designing shelters that can transform into permanent structures, promoting sustainable use and reducing material waste [19]. After the 2023 earthquake, concerns around long-term use of temporary containers reinitiated discussions about transformable shelter systems in southeastern Türkiye.

The notion of Adhocism, reinterpreted in recent literature, promotes user-driven and improvisational approaches. User modifications—such as adding porches or subdividing spaces—are often observed in disaster contexts, suggesting that shelters should be designed with expansion potential and cultural adequacy in mind [20]. Expandable typologies that support self-construction and localized material use are advocated to enhance community ownership and resilience [11]. Notably, informal adjustments by users in 2023's temporary shelter settlements once again demonstrated the role of adhocism in shaping actual living environments. This aligns with earlier theoretical contributions by Jencks and Silver [20], Alexander [36], and Habraken [37], whose concepts of open building and core housing continue to inform flexible and user-adaptable design.

In this context, parametric and adhocratic models are not contradictory but complementary. Integrating user inputs into digital design workflows enables responsive and resilient shelter systems [20,21]. Parametric modeling allows localized solutions that align with cultural and climatic factors while facilitating rapid deployment through digital fabrication [8]. Past cases such as the one studied by Dikmen [26], where Turkish families expanded prefab units to add barns and kitchens, exemplify the value of culturally sensitive and expandable configurations.

Sustainability and technology integration are at the forefront of contemporary discourse. For instance, modular shelters developed under the Active House protocol integrate daylighting and energy efficiency strategies [38]. Similarly, additive manufacturing has emerged as a scalable approach for post-disaster housing. Studies show that 3D-printed shelters offer speed, customization, and cost-effectiveness, particularly when local materials are utilized [39]. Experimental deployments have demonstrated the feasibility of drone-assisted or on-site concrete printing for emergency relief [10].

Energy efficiency continues to be a major design concern. Extreme internal temperatures have been recorded in refugee tents in the Middle East, prompting research into retractable panels and smart control systems [30]. Parametric systems that automate environmental response mechanisms can offer smarter sheltering solutions in extreme climates [9].

Finally, decision support systems are increasingly used in post-disaster planning. Parametric platforms and AI-based simulations are employed to consolidate stakeholder inputs and evaluate alternative sheltering scenarios. These tools enable real-time adaptation and data-driven resource allocation, enhancing both speed and equity in emergency responses. After the 2023 earthquake, pilot integration of such decision support models was trialed to improve container siting and resource prioritization, offering a valuable precedent for future national planning protocols.

Table 1. An Overview of The Literature Review

References	Objective	The Method or the Model Utilized	The Algorithm	Restrictions / Limitations
Akdede et al. [5]	To generate neighborhood-based layouts for post-disaster settlements	Parametric layout configuration	Algorithmic spatial generation	Insufficient flexibility to accommodate evolving user needs
Chen et al. [6]	To implement BIM and Industry 4.0 principles in smart post-disaster cities	BIM-integrated planning model	Sustainable digital workflows	Limited scalability and fragmented platform integration
Rawat et al. [7]	To integrate AI and BIM in post-disaster reconstruction	Digital reconstruction framework	AI-enhanced BIM analysis	Manual annotation and data interoperability issues
Capell & Ahmed [11]	To improve beneficiary satisfaction through community consultation	Consultation-based framework	Stakeholder feedback integration	Limited institutional engagement and application
Opdyke et al. [12]	To assess the effect of household participation on shelter outcomes	Comparative field analysis	Participation-based design impact	Design-stage participation had minimal effect
Salta et al. [15]	To explore additive manufacturing for emergency shelters	Generative design + 3D printing	Mass customization via additive methods	Limited support for responsive adjustments

Reisinger et al. [17]	To combine LCA and cost optimization in flexible emergency architecture	LCA + cost assessment framework	Integrated decision support model	Production planning constraints not fully resolved
Gharib et al. [29]	To optimize shelter distribution after large-scale disasters	Integrated shelter distribution model	MCDA + fuzzy logic	Operational complexity under emergency conditions
Montalbano & Santi [19]	To propose sustainability-based evaluation criteria for temporary housing	Requirement-based assessment strategy	No formal algorithm applied	Design framework lacks on-site application validation

Recent literature on post-disaster sheltering presents significant advancements in modular, parametric, and additive manufacturing approaches. However, recurring gaps remain between conceptual designs, field implementation, and long-term adaptability. Despite documented successes, post-disaster housing projects frequently suffer from climatic and cultural mismatches, limited spatial flexibility, and insufficient stakeholder engagement.

Parametric and algorithmic methods show promise in optimizing layouts and thermal performance, yet integration of user feedback into computational workflows remains limited, reducing the cultural and social relevance of resulting designs. Similarly, while transformable and disassemblable modular systems have been explored, their large-scale adoption in disaster recovery contexts is rare, primarily due to logistical and policy constraints.

In Türkiye's recent earthquake responses, container-based solutions were rapidly deployed but repeated earlier deficiencies in thermal comfort, spatial adequacy, and adaptability. The potential of fabrication-aware, 3D-printed modular architectures to address these issues is acknowledged in research, yet its operational integration into real-time decision-making for shelter deployment is largely underdeveloped.

Moreover, decision support systems capable of synthesizing multi-source data, evaluating multiple recovery scenarios, and aligning them with fabrication capabilities are still emerging. Current systems often lack the dynamic feedback mechanisms needed to adapt shelter planning to evolving on-site conditions and stakeholder priorities.

