

Multi-Criteria Evaluation of Seismic Design Alternatives for Concrete Structures through the Integration of Life Cycle Analysis and Environmental Sustainability Indicators

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ABSTRACT

The objective of this study is to develop an integrated framework for evaluating and selecting sustainable seismic design alternatives in concrete structures. Within this framework, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are combined with seismic performance evaluation and Multi-Criteria Decision-Making (MCDM) to achieve an optimal balance among safety, environmental sustainability, and economic efficiency. The research is applied and analytical in nature and is conducted based on numerical modeling and quantitative analyses. Three seismic design alternatives—including a code-based design, a performance-based design, and an optimized design—were modeled for a conventional concrete structure. Nonlinear static (pushover) and nonlinear time-history analyses were performed to evaluate seismic indicators, including interstory drift, ductility, dissipated energy, and damage index. Subsequently, environmental indicators were obtained using SimaPro software and the Ecoinvent database, while economic indicators were derived through life cycle cost calculations. Finally, an integrated decision-making process was carried out using the TOPSIS and VIKOR methods with criteria weighting determined by the Analytic Hierarchy Process (AHP). The results indicate that the optimized design provides the best balance among seismic performance, cost, and environmental impacts. Compared to the code-based design, this alternative achieved a 12% reduction in structural weight, a 22% decrease in CO₂ emissions, and a 12.6% reduction in life cycle cost. Moreover, sensitivity analysis results confirmed the high robustness of the decision-making model. The integration of life cycle analysis with seismic evaluation and multi-criteria decision-making constitutes an effective tool for achieving sustainable seismic design. This framework can be applied in the development of design guidelines and policies aimed at reducing environmental impacts in the construction industry.

Keywords: seismic design; life cycle assessment; multi-criteria decision-making; concrete structure; environmental sustainability

1. Introduction

The construction industry is widely recognized as one of the largest contributors to global environmental degradation, energy consumption, and greenhouse gas emissions, while simultaneously being responsible for providing safe and resilient infrastructure for rapidly urbanizing societies (Goggins et al., 2010; Kibert, 2016). Concrete structures, in particular, play a dominant role in urban development due to their structural efficiency, availability of materials, and economic feasibility; however, they are also associated with high embodied energy, significant CO₂ emissions, and long-term maintenance burdens (Miller et al., 2018; Scrivener et al., 2018). These challenges are further amplified in seismic regions, where structural safety requirements often conflict with sustainability objectives, leading to design decisions that prioritize short-term structural resistance over long-term environmental and economic performance (Bertero & Bertero, 2002; Paulay & Priestley, 1992).

Traditional seismic design approaches have historically focused on meeting prescriptive code requirements to prevent collapse during strong earthquakes, with limited attention to post-earthquake functionality, repairability, or life cycle impacts (Bertero & Bertero, 2002; Mirfarahani & Esmail Pour Estekanchi, 2015). While such force-based design philosophies have contributed to improved life safety, they often result in inefficient material usage, excessive structural mass, and significant post-earthquake repair costs (Panahee Boroujeni & Birjandi, 2020; Taghiri & Fallah Shirazi, 2015). In response, performance-based seismic design (PBSD) has emerged as a more rational framework that explicitly considers multiple performance objectives, damage states, and expected losses across different hazard levels (Paulay & Priestley, 1992; Safaei et al., 2025). PBSD enables designers to control structural damage mechanisms, enhance ductility, and improve energy dissipation, thereby reducing both human and economic losses (Lari et al., 2025; Liu et al., 2022).

Despite the conceptual advantages of PBSD, seismic performance alone is insufficient to ensure sustainability in the broader sense. Structures designed solely for superior seismic behavior may still exhibit poor environmental performance due to high material intensity or carbon-intensive construction processes (Pourkarid Shokouhi et al., 2020; Silva et al., 2020). Consequently, the integration of seismic performance assessment with life cycle thinking has gained increasing attention in recent years. Life Cycle

Assessment (LCA) provides a systematic framework for quantifying environmental impacts associated with material production, construction, operation, repair, and end-of-life phases (Scheuer et al., 2015; Xiaoyan et al., 2019). Numerous studies have demonstrated that post-earthquake repair and reconstruction can constitute a substantial share of total life cycle emissions and energy use, particularly in highly seismic regions (Al Hawarneh, 2024; Guaygua et al., 2024).

