

Capacity-Based Evaluation Of Retrofitted Residential Buildings: Integrating Damage Assessment And Maintenance Management

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Cite this paper as Miss. Sfoorti Dattu Bhalerao, Dr. Ashwini R. Patil, Mrs. Sneha Sawant, (2025) Capacity-Based Evaluation Of Retrofitted Residential Buildings: Integrating Damage Assessment And Maintenance Management .*Journal of Neonatal Surgery*, 14, (32s) 9498-9508.

ABSTRACT

This study presents a capacity-based evaluation framework for retrofitted residential buildings, focusing on integrating damage assessment and maintenance management to enhance structural integrity and longevity. As buildings age, structural integrity is often compromised by environmental exposure and design limitations, necessitating retrofitting to improve resilience against seismic and environmental stressors. However, the effectiveness of retrofitting is largely determined by post-retrofit maintenance practices. This research aims to bridge the gap between retrofitting implementation and sustained building performance through a structured methodology that combines damage assessment with proactive maintenance strategies. The study employs a mixed-methods approach, utilizing quantitative surveys and qualitative case studies to analyze real-world retrofitted buildings. The results highlight key correlations between retrofit types, damage severity, and maintenance costs, demonstrating that more severe damage typically requires higher retrofit levels and leads to increased maintenance costs. Additionally, the research advocates for predictive maintenance techniques to identify potential issues early, reducing long-term repair costs and extending the lifespan of retrofitted buildings. This research provides valuable insights for property owners, engineers, and policymakers to optimize building maintenance and retrofit practices, ensuring cost-effective management and enhanced building resilience.

Keywords: *Retrofitting, Structural Integrity, Damage Assessment, Maintenance Management, Predictive Maintenance, Building Resilience.*

1. INTRODUCTION

The structural integrity and longevity of residential buildings often face challenges due to factors like aging, environmental exposure, and design limitations [1]. With rapid urbanization and increased building demands, ensuring the resilience of these structures has become a pressing issue [2]. Retrofitting, a process of strengthening or upgrading existing buildings to improve their structural capacity, has emerged as a solution to enhance their resistance to seismic activities, environmental stressors, and load-bearing requirements [3]. However, while retrofitting can significantly improve a building's safety and durability, its long-term effectiveness is highly dependent on maintenance strategies that continue post-retrofit [3]. This research introduces a capacity-based evaluation framework for retrofitted residential buildings, aiming to bridge the gap between retrofitting implementation and sustained structural performance [4]. Conventional methods of damage assessment often fail to provide the depth required to understand the long-term impacts of retrofitting on building resilience [5]. Moreover, traditional maintenance strategies are often reactive, leading to delayed repairs and increased costs [6]. A more proactive and structured approach is needed to manage retrofitted buildings' maintenance efficiently [7].

By integrating damage assessment with systematic maintenance management, this study seeks to offer a comprehensive methodology for assessing the effectiveness of various retrofitting techniques over time [8]. This involves evaluating the residual strength of retrofitted structures, understanding deterioration patterns, and identifying the most suitable maintenance strategies to extend the life of these buildings [9]. The proposed framework not only focuses on improving the structural capacity but also emphasizes the importance of predictive maintenance techniques, which can help in identifying potential issues before they escalate into costly repairs [10]. Through a mixed-methods approach, combining quantitative data analysis and qualitative case studies, this study aims to provide valuable insights into the post-retrofit condition of residential

buildings[11]. The goal is to optimize maintenance processes, reduce the frequency of repairs, and ensure that the retrofitting measures continue to perform effectively throughout the building's lifecycle [12]. Ultimately, this research advocates for a shift from reactive to predictive maintenance, offering a more sustainable and cost-effective model for the management of retrofitted residential buildings [13].