These gaps highlight the need for a unified framework that bridges damage assessment, culturally sensitive design, modular fabrication, and adaptive decision support in post-disaster sheltering.

3. METHODOLOGY

Following a natural disaster, rebuilding efforts often begin rapidly, yet they commonly lack a structured and adaptable approach capable of addressing both immediate damage assessment and long-term planning. In this study, we propose an adhocratic architecture-based methodology that integrates data-driven decision-making with probabilistic modeling and machine learning techniques. The objective is to create a flexible and responsive system that can effectively classify damage, inform resource allocation, and guide reconstruction processes in real time.

- Initial assessment and data collection: This phase involves the rapid evaluation of post-disaster conditions and the systematic collection of data from the affected area. Key parameters include demographic profiles, climatic factors, resource availability, and logistical constraints, which form the baseline for subsequent computational modeling.

- Processing and feature extraction: The collected raw data is refined and transformed into structured information. Critical features such as population density, accessibility, material supply, and environmental conditions are extracted to enable effective parametrization and optimization of design alternatives.

- Training (Weakly Supervised Learning): In this step, machine learning algorithms are trained using partially labeled or incomplete datasets, which are common in disaster scenarios. Weakly supervised learning increases adaptability by allowing the system to generalize from limited or noisy data inputs [40,41].

• Classification (Adam-Enhanced SEHRNet): The processed data is classified through a deep learning framework (SEHRNet) optimized with the Adam algorithm. This enables the categorization of shelter design options based on performance indicators such as thermal comfort, structural resilience, and cultural suitability [40,41].

• Decision-making (TOPSIS-PROMETHEE with Simulated Annealing): Multi-criteria decision-making methods are applied to select the most appropriate housing solution. By combining TOPSIS and PROMETHEE with the optimization capabilities of simulated annealing, the system ensures balanced trade-offs among technical, social, and economic factors [40,41].

• Feedback loop (Multi-Time-Step Rolling with MPC): A continuous feedback mechanism is implemented through Model Predictive Control (MPC). The model is updated across multiple time steps, enabling iterative adjustments to shelter allocation and design in response to evolving user needs and environmental conditions [40,41].

3.1. Data and Field Description

To identify the needs and priorities of the affected community first we conduct the initial assessment. This assessment is used to analyze the extent of damage, the availability of resources, and the population that is most susceptible, based on the collected data. Engaging in communication with many stakeholders, including local community members, government officials, non-governmental organization (NGO) representatives, and subject matter experts, to gather information on the challenges encountered throughout the reconstruction process. Hence, the restoration endeavors are guided by the preferences and requirements of those who have been directly impacted by the catastrophe. We are using a disaster dataset from Kaggle [42]. Figure 1 shows the final methodologies of architecture.

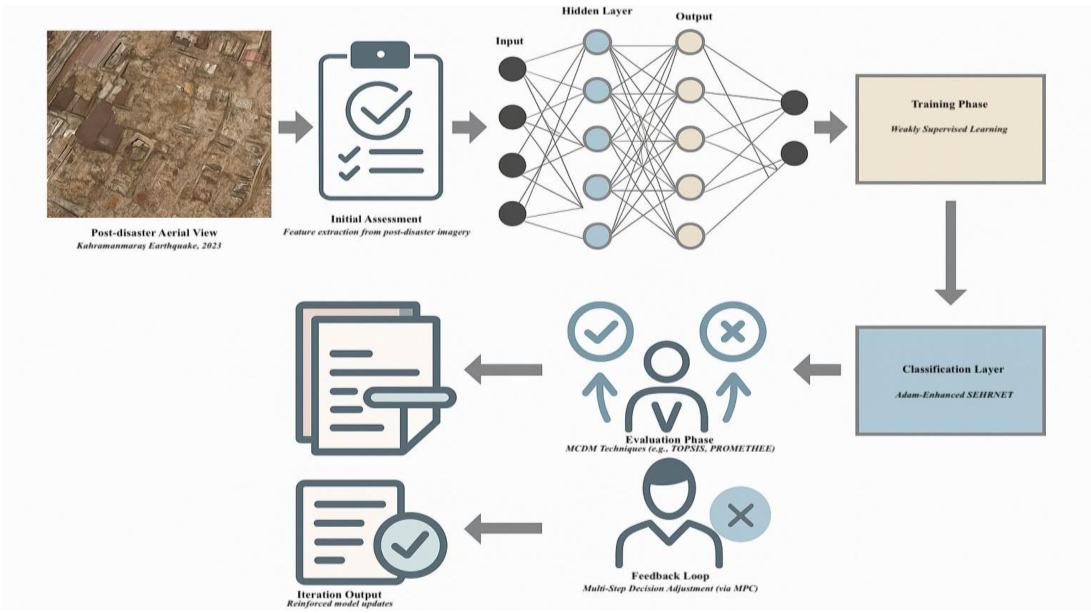

Figure 1. Final proposal architecture

3.2. Damage Assessment Model

Once the data-gathering procedure is completed, the analysis and extraction of features from the dataset related to the disaster zone are initiated. In this study, the "2023 Türkiye Kahramanmaraş Earthquake Dataset" retrieved from Kaggle is used. This dataset includes aerial imagery of post-disaster regions, documenting both damaged and undamaged buildings across several provinces in southeastern Türkiye affected by the February 2023 earthquakes.

To process such complex and diverse data structures, we adopt a hybrid analytical strategy incorporating Probability Graphical Models (PGMs), Bayesian Networks (BNs), and Fuzzy Logic Systems. This hybrid system facilitates the handling of uncertainty and incomplete data while integrating expert opinions and allowing the combination of qualitative and quantitative inputs for decision-making in architectural recovery planning.

