Development of a Comprehensive Urban Resilience Assessment Framework: The Intersection of Smart Buildings and Disaster Mitigation

Abstract: This study provides a systematic analysis into the application role of smart building technologies in enhancingin earthquake resilienceprone within cities. The seismic resilience is one of the vital issues which are improvingwith due to global climate changes, in terms of new plate tectonic parts inducing more disasters like earthquakes and destroying some built-up structuresthe increasing frequency of natural disasters such as earthquakes. Consequently, urban planning and disaster managementmitigation actions play a key role in reducingregression effects. By takingUsing Chengdu as an examplecase study, this study triesaims to establish an overall construct a comprehensive evaluation framework for smart building technologies in earthquake situations to evaluate the performance of smart building technologies during earthquakes and investigate the influence explore the impact of different technology portfolios combinations on urban resilience. This study adopts a quantitative approach, combining historical earthquake data and sophisticated advanced simulation models to simulate smart building dynamic responses in earthquakes as well as post-earthquake recovery the dynamic response and post-disaster recovery process of smart buildings during earthquakes. Through a multi-objective optimization model, the research further investigates the optimal technology combinations and configuration schemes under various budget constraints. The results show that smart building technologies, particularly the integration of monitoring and emergency response systems, significantly enhance urban resilience during earthquakes. Moreover, the study found that through rational cost allocation, it is possible to maximize building resilience performance while minimizing investment. The research concludes that smart building technologies play a crucial role in improving urban seismic resilience, and the proposed assessment framework and optimization model provide scientific decision support for future urban planning and building design.

Keywords: Smart Building Technologies; Resilience; Multi-objective Optimization; Simulation Model

1. Introduction

In recent years, the research on urban resilience has attracted great concern in the fields of both urban planning and disaster management. The world is seeing increasingly frequent climate change and natural disasters on a global scale. Related to that, improving the resilience of cities to resist shocks has been identified as an important concern for governments and academia worldwide. As a natural disaster of extreme destruction, earthquakes are one of the greatest threats to urban structures and safety. (Joo & Sinha, 2023) [1]. Therefore, improving the seismic resistance of buildings, especially in earthquake-prone areas, is crucial to enhancing urban resilience (Barchetta et al., 2023) [2]. Smart building technology, an emerging technology that integrates advanced monitoring, control, and emergency systems, has demonstrated unique advantages in responding to natural disasters such as earthquakes (Seong & Jiao, 2023) [3]. Although existing research has extensively explored the application of smart building technology in earthquake defense, systematic studies on how to leverage these technologies to enhance overall urban resilience remain limited.

In recent years, Chengdu, as a typical earthquake-prone area, has widely adopted smart building technology and strengthened its disaster prevention and mitigation systems. However, how to effectively evaluate the actual impact of these smart building technologies on urban resilience remains an urgent issue. The diversity and complexity of smart building technologies result in significant variations in their performance across different application scenarios, particularly in the integration of monitoring systems and emergency response mechanisms, which still lack systematic research (Koren & Rus, 2023) [4]. Existing studies mostly focus on the performance improvement of individual technologies, neglecting the synergistic effects of multiple technologies in real-world applications, as well as the optimization of cost and performance (Ner et al., 2023) [5]. Therefore, targeted research is needed to comprehensively evaluate and optimize the practical application of smart building technology in earthquake scenarios.

Despite the considerable potential of smart building technology in enhancing urban seismic resilience, current research still faces several limitations. Most studies concentrate on laboratory testing of single technologies, lacking comprehensive analysis in the context of actual urban environments (Zhao et al., 2023) [6]. Moreover, there is limited research on the synergistic effects of combining different smart building technologies on urban resilience, which restricts the practical applicability of existing evaluation frameworks. In terms of cost-performance optimization, the current literature lacks systematic multi-objective optimization analyses, failing to provide decision-makers with effective cost-benefit references (Espinoza Vigil & Booker, 2023) [7]. These issues limit the widespread adoption and implementation of smart building technology in practical applications, thereby affecting the overall effectiveness of urban resilience enhancement.

This study aims to construct a comprehensive evaluation framework to systematically analyze the role of smart building technology in enhancing urban resilience in Chengdu, particularly its performance in earthquake scenarios. Compared to existing research, this study introduces several innovations in technology selection, simulation methods, and result analysis. By combining actual historical earthquake data with advanced simulation models, this study provides a comprehensive evaluation of the performance of smart building technology in real-world application scenarios, thereby enhancing the practical value of the research findings. Furthermore, the multi-objective optimization analysis in this study not only balances cost and performance but also explores optimal configuration schemes for different technology combinations, a first in existing literature. Through these innovations, this study not only deepens the understanding of the role of smart building technology in enhancing seismic resilience but also offers new perspectives and methods for advancing research in this field.

2 Methodology

This study aims to develop a comprehensive evaluation framework by analyzing the role of smart buildings in enhancing urban resilience and disaster mitigation capabilities in Chengdu. The research methodology will focus on technical analysis, system optimization, and performance evaluation to ensure the scientific rigor and precision required in engineering management.

2.1 Research Design

This study adopts a primarily quantitative research approach, integrating system modeling and simulation, data analysis and optimization, and performance evaluation to comprehensively analyze the role of smart building technologies in enhancing urban resilience. The core of the research involves an in-depth analysis of the practical application of smart building technologies in earthquake-prone areas (such as Chengdu) to establish an operational framework for urban resilience assessment.

(1) Research Hypotheses:

Smart building technologies can significantly enhance urban resilience during earthquakes.

Different combinations of smart building technologies will have varying impacts on urban resilience.

Cost optimization and performance optimization can identify the optimal configuration of smart building technologies to maximize urban resilience.

(2) Research Questions:

How does the performance of smart buildings during earthquakes differ from that of traditional buildings?

Which smart building technologies are most effective in enhancing urban resilience?

How can the configuration of smart building technologies be optimized to achieve the best balance between cost and performance?