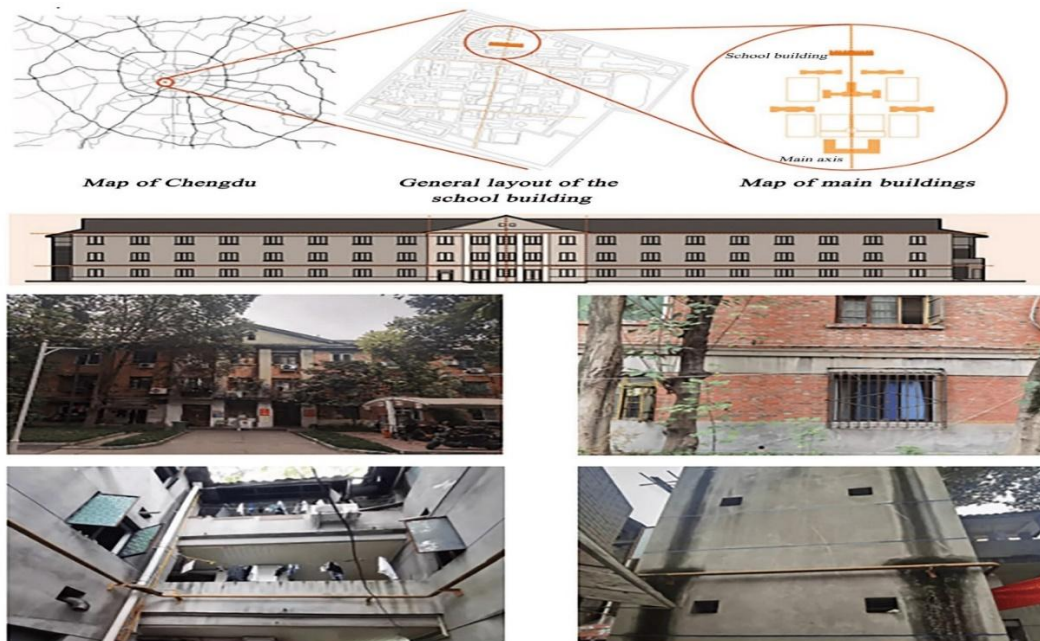


Fig 1. Retrofitting of Old Buildings [14]

Problem Statement

Despite the effectiveness of retrofitting techniques in improving structural performance, post-retrofit maintenance is still a significant concern. Many residential buildings suffer from unstructured and reactive maintenance practices, which result in unanticipated breakdowns and higher expenses. There are no standardised methods for assessing post-retrofit structural capacity, making it impossible to compare the effectiveness of various retrofitting techniques. Furthermore, the lack of long-term performance data for retrofitted buildings hampers maintenance planning. High maintenance expenses and inconsistency in damage assessment methods deter property owners from using proactive maintenance strategies. This study seeks to solve these issues by creating a structured capacity-based evaluation methodology that assures the cost-effectiveness and long-term structural durability of retrofitted residential buildings.

Objectives

- To develop a capacity-based evaluation framework for assessing damage and optimizing maintenance strategies in retrofitted residential buildings, ensuring structural integrity, longevity, and cost-effective management.
- To analyze real-world retrofitted residential buildings for identifying common damage patterns and maintenance challenges.
- To collect data from residents and experts on the effectiveness of retrofitting and maintenance strategies.
- To statistically analyze survey and case study data using SPSS for identifying key trends and correlations.
- To develop a maintenance management strategy for enhancing the durability and service life of retrofitted buildings.

2. LITERATURE REVIEW

M. Hmida et al. (2019) conducted a techno-economic assessment of energy retrofitting for educational buildings in Saudi Arabia, focusing on energy efficiency improvements. While their primary research targeted educational buildings, the methods and principles outlined are relevant for residential buildings as well, particularly in the integration of damage assessment and maintenance management for retrofitting. They explored how retrofitting techniques could optimize energy consumption and enhance building resilience, providing a framework applicable to capacity-based evaluations in residential retrofitting [15].

Manganelli, B., Mastroberti, M., & Vona, M. (2019) Capacity-Based Evaluation of Retrofitted Residential Buildings: Integrating Damage Assessment and Maintenance Management. In this study, the authors present an integrated approach for evaluating the economic feasibility and performance of retrofitting residential buildings. They combine seismic risk analysis with energy performance assessments to highlight the benefits of retrofitting in reducing seismic damage and energy consumption, thus enhancing the overall sustainability and resilience of buildings. The research provides a novel methodology for assessing both the structural and energy performance of retrofitted buildings [16].

Papangelopoulou, M.D., Alexakis, K., & Askounis, D. (2025) Assessment methods for building energy retrofits with

emphasis on financial evaluation: A systematic literature review. This study provides a systematic review of various assessment methods used for building energy retrofits, focusing on financial evaluation approaches such as Life Cycle Cost Analysis (LCCA), Cost-Benefit Analysis (CBA), and Life Cycle Assessment (LCA). It highlights the prevalence of LCCA in retrofit studies, the integration of environmental and financial indicators, and identifies significant gaps in addressing social sustainability and risk management in evaluation frameworks [17].