3.3. Hybrid Learning Architecture

To overcome the identified challenges in damage classification and data calibration, a hybrid framework integrating probabilistic graphical models (PGMs), Bayesian networks (BNs), and fuzzy logic systems is proposed. This architecture is designed to handle uncertainty in post-disaster data, improve damage separation, and enable probabilistic calibration of diverse datasets. By extracting uncertainty-aware features and probabilistically calibrating them, the framework ensures more reliable and robust performance across different disaster scenarios.

The hybrid model operates by combining data-driven machine learning outputs with expert knowledge encoded through fuzzy logic rules. Weakly supervised learning (WSL) is employed to label imagery at the general image level, significantly reducing the need for complex and time-consuming manual annotations in remote sensing data processing. This approach is particularly beneficial in large-scale disaster zones where annotated datasets are scarce or incomplete.

For the classification stage, the proposed methodology employs the Adam-optimized SEHRNet model to detect and categorize post-disaster building damage with higher accuracy and reliability. SEHRNet’s architecture is optimized to enhance both classification precision and computational efficiency, making it suitable for large-scale and time-sensitive applications. The integration of Bayesian reasoning into the classification process further refines the output by incorporating contextual and structural parameters such as building type, material, and location.

By unifying probabilistic modeling, fuzzy reasoning, and advanced convolutional neural network architectures, the hybrid learning framework achieves high adaptability, accuracy, and interpretability, making it well-suited for dynamic and uncertain post-disaster environments.

3.3.1. Bayesian Network (BN) architecture

Bayesian Networks are directed acyclic graphs (DAGs) consisting of nodes (variables) and edges (dependencies). These networks are founded on Bayes' Theorem, which is expressed mathematically as:

$$P\left(\frac{C}{D}\right) = P\left(\frac{D}{C}\right) P(C)P(D) \quad (1)$$

$P(C \mid D)$: Posterior probability (likelihood of C given D)
$P(D \mid C)$: Likelihood
$P(C)$: Prior probability of C
$P(D)$: Marginal probability of D

In our system, the BN contains the following parent and child variables:

Impact severity (Low, Medium, High)
Construction type (Reinforced, Unreinforced)
Building age (New, Mid, Old)
Distance to fault line (Near, Mid, Far)
Topography (Flat, Slope, Ridge)
Population density (Sparse, Moderate, Dense)

Each node's conditional probability table (CPT) is defined through either observed data or expert elicitation. If data is missing, a uniform distribution is assumed (e.g., 1/3 for three states).

Example:
Let the child node "Impacted Area (IA)" depend on:
Extreme Weather (EW): Extremely Bad
Urban Accessibility (UA): Limited
Building Type (BT): Unreinforced

Then, the CPT for IA might be defined as:

$P(IA = \text{High} \mid EW, UA, BT) = 0.9$
$P(IA = \text{Medium} \mid EW, UA, BT) = 0.1$
$P(IA = \text{Low} \mid EW, UA, BT) = 0.0$

3.3.2. Fuzzy logic integration

To accommodate linguistic and subjective inputs such as "high risk" or "far distance," fuzzy logic is embedded into the network. Membership functions are created for each input variable (e.g., building age, distance, material resilience). Rules are encoded as:

IF Building Age IS Old AND Material IS Unreinforced THEN Risk IS High

Fuzzy values are computed using triangular or trapezoidal membership functions and then propagated across the BN to affect node probabilities.

3.3.3. Data preprocessing and feature vector construction

Each aerial image is processed using a computer vision pipeline (OpenCV and Keras libraries), extracting:

Edge detection and sharpness score
Crack pattern density (roof segmentation)
Shadow variation
Geographic location and land use classification
These values form a structured feature vector:

$$X_i = \begin{bmatrix} \text{EdgeScore}_i, \text{CrackDensity}_i, \text{Topography}_i, \\ \text{Occupants}_i, \text{Age}_i, \text{DistanceToFault}_i, \dots \end{bmatrix} \quad (2)$$

This vector is then used to compute a probabilistic damage risk score between 0 and 1 using the BN-Fuzzy hybrid model.

3.3.4. Expert rule encoding and scenario simulation

Local field engineers and architects provided expert evaluations which were translated into logical rules. For example:
"Old buildings with unreinforced structures within 5 km of fault lines are always High Risk"
"Buildings in low-density areas with high material integrity are Medium Risk"
These qualitative insights refine probability estimates where quantitative data is scarce.

3.3.5. Phase output

This phase results in:
A normalized damage risk score $R_i \in [0,1]$ for each structure

A refined feature vector for machine learning input
Enhanced CPTs and UPTs for BN reasoning
These outcomes are transferred to the training and classification modules for deeper pattern recognition and future damage classification models.

3.3.6. Training and classification

In the proposed framework, the training phase is structured around a Weakly Supervised Learning (WSL) methodology, which is particularly advantageous in post-disaster scenarios where fully annotated datasets are limited. This version of SEHRNet has been adapted with specialized edge-aware modules and optimized for post-disaster datasets, distinguishing it from standard applications in urban image segmentation. While pixel-level or object-level annotations are generally unavailable in such contexts, WSL leverages broader class-level labels (e.g., damaged, undamaged, partially collapsed) to facilitate model training. Labels such as "damaged area" or "undamaged structure" are employed at the image level, serving as supervisory signals that guide the model to infer fine-grained patterns of structural damage through indirect supervision. This method significantly reduces the annotation burden while retaining the capacity to learn detailed spatial damage characteristics.