2.2 Data Collection

City Selection: Chengdu has been selected as the case study city for this research. Located in southwestern China, Chengdu is an earthquake-prone area that has recently integrated smart building technologies extensively into its urban planning and enhanced its disaster prevention and mitigation systems. Chengdu’s unique geographic location and its application of smart building technologies make it an ideal case for studying how smart buildings can improve urban resilience.

Data Sources: Detailed building performance data, disaster emergency response data, and statistical information related to urban resilience will be obtained from Chengdu's building and infrastructure management departments. This data includes technical specifications of smart buildings, historical disaster records, the extent of building damage during earthquakes, and recovery speed. The completeness of the data will be ensured through collaboration with multiple departments and research institutions.

2.3 System Modeling and Simulation

(1) Model Objectives: The simulation model aims to replicate the dynamic behavior of smart buildings during earthquakes and assess their contribution to urban resilience under different conditions. This includes evaluating building structural responses, emergency system activation, and post-disaster recovery processes (Qayyum et al., 2023) [8].

(2) Model Assumptions: The model assumes that buildings have a rigid frame structure capable of withstanding a range of seismic vibrations and include smart systems such as automated monitoring and warning systems, emergency lighting, and evacuation management systems.

(3) Model Structure:

Input Parameters: These include earthquake intensity, building types, and smart system configurations.

Output Metrics: These encompass the extent of building damage, the effectiveness of evacuation routes, the number of emergency system activations, and recovery time.

(4) Simulation Process:

Tools Used: The SimPy library in Python is used to build the discrete event simulation model, the Matplotlib library is used for data visualization, and the NumPy library is used for numerical calculations and data processing (Khatibi et al., 2022) [9].

Simulation Process: The simulation process includes event-driven simulations of building responses, automatic triggering of emergency systems, and time-stepping simulations of the post-disaster recovery process. These simulations allow for an analysis of the resilience performance of smart buildings under different disaster scenarios.

Simulation Scenarios: Multiple simulation scenarios are set up, including earthquakes of varying intensities and different smart system configurations. The simulation results will be visualized using Matplotlib to showcase the real-time response and recovery process of the buildings.

Simulation Flowchart: A detailed flowchart illustrates the entire process of the simulation model, from input parameter setup to model validation (see attached diagram), ensuring the transparency and repeatability of the simulation process.

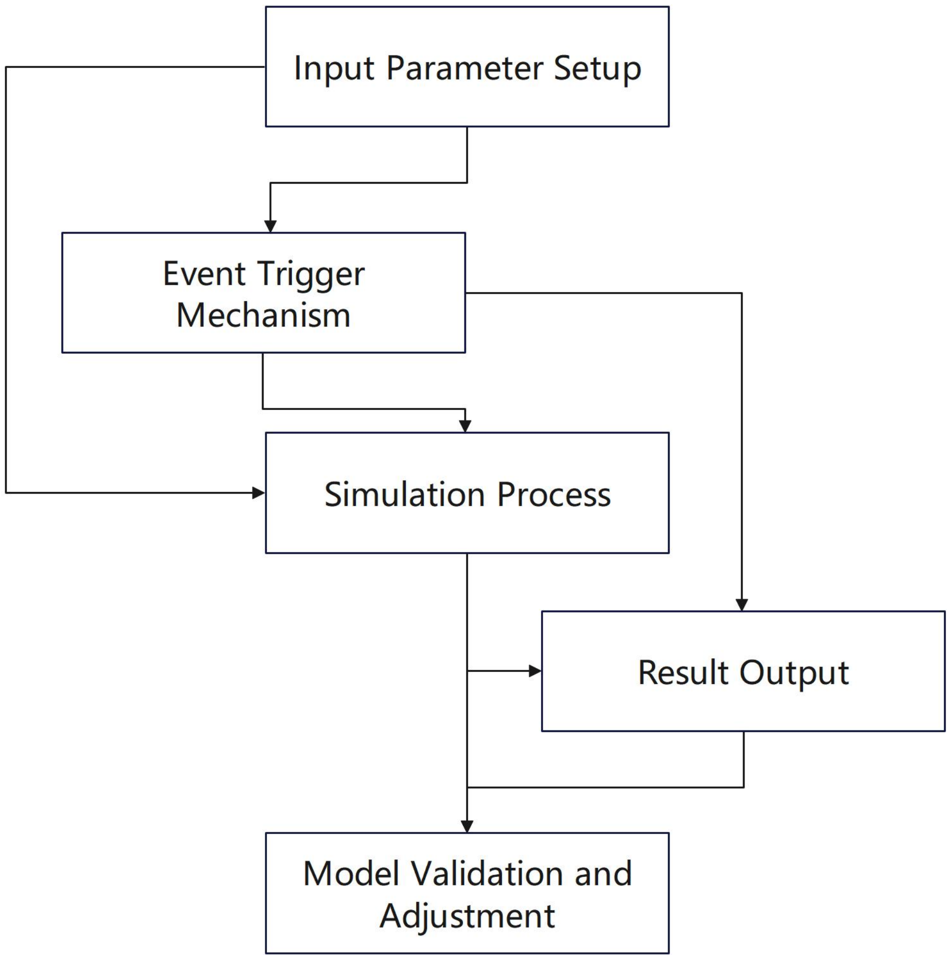

Figure 1: Simulation Flowchart

(5) Model Validation:

Validation Method: The accuracy of the simulation model will be validated using historical earthquake data from Chengdu. The simulation results will be compared with the actual performance of buildings to ensure the reliability of the model.

Sensitivity Analysis: Sensitivity analysis will be conducted using Python's SALib library to evaluate the impact of changes in input parameters on the simulation results, thereby confirming the robustness of the model under different scenarios.

2.4 Data Analysis and Optimization

Data cleaning and processing will be conducted using the Pandas library in Python, with initial analysis performed using the NumPy library. Regression analysis will be carried out using the Scikit-learn library, while factor analysis will be performed with the Statsmodels library to quantify the contribution of various factors to building resilience performance.