Keshmiry et al. (2024) focus on the capacity-based evaluation of retrofitted residential buildings, addressing the integration of damage assessment and maintenance management. They emphasize the importance of effective repair and retrofitting strategies to enhance the seismic resilience of masonry structures. The study explores various techniques for assessing structural damage and proposes methods for improving the safety and longevity of retrofitted buildings. By utilizing machine learning and structural health monitoring, their work presents a comprehensive approach to building assessment and maintenance [18].

Liu et al. (2024) develops an intelligent assistance model to enhance the diagnostic evaluation of existing residential buildings. It integrates machine learning with both qualitative and quantitative factors to assess key elements such as construction year, exterior walls, windows, balconies, and shading devices. The model significantly reduces evaluation time, achieving over 95% accuracy in large-scale assessments. It provides a more efficient, objective, and scalable method for building renovation, with practical applications through an interactive software tool designed for users, including non-experts [19].

3. PROPOSED METHODOLOGY

This study adopts a mixed-methods approach to evaluate the damage assessment and maintenance management of retrofitted residential buildings, focusing on capacity-based evaluation techniques. The research methodology is designed to meet the objectives and provide insights into the effectiveness of retrofitting strategies and their long-term maintenance needs.

1. Research Design

The research design combines both qualitative and quantitative approaches. Quantitative data will be gathered through structured surveys and capacity-based evaluations of retrofitted buildings. This data will help assess the structural conditions, capacity assessments, and the overall effectiveness of retrofitting strategies. On the other hand, qualitative data will focus on the experiences and perspectives of building managers, engineers, and architects involved in retrofitting and maintenance, providing deeper insights into the operational challenges and the effectiveness of maintenance strategies.

2. Data Collection

Primary data will be collected through two main techniques: surveys and case studies. Surveys will target professionals such as building managers, engineers, and architects, focusing on their experiences with retrofitting and maintenance practices. Case studies will analyze the performance of specific retrofitted residential buildings, providing detailed data on maintenance history, damage reports, and retrofit techniques. Secondary data will be gathered from existing building performance data, maintenance records, and relevant literature to provide additional context for the study.

3. Data Analysis

Quantitative data analysis will employ statistical tools like SPSS to analyze patterns, correlations, and trends. Descriptive statistics will be used to summarize the structural conditions and performance metrics of retrofitted buildings. Inferential statistics will examine the relationships between retrofit types, damage levels, and maintenance strategies. For qualitative analysis, thematic analysis will be applied to identify key themes from interviews and case studies, including damage assessment methods and maintenance practices. The analysis will ensure the validity of findings through triangulation, comparing quantitative and qualitative data.

4. Ethical Considerations

Ethical considerations will ensure that all participants are fully informed about the study's objectives, and their consent will be obtained prior to participation. Data confidentiality will be maintained, and participant identities will remain anonymous in all research outputs.

5. Limitations

The study's limitations include potential challenges in accessing maintenance records and the generalizability of case study findings to all residential buildings. However, these limitations will be addressed by ensuring a broad selection of case studies and using data from various sources. This research aims to contribute to the development of a comprehensive maintenance framework that ensures the long-term sustainability of retrofitted buildings.

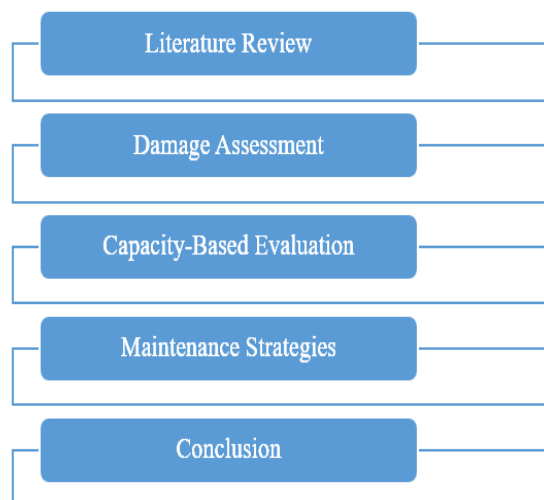


Fig 2. Research Framework

4. CASE STUDY

Pune, MH, India GPS Map Pratap Kumar Road, Viman Nagar, Pune, 411014, MH, India

Table 1: Details of the Building Analyzed

Activity	Details	Type of waste
Type of structure	Concrete	Concrete waste
Partitions	Brick and cement mortar	Broken bricks and mortar
Flooring	Porcelain and marble	Broken tiles and marble
Outside finishing	Marble and Styrofoam	Broken marbles and Styrofoam
Wall finishing	Cement mortar and gypsum	Cement and gypsum
Plumbing and water	PVC pipes	PVC pipes
Electrical network	Isolated copper wires	Copper and PVC insulation
Roofing	Concrete tile	Broken concrete tiles
Finishing	False ceiling	Plastic false ceiling
Doors	PVC and Aluminum	PVC and Aluminum
Windows	Aluminum	Aluminum