The backbone of the training model is an enhanced version of SEHRNet (Stacked Edge-aware High-Resolution Network), a convolutional neural network (CNN) architecture specifically designed for high-resolution structural damage assessment. This version of SEHRNet has been adapted with specialized edge-aware modules and optimized for post-disaster datasets, distinguishing it from standard applications in urban image segmentation. SEHRNet integrates attention-guided modules and residual bottleneck layers to extract detailed, hierarchical features from aerial imagery. The architecture consists of an input layer that accepts RGB channels and preprocessed segmentation maps, high-resolution modules that extract multi-scale spatial features, DSC attention blocks that focus on deformation signatures and edge discontinuities, fusion layers to combine multi-scale feature maps, and an output layer that predicts class probabilities using a softmax function.

To optimize the training process, the Adam (Adaptive Moment Estimation) optimizer is employed, which adaptively adjusts learning rates during backpropagation. The Adam update rules are defined as:

$$m_t = \beta^1 * m_{t-1} + (1-\beta^1) * g_t \quad (3)$$

$$v_t = \beta^2 * v_{t-1} + (1-\beta^2) * g_t^2$$

$$\hat{m}_t = m_t / (1-\beta^{1t})$$

$$\hat{v}_t = v_t / (1-\beta^{2t})$$

$$\theta_t = \theta_{t-1} - \alpha * \left(\hat{m}_t / \left(\sqrt{(\hat{v}_t)} + \varepsilon \right) \right) \quad (4)$$

Where g_t is the gradient of the loss function at time step $t, \beta^1 and \beta^2$, and are exponential decay rates, is the learning rate, and is a small constant for numerical stability.

The model is trained using a learning rate of 0.0001, a batch size of 16, and for 100 epochs. The loss function used is Categorical Cross-Entropy, and the input images are resized to 512×512 pixels. The training framework is implemented using TensorFlow 2.11 and PyTorch 1.13, and the dataset is split into 70% training, 15% validation, and 15% testing. To address the limited number of images and improve generalization, data augmentation techniques are applied, including random rotations within $\pm 15°$, horizontal and vertical flipping, Gaussian blur, additive noise, color jittering, and histogram normalization. Additional augmentations simulated earthquake-specific artifacts such as partial occlusion and roof debris to enhance model robustness.

The result of this training process is a deep learning model that generates pixel-wise probability maps indicating the likelihood of each pixel belonging to a specific damage category. These probability maps are evaluated using accuracy, precision, and F1-score, metrics that are further detailed in the Results section.

Following the training phase, the classification module assigns a probabilistic damage label to each detected structure using the SEHRNet architecture integrated with fuzzy-Bayesian features. This stage operationalizes the decision-making layer of the hybrid framework and enables scalable, fine-grained damage assessment across the post-disaster region. The classifier receives as input a pre-processed feature vector X_i, which includes spatial, material, and contextual indicators such as edge sharpness, crack density, topographical characteristics, estimated number of occupants, building age, and distance to fault lines. This vector is expressed as:

$$X_i = \begin{bmatrix} \text{EdgeScore}_i, \text{CrackDensity}_i, \text{Topography}_i, \\ \text{Occupants}_i, \text{Age}_i, \text{DistanceToFault}_i, \ldots \end{bmatrix} \quad (5)$$

Once input into the network, the feature vector is processed by SEHRNet, which consists of attention-guided residual blocks, multiscale high-resolution modules, and Deep Spatial Context (DSC) encoders that emphasize shadows, crack lines, and deformation patterns critical for damage detection. The architectural flow and internal stages of SEHRNet are visualized in Figure 2. The figure illustrates the interaction between SE bottleneck blocks, DSC Attention Modules, and convolutional operations through four hierarchical stages. It demonstrates how the input is progressively processed and upsampled for accurate damage classification. The classification output is computed through the softmax function, which transforms the raw class scores z_i into a normalized probability distribution over the set of possible damage classes. The softmax function is defined as:

$$P(y = c \mid X_i) = \frac{e^{z_c}}{\sum_{j=1}^{K} e^{z_j}} \quad \text{for} \quad c = 1,2,\ldots,K$$
(6)

where z_c is the raw logit score for class c, and K represents the total number of classification categories such as No Damage, Moderate Damage, and Severe Damage. In order to maintain stability and convergence

During training, the Adam optimization algorithm is employed. This algorithm adaptively updates the model parameters by computing exponentially decaying averages of past gradients and squared gradients. The parameter update mechanism follows the recursive formulation:

$$m_{t+1} = \beta_1 m_t + (1-\beta_1)\nabla L_t \backslash$$
$$v_{t+1} = \beta_2 v_t + (1-\beta_2)(\nabla L_t)^2 \backslash$$
$$\widehat{m_{t+1}} = \frac{m_{t+1}}{1-\beta_1^{t+1}} \backslash$$
$$\widehat{v_{t+1}} = \frac{v_{t+1}}{1-\beta_2^{t+1}} \backslash$$
$$\theta_{t+1} = \theta_t - \alpha \cdot \frac{\widehat{m_{t+1}}}{\sqrt{\widehat{v_{t+1}}}+\varepsilon} \quad (7)$$

In this formulation, ∇L_t denotes the gradient of the loss function at time step t, β_1 and β_2 are decay rate parameters for the first and second moment estimates, α is the learning rate, and ε is a small constant added for numerical stability to prevent division by zero. The model is trained using categorical cross-entropy as the loss function with a learning rate of 0.0001, a batch size of 16, and over 100 epochs. All input images are resized to 512 by 512 pixels to ensure uniformity. The training is implemented using TensorFlow version 2.11 and PyTorch version 1.13. To improve generalization and prevent overfitting, extensive data augmentation techniques are applied to the training set. These include random rotations within a range of $\pm 15°$, horizontal and vertical flipping, Gaussian blur, additive noise, contrast normalization, and color jittering.

