

A REVIEW OF MULTI-CRITERIA DECISION-MAKING METHODS FOR BUILDING ASSESSMENT, SELECTION, AND RETROFIT

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Abstract. Multiple criteria decision-making (MCDM) has experienced significant growth in recent years, owing to its capacity to integrate even contradictory criteria. This study conducted a comprehensive literature review of MCDM for assessing, selecting, and retrofitting buildings. The bibliometric search used a search algorithm in specialized databases. A filtering and expansion process was done by reviewing references, and 91 relevant articles were selected. The analysis revealed that in a group of studies, socioeconomic criteria were used to assess the vulnerability of buildings. On the other hand, some research integrated the three dimensions of sustainability (economic, social, and environmental) along with safety considerations when identifying optimal retrofit alternatives. Classic MCDMs are prevalent in research within this field. Among the most used methods, the Analytic Hierarchy Process (AHP) was employed for criteria weighting, Simple Additive Weighting (SAW) for constructing vulnerability indices, and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for building retrofitting. This literature review contributes to the path toward a holistic renovation of the existing building stock, providing recommendations for future research to improve decision-making solutions for integrating the safety and sustainability of existing buildings.

Keywords: decision making, MCDM, multi-criteria, retrofit, structural assessment, sustainability, vulnerability.

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1. Introduction

The aging of the existing building stock implies that a considerable percentage has been built with obsolete building codes and seismic standards (Palermo et al., 2018). This poses a tremendous social risk; the vulnerability of existing buildings to recent earthquakes caused structural damage, significant economic losses, severe injuries, and loss of human life (Pohoryles et al., 2022). Moreover, as they approach the end of their expected service life, risks related to the durability of materials appear that may decrease the structural capacity of the elements; the economic impact of aging and deterioration processes of structures and infrastructures is exceptionally high (Biondini & Frangopol, 2016). Informal self-managed housing construction carried out by residents or builders without formal construction training and often without permits or building code enforcement accounts for a high percentage of residential construction in low- and middle-income countries (Murray et al., 2023). In extreme conditions, these buildings will be more vulnerable.

The Sustainable Development Goals (SDGs) set out in the 2030 Agenda by the United Nations establish a need for urgent change: the construction sector is responsible for the most significant environmental impacts in terms of energy consumption, waste production, and depletion of raw materials. Sustainable designs and solutions seek to maximize benefits, reducing the negative impacts over time of the three pillars of sustainability: economy, society, and environment (Navarro et al., 2020b). Addressing structural deficiencies in the existing building stock, given the magnitude of the problem, through reconstruction is not a viable option; preference should be given to extending service life through maintenance, repair, and renovation work (Pohoryles et al., 2022). The vulnerability of buildings under extreme conditions is a complex nexus between social, economic, geological, systematic, and physical dimensions (Alam & Haque, 2022). The transition to a more sustainable society envisioned by current policies requires a comprehensive renovation of existing buildings

from various perspectives, such as structural safety, energy efficiency, comfort, and architecture (Passoni et al., 2022).

In the field of structural safety and sustainability of existing buildings, authors Menna et al. (2022) analyze the state of the art of sustainable retrofitting, finding a group of research that achieves a combined evaluation of energy consumption and seismic vulnerability, concluding the need for multi-objective evaluations to demonstrate sustainability in both the short and long term. On the other hand, Pohoryles et al. (2022) conducted a state-of-the-art review of integrated seismic and energy retrofitting and concluded that addressing seismic and energy performance through separate interventions is the standard approach currently adopted. An integrated approach to building retrofit is an emerging topic in the scientific literature. The arguments are sufficient to seek methodologies for assessing, selecting, and retrofitting vulnerable buildings that minimize economic, social, and environmental impacts, complying with structural safety standards.

In civil engineering, decision-making may need to consider multiple dimensions and evaluation criteria, some of which may be contradictory. In addition to an exhaustive evaluation of each dimension, decision-making is required from a holistic perspective. Multi-criteria decision-making (MCDM) methods offer a valuable approach in this regard. MCDMs have evolved as a comprehensive operations research method, integrating computational and mathematical tools to identify suitable solutions (Zavadskas et al., 2016). They facilitate the effective and efficient selection of the best alternatives, ranked according to preferences (Nadkarni & Puthuvayi, 2020), and help in decision-making between competitive alternatives, considering the multi-dimensional nature of real-world scenarios (Sierra et al., 2018). MCDMs enable the identification of compromise solutions in civil engineering, construction, building technology, and sustainability engineering (Zavadskas et al., 2021). Given the inherent complexity that characterizes the inclusion and integration of the often-contradictory criteria that define safety and sustainability, MCDMs have become a relevant tool that has gained importance in recent years. They allow the conflicting dimensions of sustainability to be evaluated in a multi-stakeholder and long-term context (Navarro et al., 2019).

Notable studies have explored the applications of MCDM in various civil engineering contexts in recent years. Zavadskas et al. (2018), Wen et al. (2021) and Zhu et al. (2021) studied decision-making applications in civil engineering and construction; Navarro et al. (2020b) in bridges; Sierra et al. (2018), Navarro et al. (2019) and Selvan et al. (2023) in sustainable construction, and Nadkarni and Puthuvayi (2020) and Marcher et al. (2020) in buildings. These studies demonstrate that MCDM applications have great potential for decision-making in civil engineering, construction, building technology, and sustainability. However, current trends in MCDM applications in assessing, selecting, and retrofitting vulnerable buildings require a detailed review.

The structural safety and sustainability of existing buildings is a field of knowledge that continues to evolve. However, the safety, economic, social, and environmental parameters used and the degree to which the scientific community has managed to integrate them have not yet been explored. This article provides an updated, detailed review of the use of MCDM for building assessment, selection, and retrofitting to address the previously identified knowledge gap. The main research question of this study is to assess the current trend in the use of MCDMs in integrating the three dimensions of sustainability with structural safety. Two secondary questions have also been posed: to analyze the most used MCDM methods and the relevant criteria considered. This work aims to assess current trends and look for research gaps and possible future directions in assessing, selecting, and retrofitting sustainable and safe buildings.

2. Materials and methods

This study used a combined review method that consisted of three stages: bibliometric search, quantitative analysis, and qualitative analysis. This methodology was chosen to effectively capture current trends within the scope of the study, identify research gaps, and outline future research directions. The bibliometric search involves a detailed search algorithm supplemented by a manual review of references and article citations. This process allowed obtaining relevant manuscripts in the study area. The global analysis of the results served as a quantitative criterion, while the qualitative criterion focused on addressing the research questions by examining socioeconomic and environmental considerations, analyzing the MCDM used, and evaluating the integration of structural safety with the three sustainability pillars, as illustrated in Figure 1.