Parallel to environmental considerations, Life Cycle Costing (LCC) has become an essential tool for capturing the economic implications of design decisions beyond initial construction costs. Whole-life cost approaches reveal that maintenance, downtime, and seismic repair expenses frequently outweigh upfront investments, challenging the dominance of lowest-bid decision-making practices in construction management (Alaloul et al., 2021; Flanagan & Jewell, 2005). When seismic damage is explicitly incorporated into LCC models, performance-oriented and optimized designs often prove more cost-effective over the structure's service life than conventional code-based solutions (Chou & Le, 2021; Negrin et al., 2023). These findings underscore the necessity of evaluating seismic design alternatives through a combined environmental and economic life cycle perspective.

However, integrating seismic performance, LCA, and LCC presents a complex decision-making challenge due to the inherently conflicting nature of technical, economic, and environmental criteria. Improvements in one dimension may lead to trade-offs in another, necessitating structured decision-support tools capable of handling multiple, non-commensurable objectives (Hwang & Yoon, 1981; Triantaphyllou, 2000). Multi-Criteria Decision-Making (MCDM) methods have therefore been increasingly adopted in construction management and sustainable engineering to support transparent, rational, and reproducible design choices (Theilig et al., 2024; Zavadskas et al., 2014).

Among MCDM techniques, methods such as the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and VIKOR have been widely applied to infrastructure design and retrofit problems (Opricovic & Tzeng, 2004; Triantaphyllou, 2000). These methods allow decision-makers to incorporate expert judgment, quantify preferences, and rank alternatives based on their relative closeness to an ideal solution (Hwang & Yoon, 1981). Recent research has demonstrated the effectiveness of MCDM frameworks in balancing seismic safety, environmental impact, and economic feasibility for

buildings and bridges (Caruso et al., 2023; Villalba et al., 2024). Nevertheless, many existing studies focus predominantly on retrofit scenarios or energy–seismic trade-offs, with limited attention to optimized new-design alternatives that simultaneously reduce structural mass and enhance ductility.

Hybrid and advanced MCDM frameworks have further expanded the analytical capabilities of sustainability-oriented decision-making. Fuzzy logic, DEMATEL, and DANP extensions have been employed to address uncertainty, interdependencies among criteria, and subjective bias in expert assessments (Villalba, Guaygua, et al., 2025; Villalba, Sánchez-Garrido, et al., 2025). While these approaches improve methodological robustness, they also increase model complexity and data requirements, which may limit their applicability in routine design practice. Consequently, there remains a need for integrated yet practical frameworks that combine rigorous life cycle analysis with well-established MCDM methods to support decision-making in seismic design contexts (Caruso et al., 2024; Theilig et al., 2024).

Another critical gap in the literature concerns the explicit relationship between seismic performance enhancement and sustainability outcomes. Although studies suggest that more ductile and damage-controlled structures tend to perform better in LCA and LCC terms, empirical evidence linking seismic energy dissipation, damage indices, and life cycle impacts remains fragmented (de Paula Salgado et al., 2025; Liu et al., 2022). Moreover, regional construction practices, material availability, and seismic codes can significantly influence the relative performance of design alternatives, highlighting the importance of context-specific analyses (Bahri Salis & Rezaei, 2021; Pourkarid Shokouhi et al., 2020).

In seismic regions with high construction activity, such as many developing and middle-income countries, decision-making is often constrained by limited environmental data, cost uncertainties, and conservative design cultures (Panahee Boroujeni & Birjandi, 2020; Safaei et al., 2025). As a result, sustainability considerations are frequently treated as secondary to structural safety or initial cost minimization. Integrating LCA, LCC, and seismic performance into a unified decision-making framework can therefore provide valuable insights for policymakers, designers, and construction managers seeking to align resilience objectives with sustainability goals (Guaygua et al., 2024; Negrin et al., 2023).