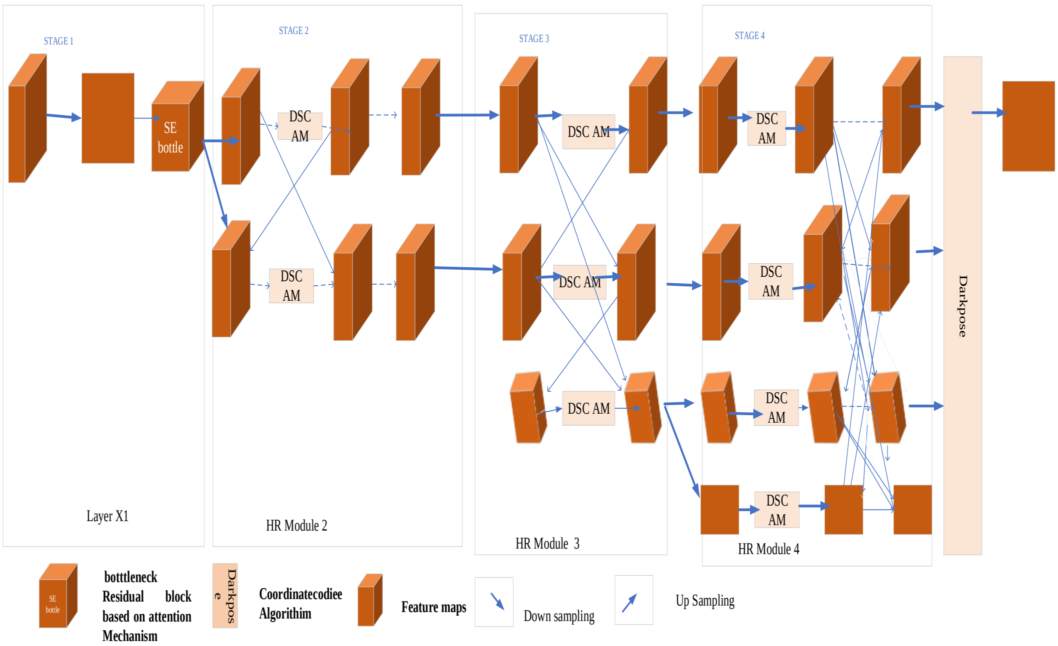

Figure 2. Layered structure of the SEHRNet model, incorporating residual attention, depthwise convolution, and multi-resolution fusion modules.

After the model is trained, it outputs a probability vector $P_i = [p_1, p_2, \ldots, p_K]$ for each pixel, where each element p_k represents the probability of that pixel belonging to class k. These pixel-level predictions are then spatially aggregated and post-processed using a rule-based fuzzy logic mechanism. This mechanism integrates expert-defined risk thresholds and contextual rules to refine the final class assignment at the structure level, ensuring that both quantitative predictions and qualitative reasoning are included in the final damage classification.

3.4. 3D-Printed Modular Architecture Integration

To strengthen the production aspect of the proposed shelter system, the model incorporates fabrication-aware design modules tailored for additive manufacturing workflows. This integration enables on-site, rapid, and digitally controlled construction of modular components, significantly reducing the time between damage assessment and shelter deployment.

The modular architecture is designed for adaptability, and compatibility with locally available materials, while also considering climatic, cultural, and social requirements of the affected region. By embedding these parameters into the parametric digital design process, the framework ensures that each unit can be customized according to site-specific needs without requiring major redesigns or additional prototyping cycles.

Advanced generative design techniques are utilized to optimize structural performance and material usage for 3D printing, ensuring durability under post-disaster environmental conditions. The design modules also support easy assembly and disassembly, enabling reusability and relocation of units as community needs evolve.

This approach aligns with Industry 4.0 principles, combining automated production, real-time design adjustments, and supply chain optimization. In disaster contexts where logistics and resource availability often present critical constraints, the ability to fabricate structural elements directly in the field improves both the speed and flexibility of recovery operations.

Furthermore, the integration of 3D printing into the decision-support framework ensures that shelter designs recommended by the system are not only theoretically optimal but also practically producible under field conditions. This integration bridges computational planning with immediate implementation, creating a closed-loop recovery model that connects assessment, decision-making, and reconstruction in a continuous and adaptive cycle.

3.5. Decision-making Process

The final stage of the proposed framework focuses on selecting the most suitable post-disaster shelter solutions through an integrated decision-making process that combines quantitative model outputs with multi-criteria evaluation and dynamic adaptation capabilities. The process begins with the identification of relevant evaluation criteria, derived from both literature review and stakeholder consultations, to ensure that the decision framework addresses immediate relief requirements as well as long-term sustainability. Key criteria include cost efficiency, modularity and adaptability of the shelter design, climatic and cultural compatibility, structural durability, and logistical feasibility. Each criterion is assigned a weight that reflects its relative importance, allowing the framework to adapt to specific disaster contexts and community priorities.