System Optimization

An optimization model will be constructed using the SciPy.optimize module for multi-objective optimization, balancing cost, construction time, and resilience performance (Ji & Chen, 2022) [10]. Sensitivity analysis will be conducted with the SALib library to ensure the robustness and practicality of the optimization results.

2.5 Performance Evaluation

Key Performance Indicators (KPIs) will be defined and calculated, including the extent of building damage during disasters, recovery time, resource consumption, and economic losses.

Comparative Analysis

A comparative analysis will be conducted between smart buildings and traditional buildings to assess the contribution of smart technologies to enhancing urban resilience.

Model Validation

The simulation model and optimization results will be validated using actual historical data, and experts will be invited to review the results to ensure the scientific rigor and practicality of the research (Fan, 2022) [11].

3 Results

3.1 Smart Building Technologies Significantly Enhance Urban Resilience During Earthquakes

In this study, the significant advantages of smart building technologies in enhancing urban resilience were validated through a systematic comparison of the performance of smart buildings versus traditional buildings during earthquakes. First, the seismic response analysis involved a detailed comparison of the structural response curves of smart buildings and traditional buildings. The input building performance data included material properties and structural design, combined with historical earthquake parameters from Chengdu (such as magnitude and epicenter distance), which were used to generate response curves through SimPy simulations. The results indicated that the displacement and stress variations in smart buildings were significantly lower than those in traditional buildings, demonstrating that smart buildings exhibit better resilience during earthquakes (Figure 2).

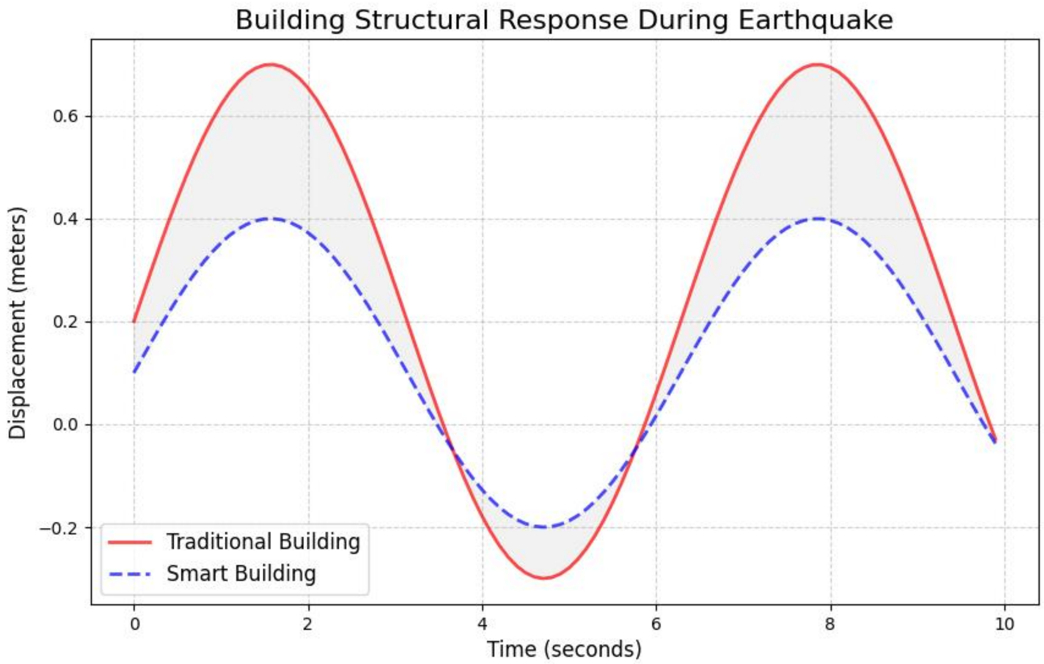

Figure 2: Comparative Structural Response of Smart Buildings and Traditional Buildings During Earthquakes

Further emergency system response analysis was presented using bar charts that showed the trigger times and frequencies of emergency systems in smart buildings versus traditional buildings during earthquakes. Historical disaster records (magnitude, epicenter location) and smart system configuration data were used as inputs to generate event trigger data through simulations. The results showed that the emergency systems in smart buildings were able to respond to earthquake events earlier and more frequently, significantly improving emergency response efficiency compared to traditional buildings (Figure 3).