The bibliometric search of this study consisted of three stages: search, filtering, and selection, as shown in Figure 1. The specialized databases Web of Science and SCOPUS were used in the first stage. A search algorithm was used with three differentiated terms connected by Boolean operators: research objective, methodology, and type of structure. For the term research objective, keywords defining assessment and retrofitting were used: *"retrofit"*, *"retrofitting"*, *"reconditioning"*, *"vulnerability assessment"*, *"seismic vulnerability"*, *"seismic evaluation"*, and *"seismic assessment"*. On the other hand, terms related to multi-criteria decision-making were used for the methodology, including specific MCDM methods: *"Multicriteria decision making"*, *"multi-criteria decision-making"*, *"multi-attribute decision making"*, *"MCDM"*, *"MADM"*, *"AHP"*, *"ANP"*, *"MACBETH"*, *"TOPSIS"*, *"VIKOR"*, *"Simple Additive Weighting"*, *"COPRAS"*, *"PROMETHEE"*, *"ELECTRE"*, *"MAUT"*, *"MAVT"*, *"MIVES"*, *"DEMATEL"*, *"CRITIC"*, *"WASPAS"*, *"ARAS"*, *"CBA"*, and *"SWARA"*. The structure type was limited to *"building"* in the search algorithm's third term.

In the filtering stage, the search was limited to articles published since 2008 and written in English. In the last

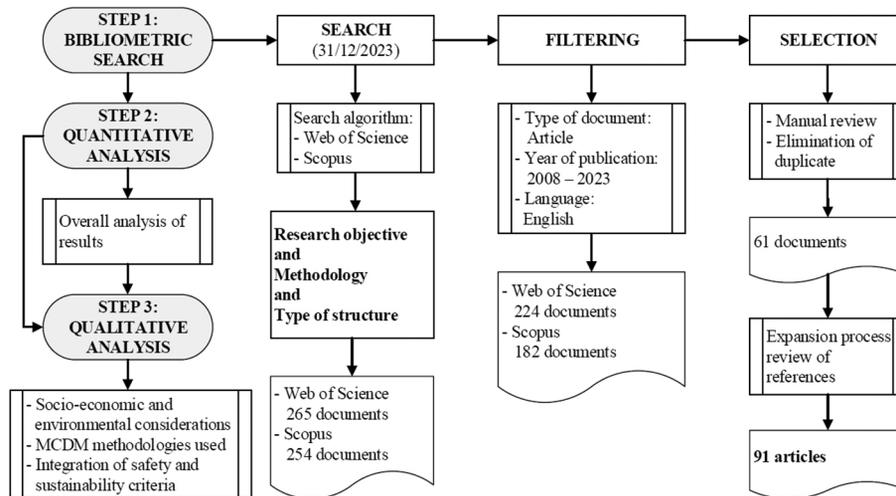


Figure 1. Research steps of the literature review

stage, the titles and abstract were reviewed, and the articles directly related to the scope of this research were selected. Finally, the references and citations of the most relevant articles were manually reviewed to address any possible limitations of the search algorithms in an expansion process, using the filtering criteria from the second stage, resulting in a final selection of 91 articles.

3. Results

3.1. Overall analysis of results

The influence of journals and the co-occurrence of research author keywords were analyzed to highlight the areas explored in the articles based on text mining. Table 1 shows an analysis of the top 10 journals relevant to research. This analysis includes information on the number of articles published, total link strength, and citations. It is important to note that the importance of a journal cannot be determined solely by its volume of publications. The average normalized citation highlights journals with the highest average influence per year, indicating their continued impact and relevance to the research field being ex-

amined. According to the analysis, *Engineering Structures*, *Structures*, *Buildings*, and *Applied Sciences* are the highest-ranked journals concerning average normalized citations.

Table 2 provides information from the co-occurrence analysis of the keywords used in the articles. Link strength represents the connections between a specific keyword and the other keywords in the data set. Analyzing the groups formed makes it possible to determine the various areas the scientific community explores. In Group C1, the keywords “uncertainty”, “cultural heritage” and “reinforced concrete” stand out. Group C2 includes “risk”, and “seismic risk”, while group C3 “AHP” and “index”. Lastly, Cluster C4 comprises “GIS” and “earthquake”. The co-occurrence analysis generally determined the areas investigated by the scientific community: the safety of buildings, the importance of built cultural heritage, the management of uncertainty for decision-makers, and the utilization of suitable MCDM methods to assess, select, and retrofit buildings.

In the exhaustive review of the selected papers, some researchers focused on selecting vulnerable structures and retrofit strategies for school buildings (18 papers) and historic and heritage buildings (11 papers). Fiore et al. (2020a)

Table 1. Analysis of relevant sources

Journal	Total Link	Documents	Citations	Avg. Citations	Norm. Citations	Avg. Norm. Citations
<i>Natural Hazards and Earth System Sciences</i>	27	5	231	46.20	14.44	0.06
<i>Sustainability</i>	26	9	106	11.78	13.25	0.13
<i>International Journal of Disaster Risk Reduction</i>	25	6	253	42.17	36.14	0.14
<i>Natural Hazards</i>	10	2	119	59.50	9.15	0.08
<i>Applied Sciences</i>	9	4	64	16.00	10.67	0.17
<i>Journal of Building Engineering</i>	9	2	46	23.00	6.57	0.14
<i>Structure and Infrastructure Engineering</i>	9	3	80	26.67	11.43	0.14
<i>Buildings</i>	8	4	17	4.25	3.4	0.20
<i>Engineering Structures</i>	8	3	53	17.67	10.6	0.20
<i>Structures</i>	7	2	19	9.50	3.8	0.20