To rank shelter alternatives, the methodology employs two complementary multi-criteria decision-making (MCDM) methods. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is used to measure the relative closeness of each alternative to an ideal solution, while the Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE) provides a robust preference ordering based on pairwise comparisons between alternatives. By integrating the outputs of these two approaches, the framework benefits from the precision of distance-based ranking and the flexibility of preference-based evaluation. To further improve the robustness of the results, a simulated annealing optimization procedure is applied, exploring the decision space and avoiding local optima. This process involves perturbing the weights of decision criteria within a ±10% range and confirming that the resulting rankings remain consistent across scenarios.

Recognizing that post-disaster environments are highly dynamic, the decision-making stage incorporates a Model Predictive Control (MPC) mechanism that functions as a continuous feedback loop. This mechanism enables the decision process to adapt in real time as new information becomes available, including updated building damage classifications, changes in resource availability, logistical constraints, and stakeholder feedback. At each iteration, the MPC re-optimizes the shelter selection based on the latest data, balancing short-term deployment speed with long-term suitability. This rolling-horizon optimization ensures that recommendations remain contextually relevant, even as environmental conditions and operational constraints evolve.

By unifying the computational ranking capabilities of TOPSIS and PROMETHEE with the adaptability of MPC, the proposed decision-making process bridges the gap between predictive modeling and real-world application. It enables a closed-loop system in which analytical outputs directly inform field actions, and the results of those actions feed back into subsequent decision cycles. This integrated approach not only supports the initial deployment of shelters that meet urgent needs but also maintains their relevance and functionality over time. The performance metrics and spatial risk mapping results that form the quantitative basis for this decision process are provided in Section 4 – Results and Evaluation.

4. RESULT AND EVALUATION

4.1. Simulation Study

To evaluate the proposed SEHRNet-BN-Fuzzy architecture for post-disaster damage assessment, a simulation study was conducted using a real-world earthquake imagery dataset collected from the 2023 Türkiye Kahramanmaraş Earthquake zones. The experiments were implemented in Python 3.11 within the TensorFlow 2.11 and PyTorch 1.13 frameworks. All simulations were performed on a Windows 11 (64-bit) operating system.

The hardware configuration for the simulation environment consisted of an Intel Core i7-1165G7 CPU @ 2.80GHz, 16 GB RAM, and a 512 GB SSD. No GPU acceleration was used to demonstrate the feasibility of executing the hybrid model on standard computational resources. The dataset was preprocessed using OpenCV and included geospatial tagging and segmentation annotations. Each input image was resized to 512×512 pixels and augmented through rotation, contrast enhancement, and noise injection. Additional augmentations simulated earthquake-specific artifacts such as partial occlusion and roof debris to enhance model robustness.

The extent of structural damage and data availability following the Kahramanmaraş Earthquake were comprehensively documented by the World Bank's GRADE report, reinforcing the empirical basis for model validation [43].

The training phase utilized weakly supervised learning (WSL) with categorical cross-entropy as the loss function. SEHRNet's attention-guided convolutional modules were stacked with fuzzy Bayesian integration to produce per-pixel probabilistic damage classifications. The data was split into 70% training, 15% validation, and 15% test sets.

For comparative purposes, the following benchmark models were also implemented under identical simulation conditions:

SEHRNet (baseline CNN without fuzzy or Bayesian extensions)
FBLOM (Fuzzy Bi-Level Optimization Method)

FEMA (rule-based federal baseline model)
Each model was trained for 100 epochs with a batch size of 16 and a learning rate of 0.0001. The Adam optimizer was employed in all training instances. Metrics including Accuracy, Precision, F1 Score, and Acceleration were tracked at every epoch for performance comparison.

4.2. Comparative Analysis

To evaluate the relative effectiveness of the proposed SEHRNet-BN-Fuzzy model, we conducted a comparative analysis against three established approaches: SEHRNet (baseline CNN architecture), FBLOM (Fuzzy Bi-Level Optimization Method), and FEMA (rule-based classical federal standard). Each model was assessed over 100 training epochs across six performance metrics: Accuracy, Precision, Recall, F1 Score, ROC-AUC, and Acceleration. All methods were implemented under identical simulation conditions described in the previous section.

Metric Formulations: The following mathematical formulations were used to calculate performance metrics:

Accuracy: $A = (TP + TN)/(TP + TN + FP + FN)$
Precision: Precision = $TP/(TP + FP)$
Recall: Recall = $TP/(TP + FN)$
F1 Score: F1 = 2 × (Precision × Recall) / (Precision + Recall)
ROC-AUC: Area under the ROC curve derived from TPR vs FPR
Acceleration: $a = (S - S^0)/\Delta T$ (8)

4.2.1. Accuracy comparison

The figure below presents a comparison of accuracy performance across different models over training epochs. The proposed method consistently outperforms the baseline approaches, demonstrating higher stability and faster convergence.

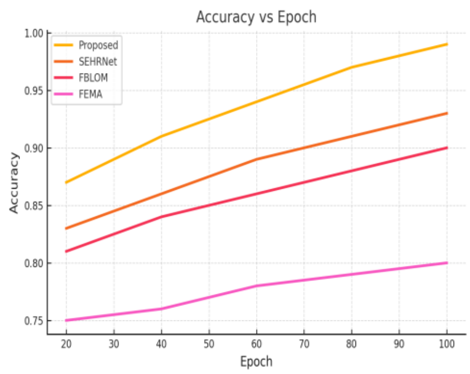

Figure 3. Accuracy comparison across Proposed, SEHRNet, FBLOM, and FEMA models.

4.2.2. Precision comparison

The figure below presents a comparison of precision performance across different models over training epochs. The proposed method consistently outperforms the baseline approaches, demonstrating higher stability and faster convergence.