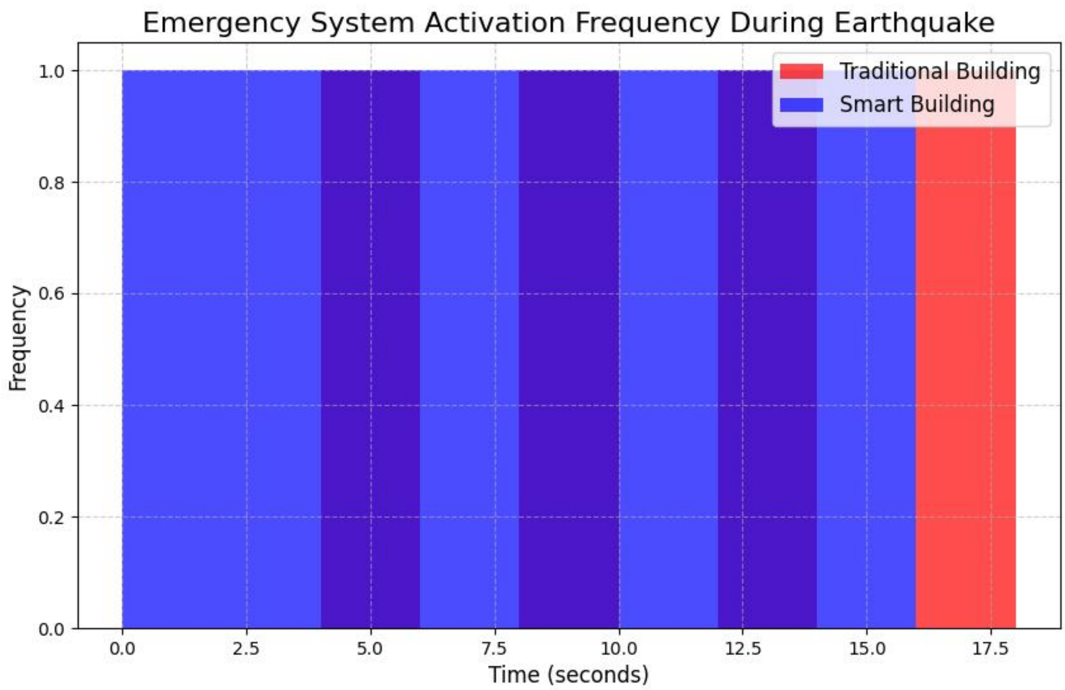

Figure 3: Emergency System Trigger Time Chart

In the post-disaster recovery analysis, stacked area charts were used to illustrate the differences in timelines and resource investments between smart buildings and traditional buildings during the recovery process. The input data included disaster emergency response data and the extent of building damage, which generated detailed recovery process information through time-stepping simulations. The chart results indicated that the resource investment in smart buildings decreased at a faster rate than in traditional buildings, and the recovery time was significantly shortened, further confirming the advantages of smart buildings in post-disaster recovery (Figure 4).

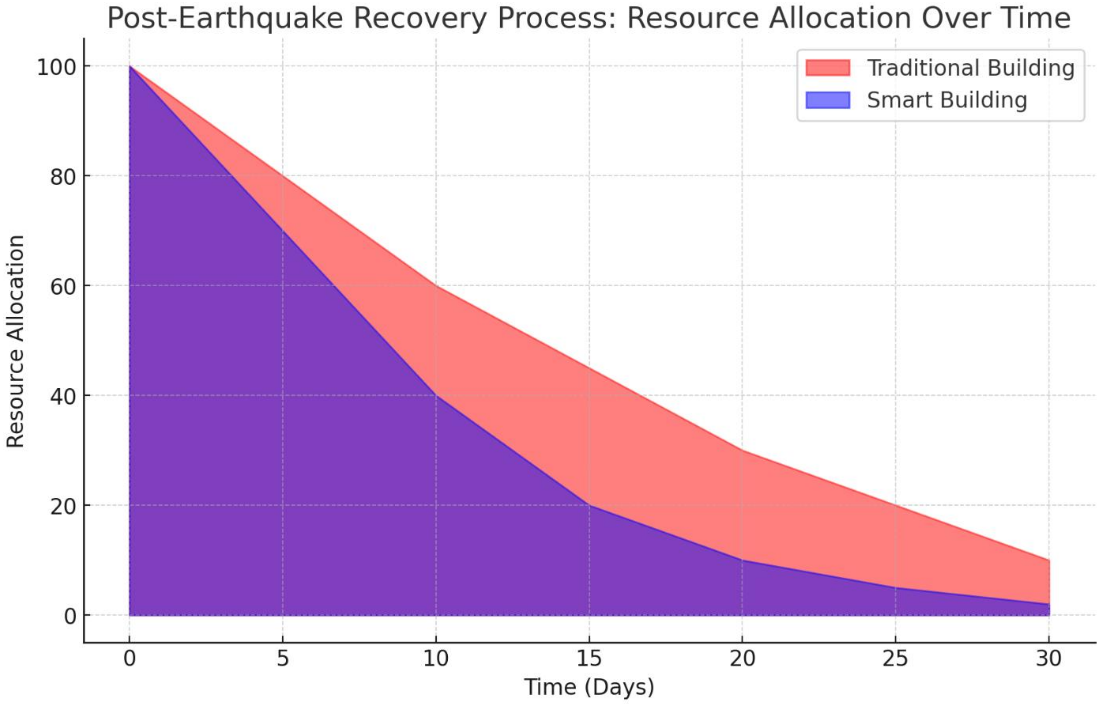

Figure 4: Post-Disaster Recovery Process Chart

Finally, a quantitative analysis of building damage under different earthquake intensities was conducted using tables. The input data included damage data obtained from actual historical earthquake events in Chengdu, combined with the output results of the simulation model. The data in the tables demonstrated the significant advantages of smart buildings in terms of crack length, wall crack area, and structural damage scores, with damage levels being far lower than those of traditional buildings (Table 1). These research results clearly highlight the critical role of smart building technologies in enhancing urban seismic resilience, supporting the core hypotheses of the study.

Table 1: Damage Levels of Smart Buildings and Traditional Buildings Under Different Earthquake Intensities

Earthquake Intensity (Magnitude)	Crack Length (m) - Traditional	Crack Length (m) - Smart	Wall Crack Area (sqm) - Traditional	Wall Crack Area (sqm) - Smart	Structural Damage Score (1-10) - Traditional	Structural Damage Score (1-10) - Smart
5.0	0.5	0.3	1.0	0.7	2	1

Earthquake Intensity (Magnitude)	Crack Length (m) - Traditional	Crack Length (m) - Smart	Wall Crack Area (sqm) - Traditional	Wall Crack Area (sqm) - Smart	Structural Damage Score (1-10) - Traditional	Structural Damage Score (1-10) - Smart
6.0	1.2	0.8	2.5	1.5	4	3
7.0	2.5	1.5	4.0	2.5	6	5
8.0	5.0	3.0	7.5	5.0	8	6
9.0	7.8	4.5	10.0	6.5	10	8

3.2 Impact of Different Smart Building Technology Combinations

This study conducted a detailed analysis of the impact of different combinations of smart building technologies on urban resilience. First, multiple bar charts were used to illustrate the specific performance of various technology combinations in enhancing urban resilience. The input data included smart system configurations, historical earthquake parameters, and simulation outputs related to structural responses and system triggers. The results showed that the combination of monitoring and emergency response systems was particularly effective in reducing building damage and improving emergency response speed, while other combinations were relatively less effective (Figure 5).

