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ASSESSING FIRE RESILIENCE IN HOSTEL BUILDINGS USING MULTI-CRITERIA DECISION-MAKING (MCDM): AN INTEGRATED AHP-TOPSIS APPROACH

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ABSTRACT

This study develops a systematic Multi-Criteria Decision-Making (MCDM) approach to enhance fire resilience in hostel buildings. The methodology incorporates the TOSE framework (Technical, Organizational, Social, Economical factors) alongside three resilience parameters: Robustness, Resourcefulness, and Redundancy. Using Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a quantitative composite Fire Resilience Index is proposed, emphasizing factors such as building vulnerability, predicted fire severity, restoration cost allocation, student traffic flow, resource availability, and regulatory compliance. The approach identifies critical vulnerabilities, aids in preparedness assessment, and guides strategic management decisions to mitigate fire hazards. Findings offer practical insights for policymakers, hostel management, and disaster management authorities seeking improved fire safety standards and resilience in public buildings.

Keywords: *Fire Resilience, Multi-Criteria Decision-Making (MCDM), Analytical Hierarchy Process (AHP), TOPSIS, TOSE factors, Robustness, Redundancy, Resourcefulness, Fire Vulnerability Index, Hostel Buildings*

INTRODUCTION

1.1 General Introduction

Fire safety in India is governed by the **National Building Code (NBC) 2021**, under the supervision of fire safety legislations formulated by the Government of India. These regulations cover a wide range of building types including college hostels, hospitals, residential complexes, apartments, shopping centers, and various commercial structures. The fire safety performance required by the NBC includes implementation of fire-resistant components such as walls, floors, shafts, refuge areas, fire detection and suppression systems, and clearly defined means of egress and firefighting access shafts.

The regulations are designed to ensure minimum safety standards, emphasizing prevention of ignition, structural integrity under fire conditions, support for firefighting operations, and prevention of fire spread to adjacent structures. However, these standards primarily focus on public welfare within the constitutional limits that safeguard property rights. As a result, strict adherence to these regulations may not always prevent fire incidents with substantial losses [Himoto, 2020].

1.2 Functional Durability During Fire

The concept of **functional durability** was introduced to express a building's performance during and after fire events. It reflects a structure's ability to maintain or quickly recover its functionality post-incident by minimizing damage extent and intensity. This concept is closely aligned with **resilience**, which is generally defined as a system's ability to withstand significant disturbances and recover within acceptable time, cost, and risk parameters [Johansson & Hassel, 2010].

In the context of fire, "functional durability" or **fire resilience** provides a broader framework beyond basic code compliance. It enables the design and evaluation of buildings with enhanced recovery capacity post-fire, which conventional regulations may not fully capture.

The importance of resilience in built infrastructure necessitates the development of comprehensive methodologies to assess and enhance this capability, particularly for high-occupancy buildings like hostels.

Three characteristic modes of fire spread, as identified in the "Real Fires for the Safe Design of Tall Buildings" project, include:

- **Fully-developed fire**
- **Steady-growing fire**
- **Travelling fire**

These modes are differentiated by their respective **fire front spread rate** and **collapse front spread rate**. Experimental demonstrations such as the **Malveira Fire Test** revealed distinct thermal behaviors for each mode, influenced primarily by spatial energy distribution. At smaller scales, **ventilation** plays a critical role in compartment fire behavior. However, the correlation between ventilation and fire dynamics in larger compartments remains under-researched [Torero et al., 2003].

1.3 Fire Resilience of Buildings

Fire resilience is a function of how a building retains or restores its functionality after fire damage. The time-variant **functionality of a building, F(t)**, typically remains at 1 (fully functional) prior to a fire but drops by a damage ratio D upon fire occurrence due to loss of usable space. If not demolished, a building undergoes **restoration**, during which functionality gradually increases, returning to initial levels over time t_{rec} [Goda et al., 2019].

The **Fire Resilience Index (FRI)** is mathematically defined as the **ratio of the time-integrated functionality after fire damage** to that in undamaged conditions over a defined period from t_0 to t_L. Parameters such as **robustness** $F(t_{ign})$ and **rapidity** D/t_{rec} form essential components of resilience [Bruneau et al., 2003].