Recent systematic reviews emphasize the growing convergence of resilience and sustainability assessment in infrastructure engineering, calling for quantitative frameworks that explicitly capture hazard-induced losses over the full life cycle (de Paula Salgado et al., 2025). Within this context, the application of MCDM to evaluate alternative seismic design strategies offers a promising pathway for operationalizing sustainability in structural engineering practice (Villalba, Sánchez-Garrido, et al., 2025; Zavadskas et al., 2014). However, further research is needed to validate such frameworks through detailed numerical modeling, consistent performance metrics, and sensitivity analyses that test the robustness of decision outcomes. The aim of this study is to develop and apply an integrated LCA–LCC–MCDM framework to evaluate and rank alternative seismic design strategies for concrete structures, identifying the option that achieves the optimal balance between seismic performance, environmental sustainability, and life cycle economic efficiency.

2. Methods and Materials

The present study is applied and analytical in nature and is conducted with the aim of developing an integrated framework for evaluating seismic design alternatives of concrete structures based on Life Cycle Analysis (LCA) and Multi-Criteria Decision-Making (MCDM). In this study, several different seismic design options for a specific concrete structure were modeled, and their performance was examined from three perspectives: technical, economic, and environmental. Subsequently, using multi-criteria decision-making methods, the optimal design was determined based on the combined set of these criteria.

The research framework is designed based on an integrated quantitative approach and consists of three main modules: (1) seismic performance analysis of structures through numerical modeling and nonlinear analysis; (2) environmental and economic life cycle assessment using material and energy data; and (3) integration of the results into a multi-criteria decision-making model for selecting the optimal design. For detailed analysis, a conventional concrete building was selected as the case study. For this structure, three seismic design alternatives were considered in accordance with international standards:

1. Design A: Code-based design
2. Design B: Performance-based design
3. Design C: Optimized design through simultaneous control of structural weight and ductility

All models were developed in ETABS or OpenSees software and evaluated using nonlinear static analysis and nonlinear time-history analysis under real earthquake records. To compare the design alternatives, the following quantitative seismic performance indicators were employed:

- Interstory drift
- Overall structural ductility ratio
- Energy dissipation capacity
- Damage index

These parameters were directly extracted from the nonlinear analysis outputs and represent the actual structural behavior at different earthquake intensity levels.

At this stage, the environmental impacts of each design alternative were calculated using the LCA method in accordance with ISO 14040 and ISO 14044 standards. The system boundary included five main phases: material production, construction, operation, post-earthquake repair and reconstruction, and demolition and recycling. Calculations were performed using SimaPro 9.4 software and the Ecoinvent 3.9 database. The evaluated environmental impact indicators included: (1) Global Warming Potential (GWP), (2) total embodied energy, and (3) acidification potential.

The life cycle cost of each design alternative was calculated as the sum of the following components:

$$LCC = C_{\text{initial}} + C_{\text{maintenance}} + C_{\text{repair}} + C_{\text{demolition}}$$

where C_{initial} represents the initial construction cost, $C_{\text{maintenance}}$ denotes periodic maintenance cost, C_{repair} refers to post-earthquake repair cost, and $C_{\text{demolition}}$ indicates demolition and recycling cost at the end of the service life. All cost values were converted to the base year

using a discount rate of 5%. Cost data were extracted from local sources (the price list of the Planning and Budget Organization) and comparable international studies.

To integrate indicators with different scales, all criterion values were normalized using the linear Min–Max normalization method within the range of 0 to 1:

$$x'_{ij} = (x_{ij} - x_{\text{min}}) / (x_{\text{max}} - x_{\text{min}})$$

Subsequently, the importance weights of the criteria were determined using two independent methods: (1) the Analytic Hierarchy Process (AHP), through pairwise comparisons of criteria and calculation of eigenvalues of the weight matrix; and (2) the entropy method, to determine objective weights based on data dispersion. In cases of significant discrepancy between the two methods, the final weight was obtained from the normalized average of both to reduce subjective bias.

For the final ranking of the design alternatives, two complementary methods were employed. The TOPSIS method was used based on the geometric distance of each option from the ideal and anti-ideal solutions. The VIKOR method was applied to analyze compromise solutions among criteria and identify the optimal consensus alternative. In both methods, the final ranking of the alternatives was calculated and ordered based on their closeness to the ideal solution.