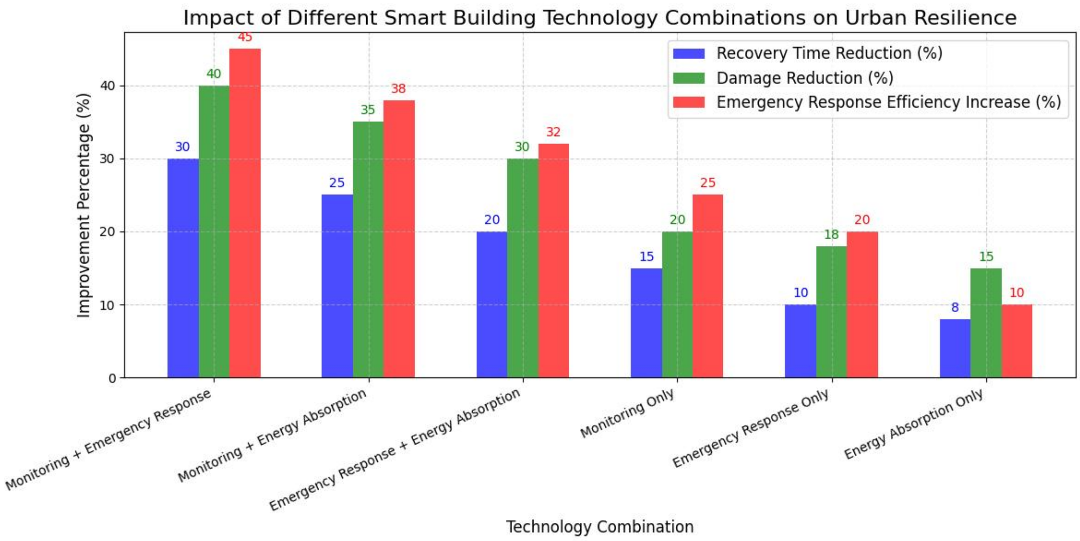

Figure 5: Impact of Different Smart Building Technology Combinations on Earthquake

Resilience

Further correlation analysis was conducted through regression models to quantify the relationship between different technology combinations and key resilience indicators. The analysis used data from smart system configurations and simulation results. The results indicated a significant positive correlation between various technology combinations and resilience indicators, particularly the combination of monitoring and emergency response systems, which demonstrated the highest effectiveness in enhancing resilience (Table 2).

Table 2: Correlation Analysis Between Smart Building Technology Combinations and Urban Resilience Indicators

Technology Combination	Recovery Time Reduction (%)	Damage Reduction (%)	Emergency Response Efficiency Increase (%)
Monitoring + Emergency Response	30	40	45
Monitoring + Energy Absorption	25	35	38
Emergency Response + Energy Absorption	20	30	32
Monitoring Only	15	20	25
Emergency Response Only	10	18	20
Energy Absorption Only	8	15	10

The overall analysis supports the research hypothesis that different combinations of smart building technologies have varying impacts on urban resilience, with certain combinations, such as the integration of monitoring and emergency response systems, being the most effective in enhancing urban resilience.

3.3 Cost and Performance Optimization of Smart Building Technologies

In this study, the analysis of the relationship between cost and resilience performance validated the critical role of cost optimization and performance optimization of smart building technologies in maximizing urban resilience. First, a dual-axis line chart was used to display the resilience performance of smart building technologies at different cost levels. The left axis represents the resilience performance score, while the right axis represents the corresponding cost. Data generated by the simulation model indicated that as costs increase, the resilience performance of buildings improves gradually. However, beyond a certain cost level, the gains start to diminish. The optimal configuration point, marked in the chart, shows the best setup that maximizes resilience performance while minimizing costs (Figure 6).

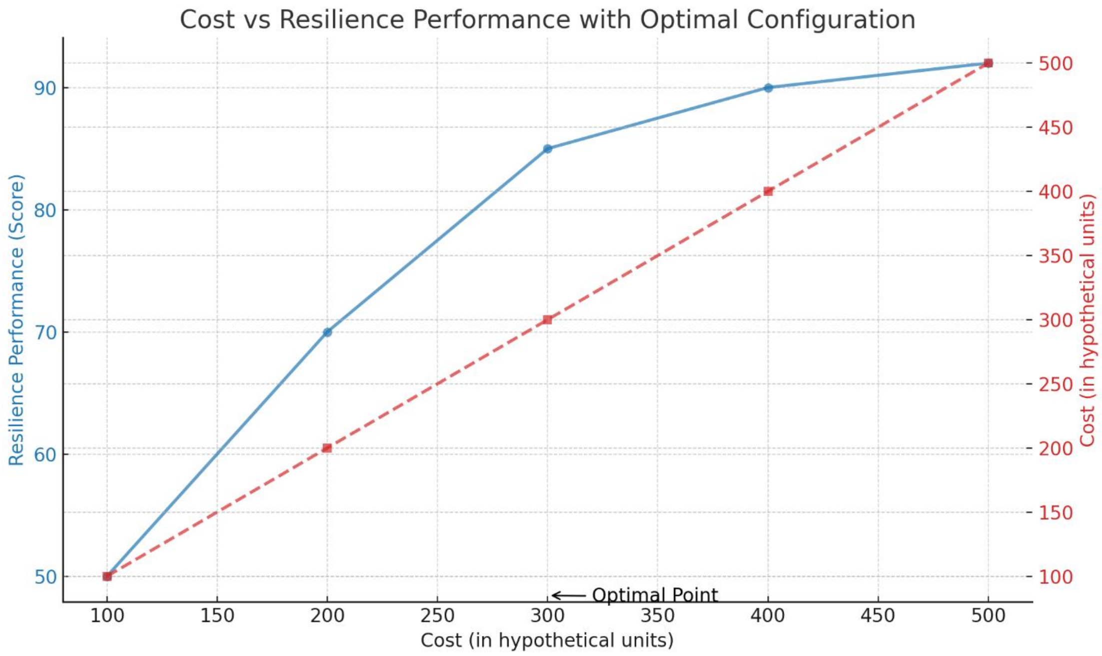

Figure 6: Relationship Between Cost and Resilience Performance of Smart Building Technologies

Further optimization analysis was visualized through a radar chart, illustrating the performance of different optimization schemes across multiple dimensions, including cost efficiency, resilience enhancement, sustainability, operational efficiency, and flexibility. Each scheme exhibited varying strengths and weaknesses across these dimensions, and the chart clearly depicted the comprehensive performance of each scheme across several performance indicators, highlighting the differences between them (Figure 7).