1.3.1 Functionality

In a multi-compartment building, fire may affect different compartments to varying extents. Therefore, **functionality must be evaluated per compartment**. The overall building functionality, F(t), is the weighted sum of the individual compartment functionalities:

$$R = \int_{t_0}^{t_L} \frac{F(t)}{t_L - t_0} dt,$$

Here, N represents the number of fire compartments, wi the significance weight, and fi(t) the functionality of compartment i. The recovery time $t_{rec,i}$ indicates how long each compartment takes to regain full functionality. While interactions between compartments can influence recovery, these effects are generally embedded in their respective recovery times to maintain analytical clarity [Himoto, 2020].

1.4 Robustness

Robustness refers to the system's ability to resist collapse or maintain function under extreme conditions. In the context of fire incidents, structural robustness is challenged by various factors including:

- Structural failure (e.g., beam or slab collapse)
- Melting of reinforcements
- Short-circuiting of electrical components
- Lift or mechanical system failure
- Fire spread through shafts or ducts

Robustness can be assessed through post-fire structural inspections, damage modelling, and fire exposure analysis. Enhancing robustness involves using fire-rated materials, designing with redundancy, and integrating advanced detection and suppression systems [Hassler & Kohler, 2014].

1.5 Redundancy

Redundancy is a critical design principle in resilient systems. It implies the existence of **alternative pathways or components** that allow system function to continue even if primary elements fail. In emergency response systems, redundancy enables uninterrupted operation under disaster conditions.

However, literature presents **mixed findings**: while some scholars argue redundancy enhances resilience by providing backup systems, others caution that unmanaged redundancy may lead to inefficiencies or system overloads [Janssen et al., 2006]. Different types of redundancy (active vs passive, structural vs procedural) come with their own advantages and risk profiles. Thus, effective management of redundancy is essential for optimizing both system resilience and performance [Comfort, 2007].

1.6 Resourcefulness

Resourcefulness is the ability of a system or community to mobilize and effectively utilize available resources during and after a disaster. This includes **human skills, materials, knowledge, communication systems, and institutional capacity**.

To quantify resourcefulness, a **Composite Resourcefulness Index** is proposed. It integrates multiple indicators sourced from empirical research and governmental reports. These indicators include availability of emergency funds, trained personnel, material stockpiles, and functional institutions. Due to data limitations, **Multiple Imputation (MI)** and **Markov Chain Monte Carlo (MCMC)** methods are employed to estimate missing values [Hosseini et al., 2016].

Resourcefulness encompasses not only tangible assets but also **social cohesion and communication effectiveness**. Measuring it requires an interdisciplinary approach, balancing quantitative indicators with qualitative community traits [Cutter et al., 2008].

2 LITERATURE REVIEW

Traditional fire assessment methodologies primarily employ probabilistic analyses, which assume that events are mutually exclusive, exhaustive, and conditionally independent. However, due to the complexity of fire incidents, characterized by multiple interdependent variables, accurately assessing risks and their correlations becomes challenging (Himoto, 2021). Consequently, developing quantitative analytical methods that integrate historical data, expert knowledge, and organizational experiences has gained prominence in recent research (Groner, 2016).

Several methodologies have emerged for identifying, evaluating, analyzing, and managing fire risks. These frameworks generally rely on quantitative techniques informed by stakeholder experiences to prioritize hazards, evaluate risks, and propose mitigation or management strategies (Cimellaro, 2010; Patel, 2020).

One widely adopted framework for fire resilience evaluation integrates dimensions of Technical, Organizational, Social, and Economical (TOSE) factors, alongside principles of redundancy, robustness, and resourcefulness (3Rs). This composite index approach systematically quantifies fire resilience by considering detailed indicators within each dimension (Patel, 2020).

The Government of India's Town and Country Planning Organization has provided detailed guidelines in the Model Building Bye-Laws (Chapter 7), highlighting modern practices for fire prevention in various building types, including hostels. These guidelines offer practical recommendations for implementing fire safety equipment (FSE) throughout a building’s operational life (Nowell, 2017).

Himoto (2021) introduced a novel perspective termed "fire resilience," emphasizing a building's functional continuity post-fire, beyond regulatory compliance. This concept underscores minimizing damage and ensuring rapid recovery to restore functionality quickly, thus advancing safety performance standards.

Furthermore, contemporary research emphasizes the use of advanced analytical methods, including Multi-Criteria Decision Making (MCDM) techniques such as the Analytic Hierarchy Process (AHP) and Technique for Order Performance by Similarity to Ideal Solution (TOPSIS), to systematically evaluate infrastructure resilience under varying hazard conditions (Taherdoost, 2020; Li et al., 2022).