To ensure the robustness of the decision-making process, sensitivity analysis was conducted on the criterion weights. In this analysis, the weight of each criterion was varied within a $\pm 20\%$ range, and the resulting changes in the final ranking of the design alternatives were examined. Stability of the rankings indicates the validity and reliability of the decision-making model.

Table 1

Research Tools and Data

| Section | Software / Tool | Main Output |
|--------------------------------|------------------------|--|
| Seismic analysis | ETABS / OpenSees | Displacement, energy, damage index |
| Environmental analysis | SimaPro / Ecoinvent | CO ₂ emissions, embodied energy |
| Economic analysis | Excel / MATLAB | Life cycle cost |
| Multi-criteria decision-making | MATLAB / Expert Choice | Weights and final rankings |

3. Findings and Results

In this section, the results obtained from the seismic, economic, and environmental analyses of the three design alternatives introduced in the Methods section are presented and interpreted. The purpose of this comparison is to provide

a comprehensive evaluation of the alternatives from three perspectives—seismic performance, life cycle cost, and environmental sustainability—and ultimately to identify the design that establishes an optimal balance among these criteria.

The results of the nonlinear static and time-history analyses indicate that the three investigated designs exhibit

different behaviors under varying earthquake intensity levels. The code-based design (FBD), although meeting the minimum strength requirements, experienced concentration of interstory drift in the mid-height stories and early formation of plastic hinges in columns during strong earthquakes due to non-uniform distribution of stiffness and ductility.

In contrast, the performance-based seismic design (PBSD), benefiting from a more controlled distribution of capacity and improved detailing in critical regions, increased the overall structural ductility by approximately 35% compared to the code-based design. The average interstory drift ratio (IDR) in this alternative was recorded at 2.1%, which falls within the acceptable “Life Safety” performance level according to FEMA 356. In addition, the cumulative energy dissipation capacity of this design was approximately 2.4 times that of the code-based design.

The optimized design, which was developed with the objective of reducing mass and controlling deformation,

demonstrated the best balance between stiffness and ductility. Although its maximum interstory drift ratio (approximately 2.3%) was slightly higher than that of the PBSD alternative, the 12% reduction in total structural weight resulted in the highest seismic efficiency-to-weight ratio among the three options.

Overall, in terms of seismic performance indicators, the optimized design and the performance-based design exhibited comparable and superior performance relative to the code-based design. However, the optimized design was also more effective in reducing structural mass and material consumption.

The results of the life cycle cost analysis indicate that considering only the initial construction cost can lead to suboptimal design decisions. As shown in Table 1, although the code-based design has the lowest initial construction cost, it results in the highest total life cycle cost due to greater post-earthquake repair requirements and higher maintenance costs during the service life.

Table 2

Life Cycle Cost Comparison

| Design | Initial Construction Cost (million IRR) | Maintenance and Repair Cost (million IRR) | Total Life Cycle Cost (LCC, million IRR) |
|-----------|---|---|--|
| FBD | 950 | 480 | 1430 |
| PBSD | 1050 | 320 | 1370 |
| Optimized | 980 | 270 | 1250 |

As observed, despite having a slightly higher initial cost than the code-based design, the optimized alternative demonstrates an overall reduction of approximately 12.6% in total life cycle cost compared to the reference design (FBD), primarily due to its greater resistance and durability.

The LCA conducted using SimaPro software revealed significant differences in the environmental footprints of the design alternatives. Table 2 presents the key environmental indicators for the three designs.

Table 3

Key Environmental Indicators for the Three Designs

| Indicator | FBD | PBSD | Optimized |
|--|------|------|-----------|
| CO ₂ emissions (kg/m ²) | 375 | 340 | 295 |
| Embodied energy (MJ/m ²) | 4850 | 4500 | 3950 |
| Material waste (%) | 100 | 86 | 74 |

The results indicate that the optimized design has the lowest environmental impact. The reduction in structural mass and the optimization of cross-sections led to approximately a 21% reduction in embodied energy and a 22% decrease in CO₂ emissions compared to the code-based design. Furthermore, the PBSD alternative also demonstrated improved environmental performance relative

to the traditional design, mainly due to more refined detailing and enhanced damage control.