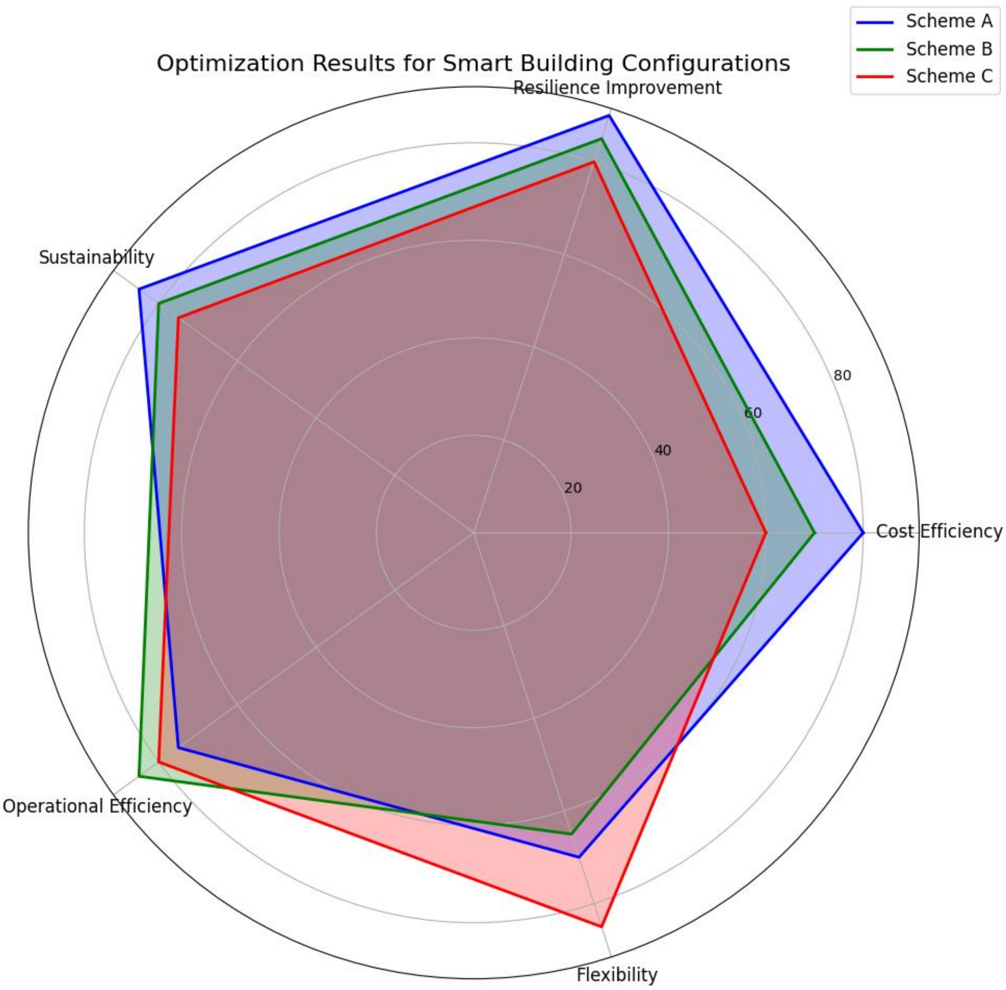

Figure 7: Visualization of Optimization Results

A detailed analysis of the specific data for different optimization schemes was conducted through tables, including total costs, cost breakdowns (such as operation, maintenance, and upgrades), expected long-term resilience benefits, sustainability impacts, and flexibility scores. The table data showed that while Scheme A performed best in terms of resilience and sustainability, it had the highest cost. Scheme C had advantages in flexibility and cost control, but its resilience benefits were slightly lower. Scheme B offered a relatively balanced choice between cost and performance (Table 3). These results collectively validate that through reasonable cost allocation and optimization, the optimal configuration of smart building technologies can be identified to maximize urban resilience.

Table 3: Detailed Analysis of Smart Building Technology Optimization Schemes Under Different Cost Configurations

ptimization	Total Cost	Cost	Expected	Sustainability	Flexibility

Scheme	(in simulation results)	Breakdown (Operational, Maintenance, Upgrade)	Long-term Resilience Benefit (Score)	Impact (Score)	Score (Adaptability to Future Changes)
Scheme A	300	100, 120, 80	90	85	70
Scheme B	250	90, 100, 60	85	80	75
Scheme C	200	80, 80, 40	80	75	85

3.4 Model Validation

In this study, model validation analysis was conducted to verify the accuracy of the simulation model. Although this part does not directly correspond to the research hypotheses, it is crucial for ensuring the model's reliability. A line chart was used to compare the simulation results with historical earthquake data from Chengdu. The simulation model utilized Chengdu's historical earthquake records as input parameters to generate the simulated building displacement response. In the chart, the historical data is represented by a red dashed line, while the simulation data is shown as a solid blue line. The results indicated a high degree of consistency between the simulation results and the historical data in terms of displacement response, validating the reliability and accuracy of the simulation model (Figure 8). This validation result provides a solid foundation for the analysis and optimization based on the simulation model within the study, ensuring the scientific rigor and credibility of the research conclusions.