Construction, an inventory was made to account for the volume and mass of waste generated during the following stages: foundations excavation, concrete structure work, masonry, plastering, floor and roof tiles, covering the outside of buildings, and MEP (mechanical, electrical and plumbing) work. Datasheets were developed to register the mass of CDW generated. The volumes of the different types of waste (sand, concrete, brick, steel, etc...) were determined, and using their density, their mass was calculated.

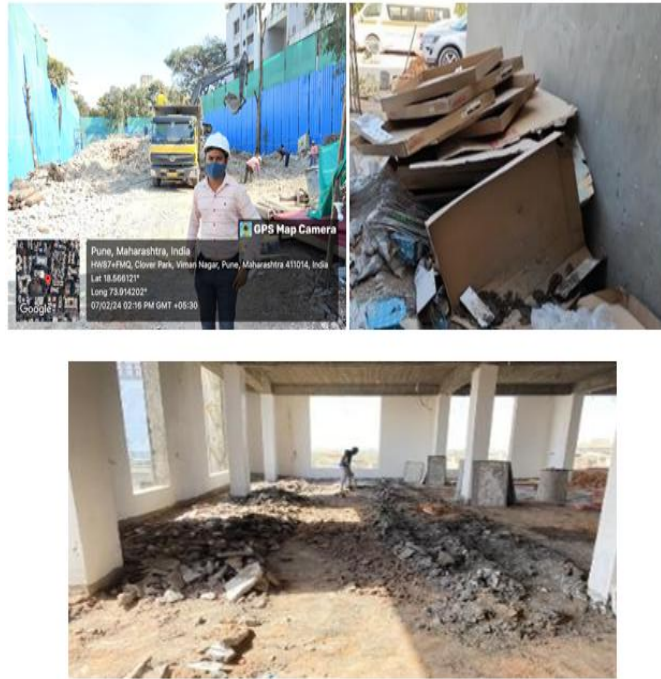
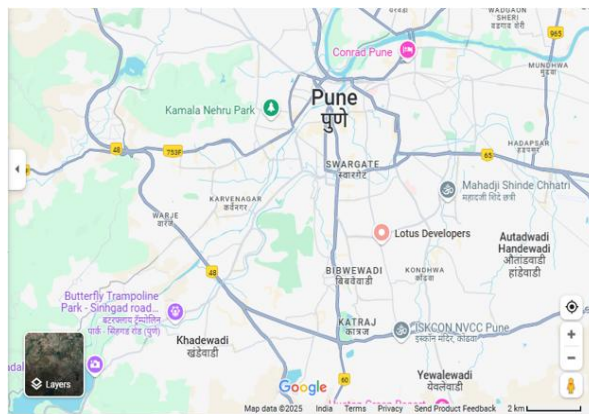


Fig 3. Site Visit Images

Amounts of The CDW Generated During the Construction of the Building with Excavation.
CDW Generated During the Construction of the Building with Excavation.



Location of the area

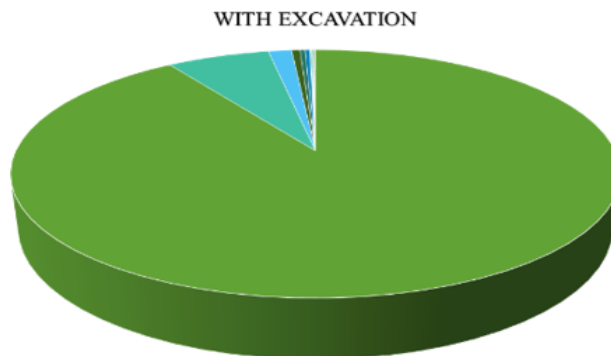


Fig 4. CDW Generated During the Construction of the Building with Excavation.