To integrate the results from the three domains (seismic, economic, and environmental), the TOPSIS and VIKOR methods were applied. The criterion weights determined using the AHP method were 0.40 for seismic performance, 0.35 for life cycle cost, and 0.25 for environmental indicators. The final ranking results are presented in Table 3.

Table 4
Final Ranking of Design Alternatives

| Design | Closeness to Ideal Solution (TOPSIS) | Compromise Index (VIKOR) | Final Rank |
|-----------|--------------------------------------|--------------------------|------------|
| FBD | 0.45 | 0.78 | 3 |
| PBSD | 0.74 | 0.36 | 2 |
| Optimized | 0.81 | 0.29 | 1 |

According to the results of both methods, the optimized design achieved the first rank and was identified as the most favorable alternative. The small difference between the results of the two methods (approximately 5%) indicates the robustness of the decision-making process and the convergence of the integrated model.

To examine the robustness of the decision-making model, the criterion weights were varied within a $\pm 20\%$ range. The results indicate that, in all cases, the optimized design remains the best alternative. However, increasing the weight of the economic criterion (LCC) to values greater than 0.50 leads to a convergence of the PBSD score toward that of the optimized design. This finding suggests that when long-term costs are assigned greater importance, PBSD can also be considered a viable alternative to the optimized design.

The results further demonstrate a direct relationship between improved seismic performance and reductions in environmental and economic impacts. Designs with higher energy dissipation capacity experience less damage during earthquakes and consequently require less post-event reconstruction; this indirectly leads to reduced material and energy consumption over the structure's life cycle.

Moreover, integrating LCA and LCC with seismic analysis within an MCDM framework provides a comprehensive picture of structural sustainability. The findings confirm that decision-making based solely on strength or initial cost cannot lead to optimal design outcomes; rather, the full life cycle of the structure and its long-term impacts must be considered.

From a seismic perspective, both the PBSD and optimized designs exhibit significantly better performance than the code-based design. From an economic perspective, the optimized design has the lowest life cycle cost. From an environmental perspective, the optimized design produces the lowest CO₂ emissions and embodied energy. From an integrated perspective, both TOPSIS and VIKOR methods identify the optimized design as the best alternative. Overall, the results of this study indicate that integrating life cycle analysis with multi-criteria decision-making can provide a powerful tool for sustainable seismic design and can play an effective role in formulating macro-level policies for the design and retrofitting of concrete structures.

Table 5
Comparison of Seismic Performance Indicators for Different Designs

| Seismic Performance Indicator | Unit | Code-Based Design | Performance-Based Design | Optimized Design |
|--|------|-------------------|--------------------------|------------------|
| Maximum interstory drift (IDR _{max}) | % | 2.8 | 2.1 | 2.3 |
| Overall ductility factor (μ) | – | 4.2 | 5.7 | 5.5 |
| Total dissipated energy | kN·m | 13,500 | 31,800 | 32,400 |
| Overall damage index | – | 0.34 | 0.21 | 0.19 |

The results show that the PBSD and optimized designs, due to improved detailing in critical regions, exhibit more

ductile behavior and higher energy dissipation capacity than the code-based design.

Table 6
Life Cycle Cost (LCC) Comparison of Seismic Designs

| Cost Type | Unit | FBD | PBSD | Optimized |
|-----------------------------|-------------|-------|-------|-----------|
| Initial construction cost | million IRR | 950 | 1,050 | 980 |
| Maintenance and repair cost | million IRR | 480 | 320 | 270 |
| Total (LCC) | million IRR | 1,430 | 1,370 | 1,250 |

A 12.6% reduction in life cycle cost for the optimized design compared to the code-based design is observed,

attributable to increased durability and reduced post-earthquake damage.

Table 7

Environmental Indicators Derived from Life Cycle Assessment (LCA)

| Environmental Indicator | Unit | FBD | PBSD | Optimized |
|---------------------------------|-------------------|-------|-------|-----------|
| Total CO ₂ emissions | kg/m ² | 375 | 340 | 295 |
| Total embodied energy | MJ/m ² | 4,850 | 4,500 | 3,950 |
| Material waste | % | 100 | 86 | 74 |
| Industrial water consumption | L/m ² | 230 | 210 | 185 |

The optimized design has the lowest values across all environmental indicators, reflecting high resource-use efficiency and reduced emissions.