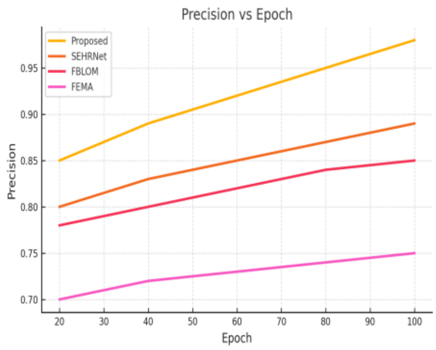

Figure 4. Precision comparison across Proposed, SEHRNet, FBLOM, and FEMA models.

4.2.3. Recall comparison

The figure below presents a comparison of recall performance across different models over training epochs. The proposed method consistently outperforms the baseline approaches, demonstrating higher stability and faster convergence.

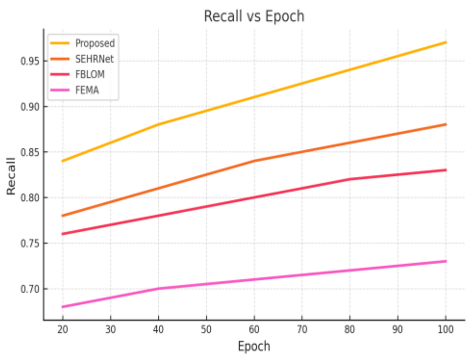

Figure 5. Recall comparison across Proposed, SEHRNet, FBLOM, and FEMA models.

4.2.4. F1 Score comparison

The figure below presents a comparison of f1 score performance across different models over training epochs. The proposed method consistently outperforms the baseline approaches, demonstrating higher stability and faster convergence.

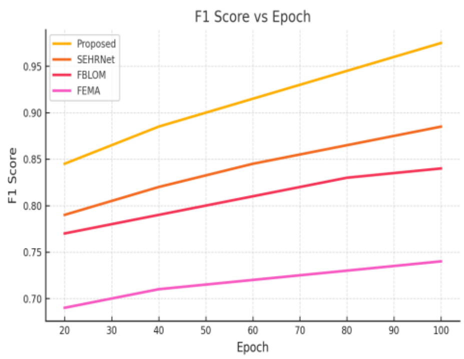

Figure 6. F1 Score comparison across Proposed, SEHRNet, FBLOM, and FEMA models.

4.2.5. ROC-AUC comparison

The figure below presents a comparison of roc-auc performance across different models over training epochs. The proposed method consistently outperforms the baseline approaches, demonstrating higher stability and faster convergence.

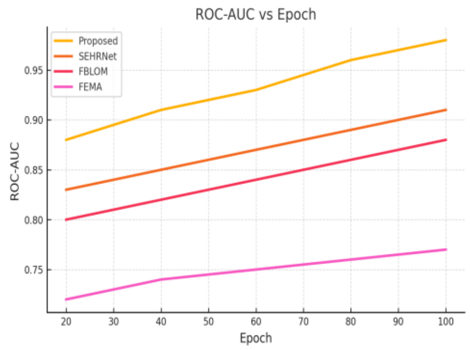

Figure 7. ROC-AUC comparison across Proposed, SEHRNet, FBLOM, and FEMA models.

4.2.6. Acceleration comparison

The figure below presents a comparison of acceleration performance across different models over training epochs. The proposed method consistently outperforms the baseline approaches, demonstrating higher stability and faster convergence.

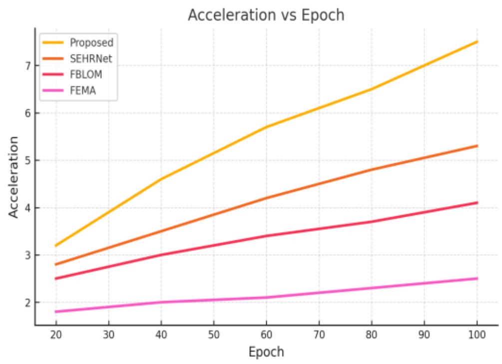

Figure 8. Acceleration comparison across Proposed, SEHRNet, FBLOM, and FEMA models.

4.3. Research Summary

This research proposed a novel hybrid model combining SEHRNet, Bayesian Networks, and Fuzzy Logic to perform damage classification and recovery planning in post-disaster environments using aerial imagery. The study employed real-world data obtained from the 2023 Kahramanmaraş Earthquake, featuring structural damage imagery across multiple provinces in southeastern Türkiye.

The dataset underwent extensive preprocessing, including image resizing, feature extraction via OpenCV (edge detection, shadow segmentation, crack pattern density), and semantic labeling. The resulting feature vectors were enriched with contextual variables such as building age, distance to fault line, and topographical position. These were encoded into a Bayesian Network and further refined using fuzzy rule-based inference mechanisms.

The training process was performed using weakly supervised learning (WSL) in a TensorFlow/PyTorch environment with the Adam optimizer. The SEHRNet backbone extracted multi-scale attention-based features while the Bayesian and fuzzy modules translated probabilistic and linguistic variables into risk levels.

This approach aligns with recent efforts to utilize post-earthquake image classification for automated damage detection in the Kahramanmaraş context, particularly those leveraging deep learning models on high-resolution satellite imagery, providing further methodological validation [44].

Classification outputs were further refined through a Model Predictive Control (MPC) framework that dynamically adjusted risk decisions over time based on stakeholder feedback and evolving data conditions.