Recent developments have also explored integrating Building Information Modeling (BIM) with augmented reality technologies to enhance fire safety equipment inspection and maintenance, offering improved precision and operational efficiency (Chen et al., 2020). Additionally, literature highlights redundancy strategies in emergency management systems, analyzing their potential benefits for system resilience and identifying potential operational risks (Nowell, 2017).

Collectively, these methodologies and frameworks present diverse, yet complementary approaches for effectively assessing, managing, and enhancing fire resilience within buildings, contributing to more robust safety outcomes.

3 METHODOLOGY

The aim of this study is to develop a Multi-Criteria Decision-Making (MCDM) system to enhance fire resilience specifically in hostel buildings. The objectives include assessing building fire resilience based on threat levels, creating a quantitative MCDM methodology using the TOSE framework (Technical, Organizational, Social, and Economical factors), and developing a Building Fire Vulnerability Index.

The problem addressed involves identifying critical TOSE factors influencing fire hazards, including structural, material, economic, and social elements, to guide fire safety management. The MCDM analysis employs techniques such as AHP and TOPSIS to systematically quantify fire resilience, considering robustness, resourcefulness, and redundancy. Key metrics evaluated include building vulnerability, predicted fire severity, student traffic flow, restoration costs, inspection techniques, BIM maturity, resource management, material and contractor availability, fire station proximity, and budget availability.

The study's scope covers practical implementation in public buildings, enhancing fire preparedness, improving safety verification, and potentially reducing training requirements. However, limitations exist such as data gaps, subjective judgments, regulatory inconsistencies, technical complexities, and validation challenges.

This research responds to India's urgent need for strengthened disaster-resilient structures and regulatory compliance, supporting safer communities through informed decision-making, regulatory improvement, and capacity-building strategies (IBRD, 2019).

4 RESULTS AND DISCUSSION

4.1 Preparing a Fire Resilience Strategy for Hostel Buildings

To enhance the fire resilience of hostel buildings, a structured and systematic strategy is crucial. This study adopts a multi-faceted methodology, utilizing Multi-Criteria Decision Making (MCDM) to evaluate preparedness, robustness, resourcefulness, redundancy, and vulnerability. The key to effective fire resilience is not only prevention and protection but also timely response and swift recovery.

4.1.1 Fire Resilience Levels Based on Threat Assessment

Hostel buildings differ considerably in their risk profiles, influenced by factors such as fire hazards, severity of potential incidents, building design, and safety infrastructure. Classifying hostels according to threat levels helps prioritize actions and resource allocation:

- **Low Threat Level:** Hostels located in safe residential areas, characterized by effective firefighting services and minimal fire hazards, usually having lower occupancy rates.

- **Medium Threat Level:** Hostels in moderately risky areas, typically with higher occupancy, proximity to some fire hazards, and average fire prevention measures.
- **High Threat Level:** Hostels situated in dense urban zones, with close proximity to flammable or hazardous materials, outdated protection systems, and high occupancy, creating significant fire risk.

Assessment of these threat levels was performed by reviewing historical fire incidents, evaluating building occupancy, inspecting structural and construction materials, and analyzing proximity to risk sources.

4.1.2 Multi-Criteria Decision Making (MCDM) Approach to Fire Preparedness

The MCDM approach effectively quantifies fire preparedness by considering multiple evaluation criteria. These criteria were grouped into six categories:

- **Building Design & Construction:** Fire-resistant materials, evacuation-friendly layouts, and effective compartmentalization.
- **Fire Protection Systems:** Presence and condition of smoke detectors, automatic sprinklers, fire extinguishers, and clearly marked emergency exits.
- **Occupant Behavior:** Regular occupant training, drills, and clear evacuation procedures.
- **Emergency Resources:** Proximity and response capacity of local fire stations, availability of firefighting equipment, and personnel accessibility.
- **Maintenance & Inspection:** Regular system maintenance schedules, routine inspections, and adherence to safety codes.
- **Risk Assessment:** Evaluation based on historical fire incident records, fire load in buildings, and inherent vulnerabilities.

Using the Analytic Hierarchy Process (AHP), each criterion received a weighted score, generating a comprehensive decision-making matrix that allowed for prioritized recommendations.

4.2 Fire Resilience Assessment for Hostel Buildings using AHP

Given the considerable occupancy and limited spatial design in hostels, robust fire resilience is paramount for ensuring safety. A comprehensive Fire Resilience Index (FRI) was developed, examining aspects such as structural integrity, fire safety mechanisms, evacuation readiness, and recovery strategies.