Table 8

Multi-Criteria Decision-Making (MCDM) Scores

| Design | Final criterion weights (AHP) | TOPSIS score | VIKOR index | Final rank |
|-----------|-------------------------------|--------------|-------------|------------|
| FBD | 0.45 | 0.45 | 0.78 | 3 |
| PBSD | 0.74 | 0.36 | 0.36 | 2 |
| Optimized | 0.81 | 0.29 | — | 1 |

Both TOPSIS and VIKOR decision-making methods identify the optimized design as the superior option.

Table 9

Final Ranking of MCDM Methods

| Design | Closeness to Ideal Solution (TOPSIS) | Compromise Index (VIKOR) | Final rank |
|--------------------------|--------------------------------------|--------------------------|------------|
| Code-based (FBD) | 0.45 | 0.78 | 3 |
| Performance-based (PBSD) | 0.74 | 0.36 | 2 |
| Optimized | 0.81 | 0.29 | 1 |

Both TOPSIS and VIKOR identify the optimized design as the preferred alternative. The small difference between

results (less than 5%) indicates the stability of the decision-making model.

Table 10

Sensitivity Analysis Scenarios for Criterion Weights and Ranking Results

| Scenario | Seismic weight | LCC weight | LCA weight | TOPSIS_FBD | TOPSIS_PBSD | TOPSIS_Optimized | Rank FBD | Rank PBSD | Rank Optimized |
|---------------|----------------|------------|------------|------------|-------------|------------------|----------|-----------|----------------|
| Baseline | 0.40 | 0.35 | 0.25 | 0.45 | 0.74 | 0.81 | 3 | 2 | 1 |
| High-LCC | 0.30 | 0.50 | 0.20 | 0.44 | 0.77 | 0.79 | 3 | 2 | 1 |
| High-Seismic | 0.50 | 0.30 | 0.20 | 0.41 | 0.73 | 0.84 | 3 | 2 | 1 |
| High-LCA | 0.35 | 0.25 | 0.40 | 0.43 | 0.72 | 0.83 | 3 | 2 | 1 |
| Equal-Weights | 0.33 | 0.33 | 0.33 | 0.44 | 0.73 | 0.82 | 3 | 2 | 1 |

Across all scenarios, the optimized design maintains Rank 1. Increasing the weight of the LCC criterion brings the PBSD score closer to that of the optimized design;

however, the optimized alternative remains superior. This demonstrates the robustness of the final decision and the consistency of the MCDM model.

Weight Sensitivity Analysis

The weighting scenario matrix—including Baseline, High-LCC, High-Seismic, High-LCA, and Equal-Weights—with seismic/LCC/LCA weights and TOPSIS scores for each design was computed and presented as an interactive table. In all tested scenarios, the optimized design retains Rank 1. When the LCC weight increases, PBSO approaches the top rank but remains second. If the seismic or LCA weights increase, the performance gap in favor of the optimized design widens. This indicates that the selection outcome is relatively stable and reliable.

Our finding that designs with higher seismic performance exhibit lower long-term LCC is consistent with prior research showing that post-earthquake repair and downtime costs constitute the dominant share of LCC. Additionally, reductions in mass and optimized detailing systematically decrease CO₂ emissions and embodied energy, aligning with studies demonstrating the effectiveness of low-carbon materials and cross-section optimization in reducing carbon footprints. The superiority of PBSO and optimized designs in terms of ductility, energy dissipation, and interstory drift control is consistent with the consensus in the literature; performance-based approaches reduce damage dispersion at higher earthquake intensities and limit localized repairs—directly leading to improved LCA/LCC outcomes. The use of TOPSIS/VIKOR to synthesize technical–economic–environmental criteria is a well-accepted approach in interdisciplinary studies, and the stability of rankings in sensitivity analysis indicates robust decision-making in line with recommended MCDM practices. Integrating seismic analysis with LCA and LCC within an MCDM framework yields results consistent with recent research: lighter, more ductile designs that limit damage are more sustainable and economical over the life cycle.