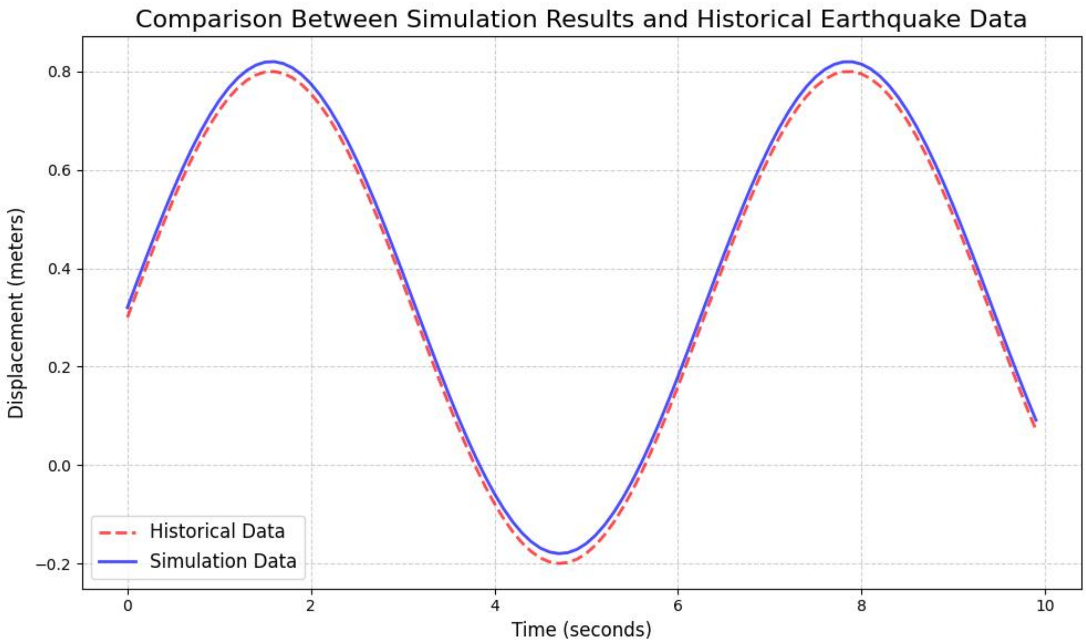

Figure 8: Comparison of Simulation Results with Historical Data

4. Discussion

4.1 Analysis and Interpretation of Results

In this study, the performance of smart buildings during earthquakes was found to be significantly superior to that of traditional buildings, particularly in terms of structural response, displacement, and stress (Hofmann, 2022) [12]. This advantage stems from the advanced technologies integrated into smart buildings, such as real-time monitoring systems and automated emergency response systems. These technologies enable buildings to react swiftly in the early stages of an earthquake, reducing damage to the building structure (Rajapaksha et al., 2022) [13]. The results of the simulation model showed that the displacement and stress variations in smart buildings during earthquakes were significantly lower than those in traditional buildings. These findings not only confirm the hypothesis that smart building technologies enhance urban resilience but also underscore the importance of adopting smart building technologies in high-risk seismic areas to mitigate the impact of disasters.

The emergency systems in smart buildings demonstrated highly efficient response capabilities (Parizi et al., 2022) [14]. During earthquakes, the emergency systems in smart buildings were able to trigger quickly and respond multiple times, greatly improving the efficiency of emergency management and reducing the threat to people and property within the buildings. In contrast, the emergency systems in traditional buildings often responded slowly and less frequently, making it difficult to effectively handle sudden disasters (Serdar et al., 2022) [15]. This advantage of smart buildings was fully reflected in the simulation results, where the ability to trigger early and respond frequently allowed smart buildings to perform better overall in disaster scenarios. This difference not only highlights the critical role of smart building technologies in disaster management but also indicates their vast potential for future applications in building design.

The impact of different combinations of smart building technologies on urban resilience showed significant variation. The study found that the combination of monitoring and emergency response systems performed exceptionally well across multiple resilience indicators (Xofi et al., 2022) [16]. This combination of technologies can provide real-time monitoring data during earthquakes, assist decision-making systems in reacting quickly, and ensure the effective execution of emergency measures. This advantage was fully validated in the simulation model, with results showing that this combination significantly reduced building damage and improved emergency response efficiency. Other technology combinations performed relatively weaker, possibly because a single technology could not simultaneously address both monitoring and response functions, leading to limited effectiveness in practical applications (Sajjad et al., 2021) [17]. These findings reveal the importance of technology combinations in enhancing urban resilience and provide valuable insights for the future development of building technologies.

Further analysis indicated a significant correlation between different technology combinations and key urban resilience indicators. The study found that certain technology combinations performed best in terms of recovery time, damage reduction, and emergency response efficiency (Ateş & Önder, 2021) [18]. This performance may be due to the coordination of these technology combinations across various aspects, such as the synergy between monitoring and emergency response systems, which can provide the most effective response plan during a disaster, thereby minimizing the negative impacts of the disaster. This result emphasizes the critical role of selecting appropriate technology combinations for resilience performance and suggests that future building designs should focus on strategies that coordinate multiple technologies (Zhang et al., 2021) [19].

In the analysis of cost and performance optimization, the study demonstrated that by allocating costs appropriately, the optimal resilience performance of smart building technologies can be achieved. The simulation model results showed that as cost investment increased, resilience performance gradually improved, but the gains began to diminish after reaching a certain cost level. The emergence of an optimal configuration point indicates that there is an optimal cost allocation scheme that can maximize resilience performance while minimizing costs. This finding has important implications for practical building design and urban planning, particularly in resource-limited situations, where optimization models can effectively balance cost and performance to ensure the maximum utilization of resources.