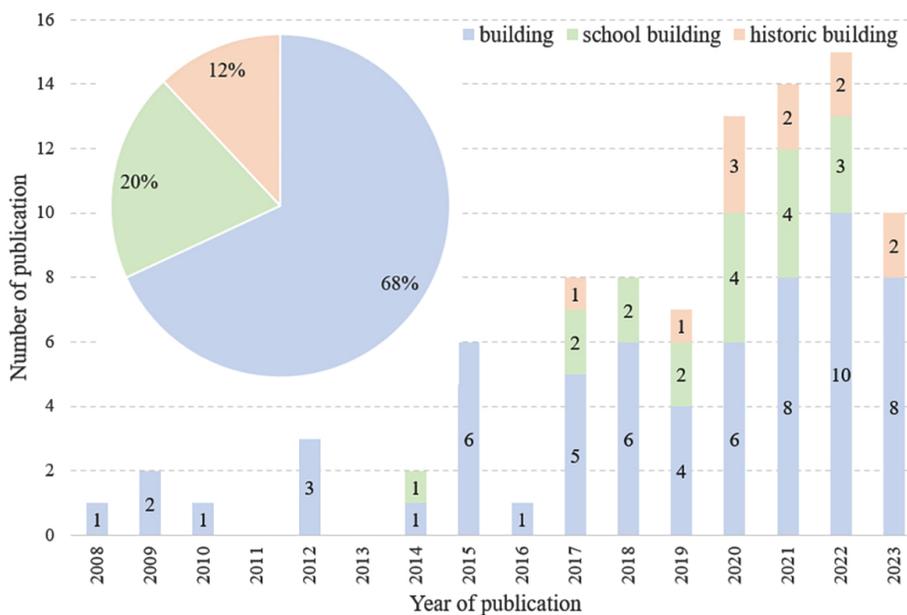
Table 2. Summary of the most studied keywords

Cluster	Keyword	Occurrences	Link strength	Cluster	Keyword	Occurrences	Link strength
C1	multi-criteria decision-making	9	11	C2	seismic risk	4	6
	seismic retrofit	9	10		multi-criteria decision-analysis	3	3
	vulnerability	6	10	C3	AHP	15	17
	reinforced concrete	3	5		risk assessment	5	7
	uncertainty	4	3		seismic vulnerability	4	7
	cultural heritage	3	3		buildings	3	4
	seismic vulnerability assessment	3	3		index	3	3
C2	retrofit	8	15	C4	GIS	14	24
	decision-making	5	8		earthquake	8	15
	risk	3	7		vulnerability assessment	5	7

point out that more than 60% of school buildings in Italy built in the late 1960s and 1970s need to meet modern technical standards for seismic prevention; these structures present a significant lack of energy efficiency and interior comfort. On the other hand, D'Alpaos and Valluzzi (2020) stress the importance of safeguarding heritage buildings; restoration and conservation decisions must consider the tangible and intangible values of both the building and the art assets. Figure 2 shows the number of annual publications by type of structure analyzed. Although Caterino et al. (2008) were among the first researchers to adopt MCDM methods in this field, research started to have a more prominent representation from 2017 onwards. Notably, 82% of the analyzed papers were published since 2017, indicating a renewed scientific interest in this field. The investigations are carried out mainly with the application of case studies, using information on the vulnerability of buildings in specific areas, with 58 articles on assessing and selecting buildings and 21 investigations on the retrofit of structures.

Figure 3 shows the countries with publications higher than three, highlighting the leading position of Italy, with 29 papers. More than 30% of reinforced concrete structures need to be improved to withstand seismic loads according to current regulations (Formisano et al., 2017). On the other hand, the "Stability Law of 2017" (Caterino & Cosenza, 2018a) introduced tax incentives for owners who invest in structural safety improvements, including earthquake resistance, allowing them to recover up to 85% of the total rehabilitation costs. This policy has resulted in a significant increase in relevant scientific publications from Italy. Another country of note is Iran, with 17 articles. According to Nazmfar (2019), factors responsible for increased earthquake losses in this country include increased population density, lack of alarm systems, inadequate monitoring of building standards, unplanned urbanization, and construction near incompatible users.

The regional vulnerability assessment framework is essential for governments and decision-makers to allocate resources optimally (Alam et al., 2012). Vulnerability as-

**Figure 2.** Distribution of contributions per year and structure type

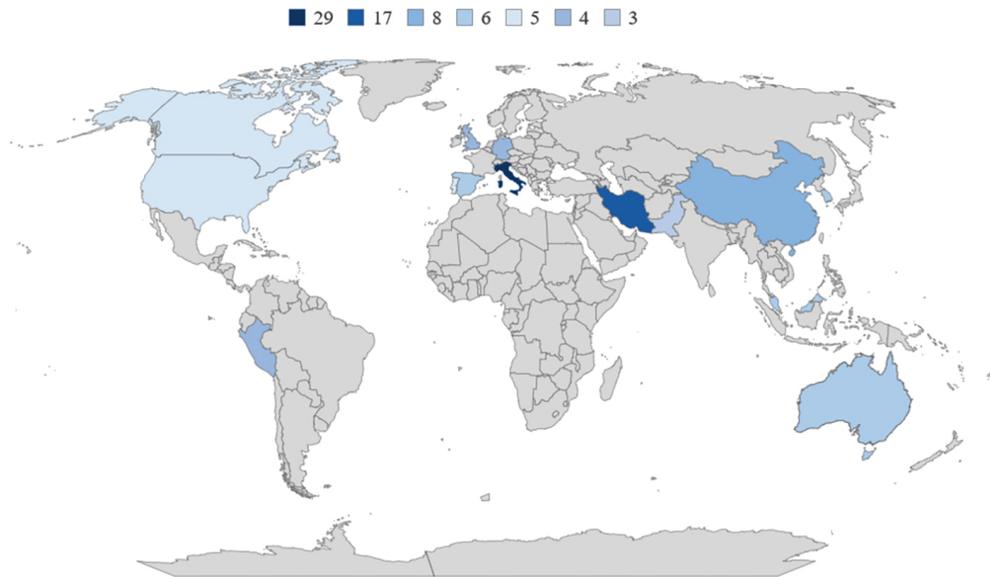


Figure 3. Distribution of contributions by country

assessments facilitate policymakers, planners, and administrators to adopt policies and actions to reduce the impact of risks and natural disasters (Jamal-ud-din et al., 2023). MCDM methods provide rapid identification of vulnerable structures requiring further analysis and prioritization of buildings to be retrofitted since upgrading all vulnerable buildings is not economically feasible (Shahriar et al., 2012). A group of researchers focuses on determining high vulnerability in urban areas (41 papers). Geographic Information Systems (GIS) facilitates vulnerability studies and natural hazards analysis as a valuable tool for managing, controlling, processing, and analyzing spatial data (Rezaie & Panahi, 2015). The combination of GIS and MCDM was used in 35 articles.

Although a large number of articles study the seismic vulnerability of buildings, a group of researchers evaluates other risks such as tsunami (Dall’Osso et al., 2009; Papatoma-Koehle et al., 2019), floods (Abdrabo et al., 2023; Gacu et al., 2023; Gandini et al., 2020; Usman Kaoje et al., 2021; Mourato et al., 2023; Zhen et al., 2022), and multi-risk: seismic impacts, floods and extreme sea waves (Mladineo et al., 2022). In addition to building assessment, Panahi et al. (2014), Gentile et al. (2019), Alam and Haque (2020), Vona et al. (2017), Anelli et al. (2019), Sangiorgio et al. (2018a, 2018b, 2020b) propose strategies to prioritize retrofit vulnerable school buildings, while Pinero et al. (2017), Uva et al. (2019), D’Alpaos and Valluzzi (2020), Sangiorgio et al. (2020a, 2021), Makoond et al. (2021), and Lallam et al. (2023) prioritize intervention in historic and heritage buildings. On the other hand, J. Choi and J. Choi (2022) propose a technical feasibility study model for renovating aging apartments.