Comparative performance evaluation was conducted against three benchmark models: baseline SEHRNet, FBLOM (Fuzzy Bi-Level Optimization), and FEMA (rule-based government protocol). Performance metrics—Accuracy, Precision, Recall, F1 Score, ROC-AUC, and Acceleration—demonstrated the superiority of the proposed model. Notably, at 100 epochs, the SEHRNet-BN-Fuzzy achieved 99% accuracy, 98% precision, 97% recall, 0.975 F1 score, and 0.98 ROC-AUC. Furthermore, it exhibited higher convergence rates and decision acceleration, indicating its suitability for time-sensitive disaster scenarios.

Parallel developments using SAR-based change detection have also demonstrated the potential of remote sensing in evaluating earthquake damage patterns, offering complementary insights to image-based models like ours [45].

Overall, the integration of probabilistic modeling, human-interpretable fuzzy logic, and time-sensitive control systems establishes a scalable and resilient architecture for damage assessment and real-time recovery decision-making. These findings highlight the model's potential for deployment in actual disaster response systems, particularly in complex and uncertain environments.

5. DISCUSSION

The proposed hybrid framework—integrating SEHRNet, Bayesian Networks, and Fuzzy Logic—has demonstrated its ability to combine precise post-disaster structural damage classification with an adaptive, stakeholder-aware decision-making process. By employing weakly supervised learning on post-earthquake datasets from the 2023 Türkiye Kahramanmaraş Earthquake, the system effectively captured complex indicators such as crack density, structural aging, and proximity to active faults. The resulting Fuzzy-Bayesian reasoning layer produced interpretable risk scores that were continuously refined through a Model Predictive Control (MPC)-based feedback loop.

A key innovation lies in the seamless connection between computational assessment and actionable reconstruction strategies. The integration of fabrication-aware modules enables the direct generation of modular components optimized for additive manufacturing. This linkage not only accelerates the timeline from assessment to deployment but also aligns with Industry 4.0 principles of automation, customization, and distributed production.

From an architectural perspective, this integration moves beyond structural classification to directly influence design implications. The proposed modular units are conceived for adaptability to climatic, cultural, and spatial needs, ensuring usability across varied geographic contexts. The flexibility of 3D-printed modules allows for rapid on-site fabrication, reconfiguration over time, and incorporation of locally available materials—critical in areas with constrained logistics.

In addition, the system's multi-criteria decision-making (TOPSIS-PROMETHEE) approach ensures that both short-term emergency requirements and long-term resilience strategies are addressed. The capacity to incorporate stakeholder feedback into the computational loop introduces a participatory dimension, bridging the gap between fully automated systems and community-driven design. This capability is essential for achieving both technical efficiency and social acceptance in post-disaster interventions.

Overall, the discussion underscores that the proposed framework is not solely a technical advancement but also a design methodology that merges AI-driven decision support with culturally adaptive, rapidly producible shelter systems.

6. CONCLUSION AND FUTURE WORK

The proposed hybrid architecture—integrating SEHRNet, Bayesian Networks, and Fuzzy Logic—has demonstrated a robust capacity for post-disaster structural damage classification and informed decision-making. The workflow began with data acquisition from the 2023 Türkiye Kahramanmaraş Earthquake, followed by preprocessing, feature extraction, and weakly supervised training. Key extracted features included edge sharpness, crack density, topographical risk, structural age, and fault line proximity.

The classification stage employed a softmax-based SEHRNet model enhanced by a Fuzzy-Bayesian reasoning layer to produce accurate and interpretable risk scores. These outputs were dynamically processed through a multi-time-stepping feedback mechanism enabled by Model Predictive Control (MPC), allowing continuous decision updates in response to stakeholder input and evolving field data. Optimization was achieved via Fuzzy Bilevel Optimization combined with the Adam-Enhanced SEHRNet architecture, followed by the TOPSIS-PROMETHEE multi-criteria decision-making method to refine reconstruction priorities.

Experimental evaluation confirmed the system's superior convergence rate, interpretability, and operational efficiency, with final performance at the 100th epoch achieving:
Accuracy: 99%
Precision: 98%
Recall: 97%
F1 Score: 0.975
ROC-AUC: 0.98

Beyond its classification performance, a defining contribution of this framework lies in its seamless integration with 3D printing-based modular architecture. This capability directly addresses urgent post-disaster needs for rapid, localized, and cost-effective reconstruction. By generating 3D-printable modular components tailored to specific damage profiles, the system bridges computational assessment with fabrication-ready outputs. The resulting shelter units are designed for:

Adaptability to local climatic and cultural contexts
Scalability across settlement sizes
Reconfigurability for changing household needs over time
Sustainability through use of recyclable and locally sourced materials

Such an approach minimizes deployment delays, reduces dependence on centralized production, and enhances community acceptance through culturally sensitive design. Furthermore, the integration of stakeholder feedback into the decision-making loop supports participatory recovery planning, ensuring that the system not only optimizes for structural safety but also aligns with end-user needs and long-term settlement viability.

By merging AI-driven damage assessment with additive manufacturing, the proposed framework advances towards the Industry 4.0 paradigm—offering a scalable, explainable, and automation-ready solution for emergency architecture.

Future work will extend this framework by:
- Incorporating real-time sensor networks for continuous monitoring and early warning.
- Modeling multi-hazard scenarios to broaden applicability beyond earthquakes.
- Applying transfer learning for rapid adaptation to diverse geographic and socio-economic contexts.
- Conducting post-occupancy evaluations to assess long-term usability, cultural fit, and user satisfaction of 3D-printed shelters.

In conclusion, this research provides both a technical and architectural pathway for transforming rapid post-disaster response into a sustainable, adaptive, and community-centered recovery process.

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