The Analytic Hierarchy Process (AHP) allowed systematic prioritization of these factors. Through pairwise comparisons, weights were established, providing a quantitative means of integrating different safety attributes into an overall resilience score. The FRI thus serves as a guideline for fire safety enhancements and regulatory compliance, shaping safer hostel environments.

4.3 Vulnerability Level Assessment of Hostel Buildings

The vulnerability of the hostel buildings was assessed through AHP by identifying relevant factors such as structural integrity, location risks, compliance levels, and historical disaster performance. Numerical scoring, defined as Excellent (5), Good (4), Fair (3), Poor (2), and Critical (1), allowed for a structured assessment.

Based on data collected, 19 cases were rated 'Excellent,' 24 'Good,' 3 'Fair,' and 4 'Poor,' with no instances of 'Critical.' Calculating the weighted average resulted in a vulnerability score of **4.16**, indicating the overall vulnerability level is low and close to a “Good” rating, reflecting strong resilience with minor improvements needed.

Table 4.1: Vulnerability Level Assessment Categories and Numerical Ratings

Vulnerability Category	Vulnerability Range (%)	Numerical Rating
Excellent (Very Low Vulnerability)	≤10%	5
Good (Low Vulnerability)	10-15%	4
Fair (Moderate Vulnerability)	15-20%	3
Poor (High Vulnerability)	20-25%	2
Critical (Very High Vulnerability)	≥25%	1

Table 4.2: Summary of Vulnerability Assessment Results

Vulnerability Level	Numerical Rating	Frequency	Weighted Score
Excellent	5	19	95
Good	4	24	96
Fair	3	3	9
Poor	2	4	8
Critical	1	0	0
Total	—	**50**	**208**
Average Score	—	—	**4.16**

4.4 Anticipated Severity of a Fire Incident

The AHP evaluation categorized severity as Normal (1), Low (2), Moderate (3), Severe (4), and Catastrophic (5). Occurrence frequency data indicated 24 cases as Normal, 11 Low, 13 Moderate, and 2 Severe, resulting in a weighted severity score of **1.86**. This score implies that anticipated fire severity predominantly falls between Normal and Moderate, generally manageable with standard fire safety measures.

Table 4.3: Summary of Anticipated Fire Severity Assessment Results

Severity Level	Numerical Rating	Frequency	Weighted Score
Normal	1	24	24
Low	2	11	22
Moderate	3	13	39
Severe	4	2	8
Catastrophic	5	0	0
Total	—	50	93
Average Score	—	—	1.86

4.5 Estimated Student Traffic Flow in Hostel Buildings

Assessing student traffic flow is crucial for efficient evacuation strategies. Categories assigned numerical values ranged from very low (1) to very high (5). The study found that high traffic (≥400 students) occurred 13 times, moderate traffic (200-300 students) 14 times, and low traffic categories also notable. Calculating the weighted average yielded a **traffic flow score of 2.52**, indicating a moderate flow of students, manageable yet requiring proactive crowd management strategies.

4.6 Allocation of Funds for Preliminary Restoration Costs

AHP analysis examined fund allocation in percentage categories, from very low (≤10%) to very high (≥25%). Most occurrences were in the moderate (15-20%) and low (10-15%) categories. The resultant weighted average was **2.8**, indicating moderate allocation of funds toward preliminary restoration, sufficient yet suggesting increased allocations would enhance resilience.

4.7 Adoption of Inspection Techniques

Effective inspection techniques reduce uncertainties significantly. Data showed minimal to high adoption categories, with a weighted average of **3.72**, suggesting a moderate-to-high adoption rate. This highlights solid inspection practices but also room for improvement in frequency and consistency.

4.8 Maturity of Planning and Scheduling Utilizing BIM

Evaluating the Building Information Modelling (BIM) integration indicated predominant maturity levels as High (16 occurrences) and Moderate (20 occurrences). The weighted average maturity score was **4.04**, indicating strong BIM maturity levels, showing that BIM processes are effectively utilized but could benefit from further optimization and standardization.

4.9 Implementation of Enterprise Risk Management (ERM)

Analysis of ERM implementation rated categories from minimal to high. Occurrences clustered around moderate (16 times) and basic (14 times). The resulting weighted average was **2.76**, indicating basic to moderate ERM implementation, emphasizing the necessity for more comprehensive integration of ERM practices across the organization.

4.10 Fund Arrangement Based on Projected Restoration Costs

This evaluation analyzed the adequacy of fund arrangements in percentages of the projected costs. The highest-rated category was ≥30% (score of 20), followed by 20-30% (score of 19). This suggests higher fund allocations are adequately addressing restoration needs, reducing risk associated with financial constraints.