In building retrofitting, three main strategies are identified: retrofitting individual components, adding lateral load-resisting elements, and reducing structural demands through supplementary devices (Clemett et al., 2022). The retrofit techniques applied to a building can vary depending on the type of material, structural stresses, and func-

tionality. The reviewed papers included the incorporation of fibers, concrete, and steel jacketing, the addition of walls, the installation of bracing, the application of base insulation, and the use of dissipators as the most commonly used methods. Among the papers reviewed, 18 researchers focused on selecting the most appropriate retrofit strategy for buildings, ten on school buildings, three on historic buildings, and one on the retrofit of historic adobe constructions.

3.2. Socio-economic and environmental considerations

Table 3 contains the most used indicators in evaluating and selecting vulnerable buildings. The height and age of buildings, materials, and construction quality are the indicators most used by researchers to evaluate safety. When prioritizing vulnerable buildings, researchers recognize the need to include social and economic criteria. The social and economic situation of society can affect the vulnerability of buildings (Aliabadi et al., 2015). There has yet to be a consensus among articles about defining the social and economic criteria. The spatial distribution of buildings, which determines the physical distance from roads and the ease of access to emergency services such as hospitals and fire departments, is often called systematic vulnerability and is a crucial consideration for many researchers (Alam & Haque, 2022). At the same time, population density is another important parameter that is considered when assessing the vulnerability of buildings in an emergency. In addition, social factors such as the vulnerability of specific populations based on their age and gender are relevant (Bahadori et al., 2017). Although uneducated populations do not necessarily increase vulnerability, a higher level of education can help increase awareness of hazards and improve emergency response. Therefore, it is considered one of the social factors used (Alizadeh et al., 2018a). The socioeconomic status of a community also has a signifi-

cant impact on vulnerability. Researchers have examined empirical economic losses based on the estimated value of socioeconomic considerations of each building (Banica et al., 2017) and economic strength (Chu et al., 2021), also considering the employment situation of the population. Other social indicators taken into account by researchers include the identification of heritage or community buildings (Hoang et al., 2021), the evaluation of school buildings based on criteria such as historical and cultural importance, socioeconomic status, and community organization (Anelli et al., 2019), the valuation of artistic assets of historic churches (Sangiorgio et al., 2021), and the capacity to respond through the possibility of using physical, financial and human resources to control and reduce impacts (Mili et al., 2018).

Table 4 contains the indicators most used by researchers in building retrofit. The literature considers cost minimization as a fundamental parameter when selecting retrofit strategies. Costs can be classified into tangible and intangible costs. Tangible costs cover the direct costs of the repair; construction and installation phase costs are the most commonly used by the reviewed publications and include the costs of materials, labor, and equipment. Maintenance costs are also included to ensure the repair's functionality throughout the building's life. As a tangible cost, tax incentives from the Italian government are taken into account in the research (Andreolli et al., 2022; Caterino & Cosenza, 2018b; Caterino et al., 2021; Santarsiero et al., 2021). These tax incentives are granted if the remodeled structure improves at least one seismic class concerning the original building, which allows the exact amount of the tax deduction to be calculated; the owner is entitled to up to 85% of the total repair costs. On the other hand, the most used intangible costs are those related to the duration of the works, which are associated with the losses incurred as a consequence of the temporary interruption of the economic activities of a building.

Functionality and architectural compatibility are crucial factors when determining the most appropriate retrofit strategy; the aim is to minimize the impact on the everyday activities of the building users while preserving the original aesthetics of the structure; this consideration is widely shared among researchers. The reversibility criterion, that is, allowing the easy elimination of any reinforcement in the case of future interventions, is considered by Juliá et al. (2024), Fiore et al. (2020b), Formisano and Mazzolani (2015), Formisano et al. (2017), Macieira et al. (2022), while Tartaglia et al. (2022) consider the ease of implementation. As an anti-corruption measure, Anelli et al. (2020), Santa-Cruz et al. (2021), and Vázquez-Rowe et al. (2021) use criteria such as modularity, standardization, and industrialization in the search for a strategy to retrofit school buildings on a large scale.

In the detailed review of the articles, 17 investigations considered environmental criteria to determine the best retrofit strategy. Of these, six investigations were related to building retrofits, eight focused on school buildings, and three on historic buildings. The authors Anwar et al.

Table 3. Indicators in the assessment and selection of vulnerable buildings

Criteria category	Indicator	Assessment	Documents
Safety	Peak ground acceleration value (PGA)	Quantitative	14
	Distance to faults	Quantitative	17
	Slope	Quantitative	17
	Age of buildings	Qualitative	31
	Type of buildings	Qualitative	17
	Building materials	Qualitative	36
	Building height	Quantitative	35
	Quality of construction	Qualitative	29
Socio-economic	Density of buildings	Quantitative	23
	Population density	Quantitative	24
	Age and gender	Quantitative	14
	Level of education	Qualitative	12
	Physical distance to emergency facilities	Quantitative	24
	Labor situation	Quantitative	10
Economic considerations	Quantitative	11	

Table 4. Indicators in building retrofit

Criteria category	Indicator	Assessment	Documents
Safety/Technical	Structural performance	Quantitative	27
	Intervention in foundations	Quantitative	12
	Ease of installation/reversibility	Qualitative	13
Economic	Construction costs	Quantitative	30
	Maintenance costs	Quantitative	18
Social	Architectural impact/functional compatibility	Qualitative	22
	Duration of works/disruption of use	Quantitative	27
	Skilled labor	Qualitative	10
Environment	Carbon emissions	Quantitative	8
	Energy performance	Quantitative	6
	Other environmental parameters	Quantitative	11

(2020, 2023), Macieira et al. (2022), and Zuluaga et al. (2022) included embodied energy and carbon emissions, while Fiore et al. (2020a) focused on energy performance and environmental impact through the amount of waste production and recycling. Briz et al. (2023) included the indicators of recyclable, reusable, and CO₂ emissions. The impact on human health, global warming potential, energy consumption, and air quality were considered by Santa-Cruz et al. (2021). On the other hand, Fiore et al. (2020b), Gallo et al. (2022), and Clemett et al. (2023) combined traditional retrofit alternatives with energy retrofit strategies to achieve seismic and energy efficiency. The life

cycle analysis (LCA) was used by authors Formisano and Mazzolani (2015), Terracciano et al. (2015), Formisano et al. (2017), Carofilis et al. (2021), Vázquez-Rowe et al. (2021), Clemett et al. (2022), and Caruso et al. (2023) consider the environmental impact associated with the different phases of a building's life. Researchers have increasingly strived to include environmental parameters in retrofit strategies in recent years in line with the Sustainable Development Goals (SDG) publication in 2015 to reduce CO₂ emissions.