Table 2: Amounts of the CD-W Generated During the Building Construction Without Excavation

Waste Material	Quantity, kg	Waste Material	Quantity, Kg
Brick	24,650.0	Plastic	304.6
Mortar	5,584.0	Steel can	295.0
Steel	1,992.0	Cartoon	225.0
Wood	1,240.0	Aluminum	160.0
Subbase	1,058.4	Fibers	37.2
PVC	342.0	Cooper	70.0
Total	35957.8		

Table 3: Material Name, Total Quantity, Reuse and Scrap and Demolition Quantity

Material Name	Total Quantity	Reuse Quantity	Demolition and Scrap Quantity
Brick	24,650.0	7395	17255
Mortar	5,584.0	1954	3630
Steel	1,992.0	1035	957
Wood	1,240.0	682	558
PVC	342.0	290	52
Window	114	45	69
Door	105	55	50
Window Frame	114	45	69
Basin	75	33	42

5. RESULT AND DISCUSSION

Table 4: Distribution of Frequency and Percentage for Building Condition, Maintenance, and Usage Characteristics

Options	Frequency (n)	Percentage (%)
Crack Severity	-	-
No cracks	10	10%
Minor cracks	25	25%
Moderate cracks	30	30%
Severe cracks	20	20%
Very severe cracks	15	15%
Surface Quality	-	-
Excellent	8	8%
Good	22	22%

Options	Frequency (n)	Percentage (%)
Fair	35	35%
Poor	20	20%
Very Poor	15	15%
Leakage Severity	-	-
No leakage	12	12%
Rare leakage	28	28%
Occasional leakage	30	30%
Frequent leakage	20	20%
Severe leakage	10	10%
Peel-off Severity		
No peel-off	15	15%
Slight peel-off	20	20%
Moderate peel-off	30	30%
Major peel-off	25	25%
Extreme peel-off	10	10%
Frequency of Usage (per month)	-	-
1-4	22	22%
5-6	38	38%
7-8	25	25%
9-10	15	15%
Time to Resolve	-	-
1 month	10	10%
2-3 months	20	20%
4-7 months	40	40%
8-11 months	25	25%
Unresolved	5	5%
Maintenance Cost (per year)	-	-
₹50,000 – ₹1,00,000	10	10%
₹1,00,000 – ₹2,00,000	30	30%
₹2,00,000 – ₹3,00,000	40	40%
₹3,00,000 – ₹4,00,000	15	15%
₹4,00,000 – ₹5,00,000	5	5%
Maintenance Frequency	-	-
Never	5	5%

Options	Frequency (n)	Percentage (%)
Once a year	15	15%
2–3 times/year	30	30%
Every 2–3 months	35	35%
Monthly+	15	15%

The table 4 provides a detailed breakdown of building conditions, maintenance costs, and usage frequency. The majority of the buildings exhibit moderate cracks (30%) and surface conditions rated as fair (35%). Leakage severity is also common, with 30% reporting occasional leakage. In terms of maintenance, 40% of buildings incur annual costs between ₹2,00,000 and ₹3,00,000, and 35% of users perform maintenance every 2–3 months. This distribution highlights the need for targeted maintenance strategies, particularly for buildings facing moderate damage and frequent leakage.

Table 5: Regression Analysis for Maintenance Cost Prediction

Variable	Type	Description	
Maintenance Cost	Dependent	Actual cost incurred per unit (in ₹)	
Building Age	Independent	Age of the building in years	
Retrofit Type	Independent	Type of work (0 = Minor, 1 = Major)	
Material Quality	Independent	Quality rating (1 = Poor to 5 = Excellent)	
R	R Square	Adjusted R Square	Std. Error of the Estimate
0.78	0.61	0.59	₹12,500

The table 5 shows that the independent variables (Building Age, Retrofit Type, and Material Quality) explain 61% of the variation in the maintenance cost, with an adjusted R-square of 0.59, indicating a good fit. The standard error of the estimate is ₹12,500, indicating the average deviation of the predicted values from the actual maintenance cost.

Table 6: Pearson Correlation between Retrofit Type, Damage Severity, and Maintenance Cost

Variables	Retrofit_Type	Damage_Severity	Maintenance_Cost
Retrofit_Type	1	0.64	0.58
Damage_Severity	0.64	1	0.73
Maintenance_Cost	0.58	0.73	1
Retrofit_Type	1	0.68	0.62
Damage_Severity	0.68	1	0.76
Maintenance_Cost	0.62	0.76	1

The table 6 shows Pearson correlation coefficients between Retrofit Type, Damage Severity, and Maintenance Cost. A moderate positive correlation exists between Retrofit Type and Damage Severity (0.64 to 0.68), indicating that more severe damage tends to require higher levels of retrofit. There is a significant positive correlation between Damage Severity and Maintenance Cost (0.73 to 0.76), suggesting that more severe damage leads to higher maintenance costs. Retrofit Type also correlates moderately with Maintenance Cost (0.58 to 0.62), indicating that more intensive retrofitting tends to increase the

cost of maintenance.