4.11 Availability of Materials and Equipment for Restoration

Assessment found moderate to high availability levels of required materials and equipment, indicated by an average availability score of **2.8**. While generally adequate, there remains room to enhance the preparedness and availability of essential restoration resources.

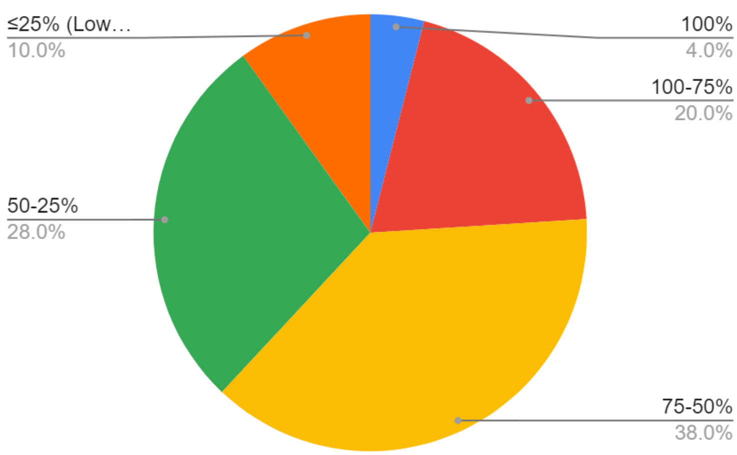

Figure 4.1 Percentages of Required Materials and Equipment for Restoration

4.12 Availability of Backup Contractors

Analysis revealed predominantly low-to-moderate availability of backup contractors, with an average score of **1.5**. This highlights the need for increased contractor network and contingency planning to improve resilience.

4.13 Distance from the Nearest Fire Station

Evaluating fire station proximity, the average distance score calculated was **3.96**, denoting moderate closeness (between 5-10 km). This suggests effective emergency response capability, though optimizing locations closer to stations could improve response times.

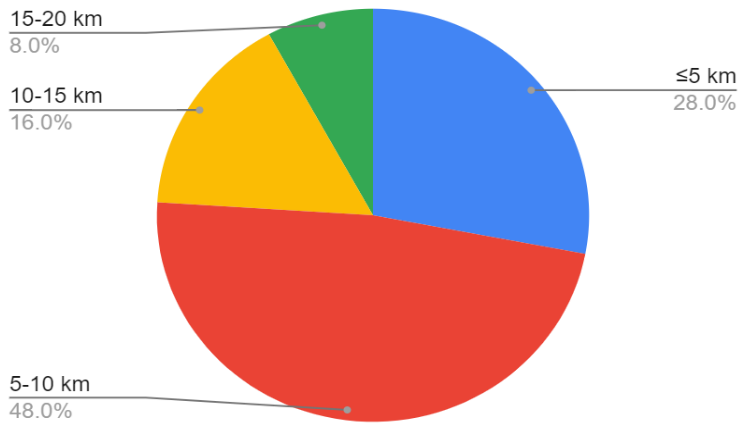

Figure 4.2 Distance From The Nearest Fire Station

4.14 Annual Budget Availability

Finally, the evaluation indicated moderate fund availability, with an average score of **2.62**. While generally sufficient, strategic financial planning is recommended to avoid potential funding shortages, ensuring sustained resilience improvement.

Table 4.4: Summary of Preliminary Restoration Cost Fund Allocation Assessment

Allocation Category	Numerical Rating	Frequency	Weighted Score
≥25%	5	9	45
20-25%	4	0	0
15-20%	3	19	57
10-15%	2	16	32
≤10%	1	6	6
Total	—	**50**	**140**
Average Score	—	—	**2.8**

CONCLUSION

This study developed a Fire Resilience Index for the MIT CORER Hostel Building in Barshi, utilizing Multi-Criteria Decision-Making (MCDM) integrating TOSE factors (Technical, Organizational, Social, Economic) and the 3R framework (Robustness, Resourcefulness, Redundancy). Analysis revealed moderate fire vulnerability, manageable fire severity, adequate traffic flow, and moderate fund allocation. Key recommendations include upgrading fire safety equipment, adopting fire-resistant materials, increasing fund allocation, improving inspection techniques, fully implementing Enterprise Risk Management, enhancing BIM usage, ensuring proximity to fire stations, regular training, periodic policy reviews, technological integration, and fostering community collaboration to enhance overall resilience.

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