3.3. MCDM methods used

In decision-making, MCDM can be classified according to their characteristics, namely direct scoring methods, distance-based methods, those based on pairwise comparisons, outranking methods, and utility/value methods (Hajkowicz & Collins, 2007; de Brito & Evers, 2016). In scoring methods, we have Simple Additive Weighting (SAW) and Complex Proportional Assessment (COPRAS), an evolution of SAW. Among the most widely used distance-based methods are the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS), which selects the best alternative by considering the distance to the ideal solution and the non-ideal solution simultaneously, and Multi-criteria Optimization and Compromise Solution (VIKOR) is based on the distance to the ideal solution. Pairwise comparison methods are used to determine the weight of different criteria based on decision-makers' knowledge; the Analytic Hierarchy Process (AHP) is the first method presented and one of the most widely used in decision-making problems. Other methods are the Analytic Network Process (ANP), which considers the interdependence and feedback relationships between criteria and alternatives, the main problem of the AHP, and the Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH), an alternative to the AHP. Outranking methods, such as the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) or the Elimination and Choice Expressing Reality Method (ELECTRE), base the decision on establishing a degree of dominance between alternatives. Utility/value

methods consider the best alternative as a function of the degree of satisfaction they provide, among them the Multiple Attribute Utility Theory (MAUT), Multi-Attribute Value Theory (MAVT), or MIVES, which is a derivative of the previous ones in which the equations defining the different satisfaction functions are provided.

Figure 4a shows the MCDMs used in the final classification, where the distance-based and pairwise comparison methods are the most used in building assessment and retrofit. Researchers use the MCDMs in their original form, as improved versions (5 papers) or combined with other MCDMs (55 papers). Figure 4b shows the specific MCDMs considered in publications. AHP is used in 35% of the articles, combined with TOPSIS in 31% and SAW in 11%. ANP is used by Alizadeh et al. (2018b), Nazmfar (2019), Nazmfar et al. (2019), and Maqsoom et al. (2024). MACBETH by Juliá et al. (2024), PROMETHEE is used by Mladineo et al. (2022), VIKOR by Jena et al. (2020), and MIVES by Gandini et al. (2020), Pinero et al. (2017), and Briz et al. (2023). Other methods include the ordered weighted average (OWA) (Tsfamariam et al., 2010; Moradi et al., 2015; Ghajari et al., 2017; Nuno Martins et al., 2012); the Spatial Multi-Criteria Analysis and Ranking Tool (SMART) (Sinha et al., 2016), choosing by advantages (CBA) method (Vázquez-Rowe et al., 2021), Simultaneous Evaluation of Criteria and Alternatives (SECA) (Es-haghi et al., 2022) and step-wise weight assessment ratio analysis (SWARA) (Lee et al., 2019).

AHP is one of the most well-known multi-criteria decision-making methods due to its simplicity, accuracy, popularity, and theoretical robustness. This method is used in its original form, with adaptations, or in combination with other methods. An optimized O-AHP to overcome the reliability problems of AHP results due to inconsistency in the judgment matrix, especially in the case of large systems, is used by Sangiorgio et al. (2018a). The G1 method is a subjective assignment improved on AHP used by Zhu et al. (2023). The rough analytical hierarchy process (Rough AHP) proposed by Guo and Kapucu (2020) results from combining a Rough Set (RS) with a conventional AHP.

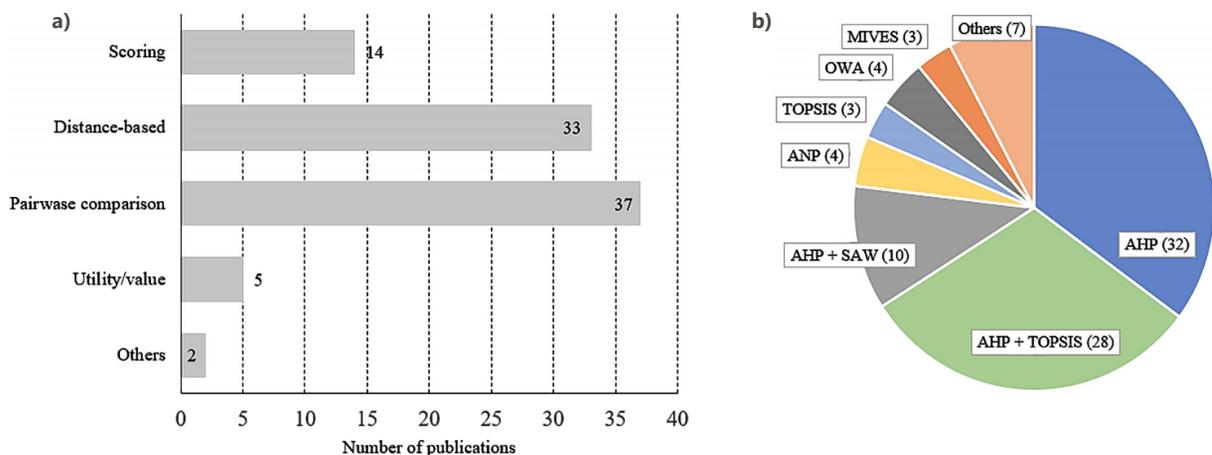


Figure 4. MCDM methods used in assessing and retrofitting buildings: a – By category; b – Specific MCDM

Several authors have identified the TOPSIS method as the most suitable approach, given the clarity of its results and the ability of the method to adapt judgment (Requena-Garcia-Cruz et al., 2022). Researchers have compared various options to find the most appropriate MCDM method that will allow them to obtain the best results. For example, Vona et al. (2017) compared TOPSIS and VIKOR and concluded that TOPSIS is more suitable for large-scale problems with numerous alternatives, while VIKOR may be more useful when the number of alternatives is limited. The article by Hoang et al. (2021) compared TOPSIS and VIKOR for retrofit priority ranking and obtained similar results. In another study, multiple methods were used: weighted sum, weighted product, MAUT, ELECTRE, and PROMETHEE, VIKOR, and TOPSIS, concluding that TOPSIS and VIKOR are the most appropriate for building retrofit selection problems due to their ability to cope with different judgment criteria, clarity of results and ease of handling parameters and options (Caterino et al., 2009). TOPSIS and CBA methods delivered similar results (Santa-Cruz et al., 2021). On the other hand, Anwar et al. (2020) modified TOPSIS to add a risk attitude.