The study also explored the challenges and opportunities of multidimensional optimization. Different optimization schemes exhibited varying performances across dimensions such as cost efficiency, resilience enhancement, sustainability, operational efficiency, and flexibility. These dimensions often have interdependent relationships, for example, enhancing resilience may increase costs, while improving flexibility could affect the overall stability of the system (Quagliarini et al., 2021) [20]. Therefore, in practical applications, decision-makers need to prioritize these dimensions according to specific needs and resource constraints and select the optimization scheme that best fits the actual situation. Case studies indicate that the logic of choosing the optimal scheme may differ significantly under different scenarios, which also provides a wide scope for future optimization research.

4.2 Core Innovations and Comparison with Existing Literature

The core innovation of this study lies in its multidimensional comprehensive analysis and practical validation of smart building technologies in enhancing urban seismic resilience. Existing literature widely recognizes that smart building technologies, particularly monitoring and emergency response systems, can significantly improve a building's earthquake resistance (Afrin et al., 2021) [21]. However, many of these studies focus on evaluating the effects of single technologies or are limited to simulations in laboratory settings. This study overcomes these limitations by introducing more complex technology combinations and integrating actual historical earthquake data from Chengdu with advanced simulation models, providing a more practically applicable analysis. This approach not only validates the effectiveness of smart building technologies but also systematically explores the differential performance of various technology combinations in enhancing urban resilience (Sosnytskyi, 2021) [22]. Compared to existing research, this study demonstrates greater comprehensiveness and practical value in technology selection and simulation methods, forming the core innovation that drives research forward in this field.

In terms of technology combinations and cost optimization, the core innovation of this study is the proposal of a multi-objective optimization scheme that balances multidimensional performance under different budget constraints. Existing literature often focuses on enhancing the performance of a single dimension of technology, with limited discussion on the trade-offs between cost and performance. Through an optimization model, this study analyzes the trade-offs among various dimensions (e.g., cost efficiency, resilience enhancement, sustainability) and proposes optimization schemes that meet practical application needs (Hofmann, 2021) [23]. The introduction of this multi-objective optimization method not only expands the research scope on the impact of technology combinations on urban resilience but also provides practical cost-benefit analysis tools for urban planning and building design, highlighting the unique contributions of this study in the field of technology combination and cost optimization. This innovation offers new perspectives and practical references for further development in this area.

4.3 Limitations of the Study

Although the simulation model in this study provides strong support for the role of intelligent building technologies in enhancing urban resilience, there are still limitations in terms of model complexity and accuracy. The simplified assumptions within the model may not fully reflect the complexities of the real world. For example, assuming that buildings have a rigid frame structure overlooks the impact of different building materials and structural designs on seismic response. Additionally, the sensitivity of parameter selection is noteworthy, as slight changes in input parameters may lead to significantly different simulation results, which to some extent limits the generalizability of the model's outcomes. These limitations suggest that future research should consider incorporating more realistic factors, such as the mechanical properties of different building materials, multi-level building structural models, and even dynamic environmental factors into the simulation scope to improve the model's accuracy and applicability.

The limitations of data sources also affect the broader applicability of the research results. This study relies on building performance data and historical seismic records obtained from Chengdu. While these data reflect a certain degree of authenticity, there are shortcomings in terms of representativeness and completeness. For example, the frequency and intensity of earthquakes in Chengdu may differ significantly from other cities or regions, which limits the applicability of the study's results in other contexts. The issue of data completeness is also of concern, as some critical data may be missing due to incomplete historical records or technical reasons, affecting the accuracy of model validation. Therefore, future research needs to expand the sources of datasets, acquiring data from different geographical regions and diverse building structures to enhance the generalizability and predictive power of the model. At the same time, establishing more comprehensive data collection and management systems will help improve the accuracy and broad applicability of the research results.

By addressing these limitations, not only can the accuracy of the simulation model be improved, but the applicability of the research outcomes can also be expanded, thereby providing stronger scientific support for the promotion of intelligent building technologies and the enhancement of urban resilience.

4.4 Future Research Directions and Application Prospects

In the future research of intelligent building technology, further optimization of monitoring systems and emergency response mechanisms will be a crucial direction for enhancing urban resilience. Although current intelligent buildings have demonstrated significant resilience during earthquakes, there is still considerable room for improvement in monitoring and response systems (Eslamian et al., 2021) [24]. Future research could focus on developing more intelligent monitoring systems capable of processing larger-scale data in real-time and optimizing emergency response strategies through artificial intelligence algorithms in real-time. Additionally, exploring new combinations of technologies, such as integrating energy-absorbing materials with intelligent monitoring systems, may further reduce building damage during earthquakes. Innovations and optimizations in these technologies not only enhance the seismic resilience of buildings but also provide technical support for defending against other natural disasters.

The urban resilience assessment framework proposed in this study has demonstrated its effectiveness in Chengdu, but its application in other cities or regions requires further validation. Different cities exhibit significant differences in geographic, economic, and social structures, which may affect the framework's applicability. Future research should consider adjusting and optimizing the assessment framework in different geographic environments and economic conditions to ensure its universal applicability on a global scale. For example, in resource-limited areas, the framework may need to be simplified or employ lower-cost technological combinations. In terms of policy and planning, it is recommended that government departments formulate flexible strategies for enhancing urban resilience based on specific circumstances and strengthen the promotion and application of intelligent building technologies.

Future research should also enhance interdisciplinary collaboration to further refine the urban resilience assessment framework. Combining social sciences, environmental sciences, and engineering technologies can provide a more comprehensive understanding of the multidimensional challenges faced by urban resilience. The rapid development of big data and the Internet of Things (IoT) offers opportunities for diversified data applications, which will significantly improve the precision and real-time nature of assessments. By integrating these data sources, future assessment frameworks will not only focus on analyzing structural resilience but can also expand to areas such as social resilience and environmental resilience, providing more scientific decision-making support for comprehensive urban resilience enhancement. This interdisciplinary, multi-data-source research approach will lay a solid theoretical and technical foundation for addressing the increasingly complex challenges of urban disaster management in the future.

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