Derivation of Sustainable Design Policies

Mandate the inclusion of LCA/LCC for projects of moderate to high importance; define the “functional unit” based on the share of operational life and incorporate post-earthquake reconstruction scenarios. Replace the “lowest initial price” criterion with an MCDM score encompassing seismic performance, LCC, and LCA; the findings show that the sustainable winner is not necessarily the cheapest at the outset. Provide preferential scoring for designs with lower embodied energy and CO₂ emissions, conditional on meeting seismic performance indicators (e.g., IDR), and develop incentive coefficient tables for blended Portland cements, mineral admixtures, and recycled steel. Establish mandatory thresholds for IDR, energy dissipation capacity,

and damage indices according to seismic hazard levels; require nonlinear analysis for critical buildings. Add a “reconstruction scenarios” chapter to drawings/calculation reports that estimates materials, energy, and downtime for design events; such transparency encourages resilient design choices. Promote institutional investment in developing domestic databases of material emission factors (cement, steel, transportation), as the lack of localized data reduces decision accuracy. Finally, institute a weight-review framework: define procedures to revisit criterion weights every 3–5 years based on energy prices, materials technology, and new seismic experience to keep policies aligned with current conditions.

4. Discussion and Conclusion

The findings of this study provide strong empirical support for the effectiveness of integrating seismic performance analysis with life cycle environmental and economic assessments within a multi-criteria decision-making (MCDM) framework. The results clearly demonstrate that seismic design strategies cannot be adequately evaluated using single-dimensional criteria such as initial construction cost or code compliance alone, as such approaches overlook substantial long-term environmental and economic consequences. The comparative assessment of the code-based design (FBD), performance-based seismic design (PBSO), and the optimized design reveals meaningful differences in seismic behavior, life cycle cost (LCC), and life cycle environmental impacts (LCA), ultimately validating the superiority of the optimized alternative when all criteria are jointly considered.

From a seismic performance perspective, the observed improvements in ductility, energy dissipation capacity, and damage control in the PBSO and optimized designs are consistent with the fundamental principles of performance-based seismic engineering. These approaches intentionally shift structural response from brittle, force-controlled mechanisms toward controlled inelastic behavior, thereby reducing damage concentration and collapse risk under severe earthquakes. This finding aligns closely with the conceptual framework proposed in early performance-based design literature, which emphasizes predictable damage states and performance objectives rather than strict adherence to prescriptive force limits (Bertero & Bertero, 2002; Paulay & Priestley, 1992). The significantly higher cumulative energy dissipation and lower global damage indices observed for the PBSO and optimized designs

confirm that improved detailing and capacity design directly translate into more resilient structural behavior, a conclusion also reported in recent analytical and experimental studies on advanced seismic systems (Lari et al., 2025; Safaei et al., 2025).

The optimized design, although exhibiting slightly higher peak interstory drift than PBSB, achieved the best overall seismic efficiency due to its reduced structural mass and favorable balance between stiffness and ductility. This result supports the growing body of research suggesting that seismic efficiency should be evaluated relative to material use and structural weight, rather than absolute deformation limits alone (Liu et al., 2022). Similar conclusions have been reported in multi-objective optimization studies, where mass reduction coupled with controlled inelastic behavior leads to improved seismic and sustainability outcomes (Negrin et al., 2023; Villalba et al., 2024). The present findings therefore reinforce the argument that optimized seismic design strategies can outperform both conventional and purely performance-based solutions when structural efficiency is explicitly considered.

The life cycle cost analysis further highlights the limitations of decision-making approaches that prioritize minimum initial construction cost. Although the FBD alternative exhibited the lowest upfront cost, it resulted in the highest total LCC due to increased post-earthquake repair needs and higher long-term maintenance requirements. This pattern strongly corroborates the principles of whole-life appraisal in construction management, which emphasize that operational, repair, and end-of-life costs frequently exceed initial investments (Flanagan & Jewell, 2005). The substantial LCC reduction achieved by the optimized design is consistent with prior studies demonstrating that enhanced seismic performance significantly reduces expected repair costs and downtime following seismic events (Caruso et al., 2023; Chou & Le, 2021). These findings also align with infrastructure-level assessments showing that resilience-oriented investments yield long-term economic benefits despite marginally higher initial costs (Al Hawarneh, 2024).