Artificial neural networks (ANN) models combined with MCDM were used in earthquake vulnerability assessment. For example, ANN was used with ANP (Alizadeh et al., 2018b; Maqsoom et al., 2024), with AHP (Yariyan et al., 2020), and with AHP – TOPSIS (Jena & Pradhan, 2020).

There is great concern about subjectivity in some steps of MCDM methods and how it can affect final decision-making. Real-world problems are often not precisely defined, and most engineering decisions are made under conditions of uncertainty. The most subjective step in decision-making is usually the weighing of criteria; conventional logic (crisp numbers) presumes every assignment to be certain and precise (Navarro et al., 2020b). Data sets from real-world problems can have confusing uncertainties, such as ambiguity, vagueness, and imprecision, making it difficult for decision-makers to express their thoughts using exact numbers (Fallahpour et al., 2020). In recent years, alternative mathematical logic has been used to handle linguistic variables and address problems of uncertainty. Fourteen articles that consider decision-making under uncertainty were identified in the publications reviewed in this study.

Several studies have combined pairwise comparison MCDM methods with fuzzy methodologies to improve the accuracy of decision-making processes: the hierarchical analytic fuzzy method using fuzzy triangular numbers (Hamdia et al., 2018; Lallam et al., 2023; Pashaei & Moghadam, 2018; Vahdat et al., 2014; Yariyan et al., 2020), analytical hierarchy process including fuzzy normalization (Narjabadifam et al., 2021) and ANP for criteria weighting and weighted fuzzy overlay in building vulnerability assessment (Nazmfar, 2019; Nazmfar et al., 2019). Other researchers have explored combining different MCDM methods in decision-making under uncertainty: hierarchical fuzzy TOPSIS (Sadrykia et al., 2017; Shahriar et al.,

2012; Ranjbar & Nekooie, 2018) and the fuzzy hierarchical analytical method with OWA (Ghajari et al., 2017). In Maqsoom's et al. (2021) study, several hybrid models were compared to determine their effectiveness. Weights were generated by averaging the ANP and AHP models; LR and OWA logistic regression were used to run the hybrid A-OWA, A-fuzzy, OWA-LR, and fuzzy-LR models. The most accurate model results were obtained with A-OWA and OWA-LR. The paper by Tesfamariam et al. (2010) considers several cases using Bayesian probability theory, fuzzy sets, and Dempster-Shafer DS (random sets) theory, using OWA in rehabilitation selection for a reinforced concrete building. The proposed MCDM framework is versatile as it allows decision-making under different uncertainties.

When assessing the reliability of the results, sensitivity analyses can identify whether there are factors that can significantly alter the decision-making conclusions. The choice of criteria weights is the most significant source of uncertainty in the application of MCDMs and can significantly affect decision-making results (Caruso et al., 2023). Therefore, 29 articles included sensitivity analyses through the variation of criteria weights. Among the procedures most used in the articles are considering established ranges of variation, assuming one or more of the criteria as dominant, creating new scenarios by eliminating criteria, or calculating all possible combinations to determine the most sensitive criteria. On the other hand, 14 investigations consider uncertainties in expert judgments through fuzzy MCDM methods, of which 12 investigations correspond to the evaluation and selection of vulnerable buildings. Another group of authors, as sensitivity checks, consider the verification of the stability of the solution obtained by comparing the results with the application of other MCDMs (13 works). It should be noted that six studies compare the results of TOPSIS with other classical methods.

3.4. Integration of safety and sustainability criteria

Ensuring the safety of buildings is a significant concern in the construction industry, making it imperative to base vulnerability assessments and the selection of retrofit strategies on rigorous criteria. The articles reviewed demonstrate the keen interest of researchers in using state-of-the-art tools and methodologies to achieve this goal. Although safety remains paramount, assessing building vulnerability also considers economic and social considerations, as highlighted by several authors. In addition, selecting the best retrofit alternative for buildings requires the simultaneous combination of four dimensions, including safety, economic, social, and environmental criteria, thus allowing the integration of safety and sustainability. Figure 5 provides an overview of the number of publications grouped according to criteria or dimensions, the type of building analyzed, and whether they focus on vulnerability assessment or building retrofitting. Including social criteria in prioritizing vulnerable structures is particularly

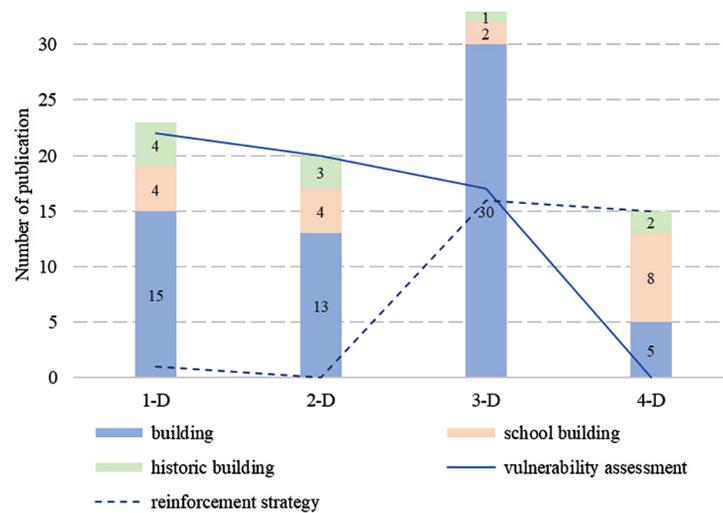


Figure 5. Dimensions considered in the evaluation and reinforcement of buildings

significant; thus, 20 articles include social criteria, highlighting their importance. In addition, 17 articles simultaneously consider economic and social criteria, making it possible to incorporate three dimensions in identifying vulnerable buildings.

In retrofit buildings, 14 papers, in addition to safety parameters, use economic and social criteria, while two papers consider economic and environmental criteria. However, in 15 papers, the researchers simultaneously integrated the four dimensions, namely safety, economic, social, and environmental, thanks to multi-criteria decision-making (MCDM) techniques. In the case of school buildings, eight papers considered all four dimensions when selecting retrofit strategies; this reflects the interest of researchers in this field and highlights the importance of ensuring the safety of these structures with sustainability criteria.