Table 7: Factor Loadings for Structural Integrity, Aesthetic Condition, Maintenance, and Resident Satisfaction

Variable	Factor 1: Structural Integrity	Factor 2: Aesthetic Condition	Factor 3: Maintenance and Upkeep	Factor 4: Resident Satisfaction
Severity of Cracks	0.82	0.1	0.5	0.05
Plaster Condition	0.75	0.2	0.4	0.15
Water Leakage	0.79	0.12	0.45	0.1
Paint Peel-Off	0.1	0.85	0.3	0.05
Resident Satisfaction	0.2	0.05	0.15	0.9
Maintenance Response Time	0.4	0.25	0.8	0.1
Maintenance Cost	0.5	0.3	0.75	0.05
Repair Frequency	0.6	0.1	0.85	0.15

This table 7 shows the factor loadings for four factors: Structural Integrity, Aesthetic Condition, Maintenance and Upkeep, and Resident Satisfaction. Variables like Severity of Cracks, Plaster Condition, and Water Leakage have high loadings on Structural Integrity, suggesting their strong relevance to the overall structural health of the building. Paint Peel-Off is heavily associated with Aesthetic Condition (0.85), emphasizing its impact on the building's appearance. Maintenance Response Time, Maintenance Cost, and Repair Frequency all show substantial loadings on Maintenance and Upkeep, highlighting their importance in the upkeep process. Lastly, Resident Satisfaction is highly correlated with itself (0.9), confirming its central role in assessing resident contentment.

6. CONCLUSION

This study provides an in-depth analysis of retrofitting residential buildings, focusing on integrating damage assessment and maintenance management to enhance structural integrity and longevity. The research highlights the significance of transitioning from reactive to predictive maintenance strategies, emphasizing the importance of long-term post-retrofit evaluations. By developing a capacity-based evaluation framework, the study addresses the critical gap in current building maintenance practices, offering a comprehensive methodology for assessing the effectiveness of various retrofitting techniques. The findings reveal a clear connection between retrofit type, damage severity, and maintenance cost, suggesting that buildings with more severe damage require more intensive retrofitting and incur higher maintenance costs. Additionally, the study identifies that structural integrity, aesthetic condition, and maintenance practices play pivotal roles in determining overall resident satisfaction. The research also emphasizes the need for proactive maintenance, which can help in identifying potential structural issues before they escalate into costly repairs. This approach not only extends the lifespan of retrofitted buildings but also reduces maintenance costs over time. By integrating quantitative data analysis with qualitative case studies, the study provides valuable insights into optimizing maintenance strategies for retrofitted buildings, contributing to sustainable building management practices. Ultimately, this research underscores the importance of a structured, capacity-based approach to retrofitting and maintenance, offering significant benefits to property owners, residents, and the broader construction industry.

7. FUTURE SCOPE

The findings from this study lay a robust foundation for improving the management and maintenance of retrofitted residential buildings. However, there are several areas where future research can further enhance the proposed capacity-based evaluation framework and its application across various sectors. One promising avenue is the integration of advanced technologies such as artificial intelligence (AI) and machine learning (ML) to improve predictive maintenance. These technologies can analyze vast amounts of data from structural health monitoring systems, offering more accurate forecasts of maintenance needs and identifying potential issues before they become critical. Additionally, real-time monitoring using IoT (Internet of Things) sensors can optimize the maintenance process, reducing manual interventions and enhancing efficiency. Moreover, while

this study primarily focused on residential buildings, the framework's applicability can be expanded to other types of structures, such as commercial and industrial buildings. Adapting the evaluation methodology to different building typologies, considering environmental factors and regional challenges, would make it a more generalized model for retrofitting and maintenance management. Another important area for future research is long-term performance monitoring of retrofitted buildings. Establishing long-term case studies to assess the sustained effectiveness of retrofitting strategies would provide deeper insights into the durability and resilience of various approaches. Furthermore, future studies could include cost-benefit analyses of retrofitting combined with the evaluation framework, helping stakeholders make informed decisions. Exploring sustainability and environmental impacts of retrofitting, including energy efficiency and carbon footprint, would also align with global goals for sustainable urban development. These future avenues of research would refine retrofitting practices, making them more efficient, cost-effective, and applicable to a broader range of building types..

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