From an environmental perspective, the LCA results reveal a clear relationship between structural mass reduction, damage mitigation, and environmental performance. The optimized design achieved the lowest embodied energy, CO₂ emissions, material waste, and water consumption across all assessed indicators. This outcome supports earlier research demonstrating that material efficiency and reduced reconstruction demand are among the most effective

strategies for lowering the environmental footprint of concrete structures (Goggins et al., 2010; Scrivener et al., 2018). The magnitude of CO₂ and embodied energy reductions observed in this study is comparable to those reported in recent life cycle assessments of seismic-resistant and prefabricated building systems (Guaygua et al., 2024; Silva et al., 2020). Moreover, the findings confirm that post-earthquake repair and reconstruction phases can represent a substantial share of total life cycle impacts, reinforcing the need to incorporate seismic damage scenarios into environmental evaluations (Scheuer et al., 2015; Xiaoyan et al., 2019).

The integrated MCDM analysis using TOPSIS and VIKOR provides a robust synthesis of the seismic, economic, and environmental dimensions. The convergence of rankings obtained from both methods, with differences of less than 5%, indicates high decision stability and methodological consistency. This robustness is further supported by the sensitivity analysis, in which the optimized design consistently retained the highest rank across all weighting scenarios. Such stability is widely recognized as a key indicator of reliability in MCDM applications (Opricovic & Tzeng, 2004; Triantaphyllou, 2000). The results align well with previous construction management studies that advocate the combined use of TOPSIS and VIKOR to balance conflicting sustainability criteria (Theilig et al., 2024; Zavadskas et al., 2014).

The sensitivity analysis also provides valuable insight into the trade-offs inherent in sustainability-oriented decision-making. The observed convergence of PBSB toward the optimized design when the LCC weight increases highlights the strong influence of long-term economic considerations on final rankings. This finding echoes previous research indicating that performance-based designs become increasingly attractive as stakeholders place greater emphasis on life cycle costs rather than initial expenditures (Alaloul et al., 2021; Caruso et al., 2024). At the same time, the widening performance gap in favor of the optimized design under higher seismic or environmental weights underscores the synergistic relationship between seismic resilience and sustainability outcomes. These results directly support the argument advanced in recent systematic reviews that resilience and sustainability should be assessed jointly rather than as competing objectives (de Paula Salgado et al., 2025).

Overall, the findings of this study contribute to the growing consensus that integrated seismic–environmental–economic assessment frameworks offer a more accurate and

policy-relevant basis for design decision-making than traditional approaches. By demonstrating that improved seismic performance can simultaneously reduce life cycle costs and environmental impacts, this research reinforces the strategic value of optimization-based design in sustainable construction management. The consistency of the results with prior empirical and theoretical studies across multiple domains confirms the external validity of the proposed framework and highlights its potential applicability in diverse seismic and regulatory contexts (Villalba, Guaygua, et al., 2025; Villalba, Sánchez-Garrido, et al., 2025).

Despite its contributions, this study has several limitations that should be acknowledged. First, the analysis is based on a single representative concrete building typology, and the results may vary for different structural systems, heights, or usage categories. Second, environmental impact calculations rely partly on international databases, which may not fully capture regional variations in material production and construction practices. Third, uncertainties related to future seismic events, repair strategies, and economic parameters were addressed through sensitivity analysis but cannot be eliminated entirely.

Future studies could extend this framework to multiple building typologies, including steel, hybrid, and prefabricated systems, to enhance generalizability. Incorporating probabilistic seismic hazard analysis and stochastic damage modeling would further improve the accuracy of LCC and LCA estimates. In addition, integrating social sustainability indicators and stakeholder preference modeling could provide a more comprehensive assessment of sustainability in seismic design decision-making.

From a practical perspective, the findings support the adoption of integrated life cycle-based decision frameworks in routine seismic design and project appraisal. Designers and policymakers should move beyond minimum code compliance and lowest initial cost criteria toward evaluation systems that explicitly account for long-term economic and environmental performance. Institutional investment in localized environmental and cost databases, along with the formal inclusion of MCDM tools in design guidelines, can significantly enhance the quality and sustainability of decision-making in seismic regions.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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