4. Discussion of the results

This literature review highlights the importance of MCDMs in integrating sustainability and safety pillars when assessing, selecting, and retrofitting buildings. The vulnerability of a building to natural hazards, in addition to safety parameters, requires consideration of economic and social aspects, which have been extensively addressed in several articles. On the other hand, when choosing the most effective retrofit option, the current trend calls for a four-dimensional approach encompassing safety, economy, society, and environment. As these criteria are different and often conflicting, multi-criteria decision-making methods can effectively resolve these conflicts. This section examines the trends identified in the research in this field through a critical analysis of the results obtained in the quantitative and qualitative analyses. In addition, possible future research directions in evaluating, selecting, and retrofitting buildings with MCDM are suggested, which build on the gaps identified in this study.

4.1. Trend analysis

Quantitative analysis reveals the specific areas that the scientific community has explored. It highlights the efforts to incorporate parameters that determine social vulnerability and the need to consider uncertainty in decision-making processes. Although the main focus of the research is on residential buildings, significant attention has also been devoted to studying school buildings, given their fundamental role as public infrastructure and historical heritage buildings. Scientific production has grown significantly in the last seven years, particularly in countries like Italy and Iran; this demonstrates the scientific community's growing interest in integrating security with economic, social, and environmental parameters.

According to Figure 6, this literature review shows that 34% of the results are equitable, 2% are viable, and 17% meet the criteria for integrating safety and sustainability. Despite the efforts in research to include economic, social, and environmental criteria, it is necessary to establish a consensus on the specific criteria and sub-criteria that should be used for decision-making. Life cycle assessment (LCA) is a powerful and versatile tool that can be used to consider all environmental impacts caused by construction processes during the entire life cycle of the structure (Pons et al., 2018). This literature review highlights that only seven articles on selecting the best retrofit alternative include LCA studies.

The use of AHP dominates research, reaching 71% of the papers, individually or in hybridization with other MCDMs. AHP can handle both qualitative and quantitative criteria and, more importantly, measure the consistency of results (Pour, 2015), so researchers widely recognize and use it. The scientific community widely accepts the joint application of TOPSIS and AHP in this field. It produces a comprehensive ranking of all alternatives for each criterion while requiring the minimum number of parameters to be set by the DM (Gentile & Galasso, 2021). The integrated

use of AHP and TOPSIS increases the consistency of the results to reach a consensus in decision-making in vulnerability analysis (Fayaz et al., 2023), giving the best results for seismic vulnerability assessment (Harirchian et al., 2020). This is corroborated in other areas of civil engineering, such as sustainability in civil engineering, construction, and building technology (Zavadskas et al., 2018) in the application of fuzzy criteria in civil engineering (Wen et al., 2021) as well as in the study of MCDMs in construction (Zhu et al., 2021).

Another method used in combination with relevant AHP is SAW. This scoring method is used for its simplicity and ease of interpretation of the results. However, it should be noted that this technique has limitations when it comes to complex problems involving conflicting criteria, such as the integration of safety and sustainability. In these cases, an adequate normalization of the criteria is required to overcome this limitation (Navarro et al., 2020b). Other relevant methods explored in the literature include ANP and OWA. MIVES stands out for decision support using different satisfaction or value functions (Sánchez-Garrido & Yepes, 2020).

The correspondence analysis in Figure 7 demonstrates how the MCDM categories used in the articles relate to the objectives of the studies. This analysis provides a two-dimensional map that reveals the inertia and association relationships of the variables. IBM SPSS Statistics 25.0 software was used to analyze the results and show how the MCDM categories interact with the study's objectives. The closer the points of the MCDM category and the target, the higher the correlation. There is a clear correlation between scoring methods and building assessment. Researchers use methods such as SAW to determine vulnerability indices that combine physical, economic, and social criteria. Developing indices that integrate several dimensions allows policymakers to target resources, design appropriate prediction and mitigation strategies, and improve the resilience of cities (Alam & Haque, 2022).

On the other hand, distance-based methods are statistically related to building retrofitting and, to a lesser extent, school building retrofitting. Numerous studies have considered TOPSIS an appropriate method for selecting retrofit alternatives (Caterino et al., 2009; Hoang et al., 2021; Vona et al., 2017). Methods such as OWA, MIVES, PROMETHEE, MACBETH, and others do not have a solid statistical interaction with the analyzed variables.

Of the 91 articles reviewed, 14 (15%) consider non-probabilistic uncertainty associated with human thinking in decision-making. Fuzzy set theory, in combination with AHP and ANP pairwise weighting methodologies, is used in 8 manuscripts. The hybrid AHP + TOPSIS + fuzzy methodology demonstrates a flexible adaptation when considering uncertainty in decision-making. One paper examined cases with different uncertainties using Bayesian probability theory, fuzzy sets, and DS theory of random sets using OWA, demonstrating the versatility of the proposed model.

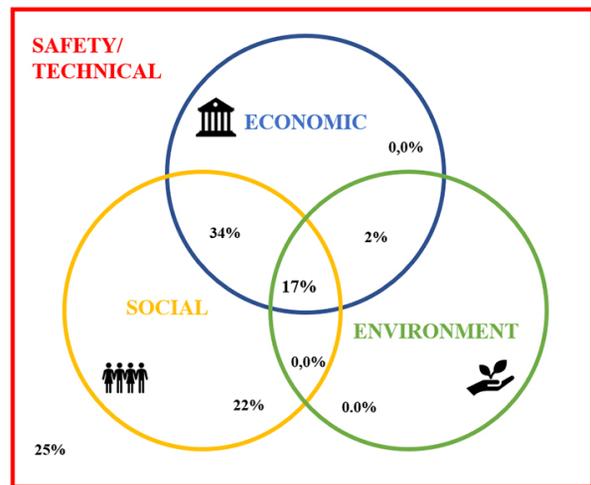


Figure 6. Integration of safety and sustainability in the evaluation and reinforcement of buildings

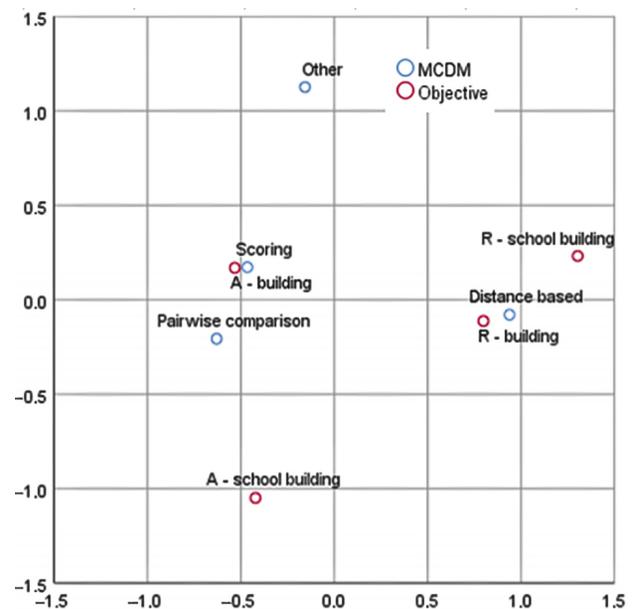


Figure 7. Simple correspondence analysis for the objective of the studies and the MCDM category used

4.2. Future directions

The literature review underscores the necessity of achieving consensus within the scientific community regarding the criteria to be evaluated across various dimensions. Life Cycle Cost (LCC), Environmental Analysis (LCA), and Social Life Cycle Analysis (SLCA) offer valuable insights toward this objective. Although LCA has been utilized in several articles within this review, social life cycle analyses have been largely overlooked. Notably, studies in civil engineering have incorporated SLCA methodologies in analyzing bridges (Martínez-Muñoz et al., 2022; Navarro et al., 2018) and buildings (Sánchez-Garrido et al., 2022).

The use of classical decision-making methods dominates research. Despite the emergence of newer and more sophisticated methods, they have yet to be given due attention or application in the field. Given the proliferation

of new decision-making methods in recent years, there is the potential for these approaches to offer greater accuracy and applicability, thus presenting viable solutions to current challenges. Among the pairwise comparison methods, the Best-worst method (BWM) proposed by Rezaei (2015) offers better results. It is easier to apply than AHP and ANP, thus proving its superiority (Zhu et al., 2021). Although several researchers have validated the use of TOPSIS by comparing the results with other classical MCDMs, newer methods could be used: Integrated Simple Weighted Simple Sum-Product (WISP) (Stanujkic et al., 2023), Combinative Distance-based Assessment (CODAS) (Keshavarz Ghorabae et al., 2016); comprehensive distance-based ranking (COBRA) (Krstic et al., 2022); Evaluation based on Distance from Average Solution (EDAS) (Keshavarz Ghorabae et al., 2015), among others. The term “deferral effect” summarizes the current status of the analyzed studies, indicating the lag in this field in terms of MCDM research and application (Zhu et al., 2021).

Most traditional MCDMs operate under criteria independence; several interactions among criteria might occur in real-life situations, so more sophisticated/intelligent techniques are required to deal with the needs of the problem in decision-making (Golcuk & Baykasoglu, 2016). A common criticism against ANP is its complexity, which hampers practical application. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique can build the influential relation matrix to construct the influential network relations map (INRM) and determine the influential weights of DANP (DEMATEL-based ANP) using the basic concepts of ANP (Penadés-Plà et al., 2016). The DANP methodology is used to model criteria interactions in the research of numerous fields such as tourism, commerce and finance, industry, information technology, and construction (Nguyen, 2023).

The exploration and utilization of fuzzy MCDM models remain relatively limited within the scope of this literature review. However, several practical tools for expressing fuzzy information have emerged recently and gained widespread adoption. These include linguistics terms set neutrosophic, hesitant fuzzy probabilistic linguistic, and continuous interval-valued (Wen et al., 2021). Notably, linguistics terms neutrosophic techniques have been increasingly employed in civil engineering applications. They have been utilized in assessing the sustainability of bridges (Navarro et al., 2020a), single-family houses (Sánchez-Garrido et al., 2021), and prioritizing maintenance in sanitary facilities (Ahmed et al., 2021). Such methodologies offer valuable support in managing uncertainty inherent in the evaluation and reinforcement of buildings.

5. Conclusions

This study reviews 91 articles published since 2008 focusing on assessing, selecting, and retrofitting buildings using multi-criteria decision-making methods. The overall analysis suggests that this topic has recently generated

considerable interest in the scientific community. There is evidence of many investigations studying public buildings, particularly schools and historic buildings. A review of the criteria reveals that researchers assess and select vulnerable buildings with economic and social considerations. Regarding building retrofitting, the current approach emphasizes the integration of four dimensions: safety, economic, social, and environmental. However, there has yet to be a consensus on the specific criteria for each dimension. Given the complexity of integrating the pillars of sustainability and safety, the MCDM proves to be a helpful tool. Despite research efforts, only 15 of 32 articles selected the best retrofit option integrating safety and sustainability, with limited involvement of life cycle analysis studies.

The hierarchical analytical process (AHP) is the most widely used method for criteria weighting and is used in adapted or hybrid versions with other MCDM techniques. Given the complexity of the relationships between sustainability and safety criteria, the scientific community widely accepts the TOPSIS method. This conclusion is supported by the results of the statistical correspondence analysis performed on the MCDM category variables and the research objective, in which the correlation between building retrofit and TOPSIS is evident. In addition, the literature explores other relevant methods, such as SAW, ANP, MIVES, and OWA.

The main problem with traditional MCDM is the subjective nature of the decision-maker's involvement phase. This literature review revealed that most of the articles use a crisp approach. However, 15% of the articles incorporate decision-making under uncertainty, using hybrid MCDM criteria with fuzzy methods, such as AHP, ANP, TOPSIS, and OWA. Only one article explores other methods, such as Bayesian networks and random ensembles, highlighting a knowledge gap. Based on the results, further research is needed to address the subjectivity and bias inherent in expert judgments, using current methodologies to assess the pillars of sustainability and allow for real integration with safety.

This literature review makes a significant contribution to the field of research for a holistic renovation of the existing building stock. It critically examines current trends and proposes new research directions for integrating safety and sustainability into existing buildings using MCDM. The key findings of this research can be succinctly outlined as follows: Firstly, it identifies the most utilized criteria across safety, economic, social, and environmental dimensions by researchers. This identification fosters consensus-building for future studies, highlighting the significance of incorporating life cycle analysis in assessing building pathologies and retrofit strategies. Secondly, a critical discussion of existing research trends reveals a predominant use of traditional single or hybrid MCDMs to integrate structural safety with sustainability in existing buildings. Lastly, the study pinpoints research gaps, laying the groundwork for future research directions. These recommendations advocate for the exploration of new and

sophisticated MCDMs, the consideration of criterion interactions, and the management of uncertainty in expert judgments. Lines of research are promising in the search for improved solutions in integrating safety and sustainability in the assessment, selection, and retrofitting of existing buildings.

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Author contributions

This paper represents a result of teamwork. The authors jointly designed the research. P. V. developed the methodology, investigated, and drafted the original manuscript. P. V., A. J. S.-G. and V. Y. edited and improved the manuscript until all authors were satisfied with the final version. All authors have read and agreed to the published version of the manuscript.

Disclosure statement

The authors declare that there are no conflicts of interest regarding the publication of this article.

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