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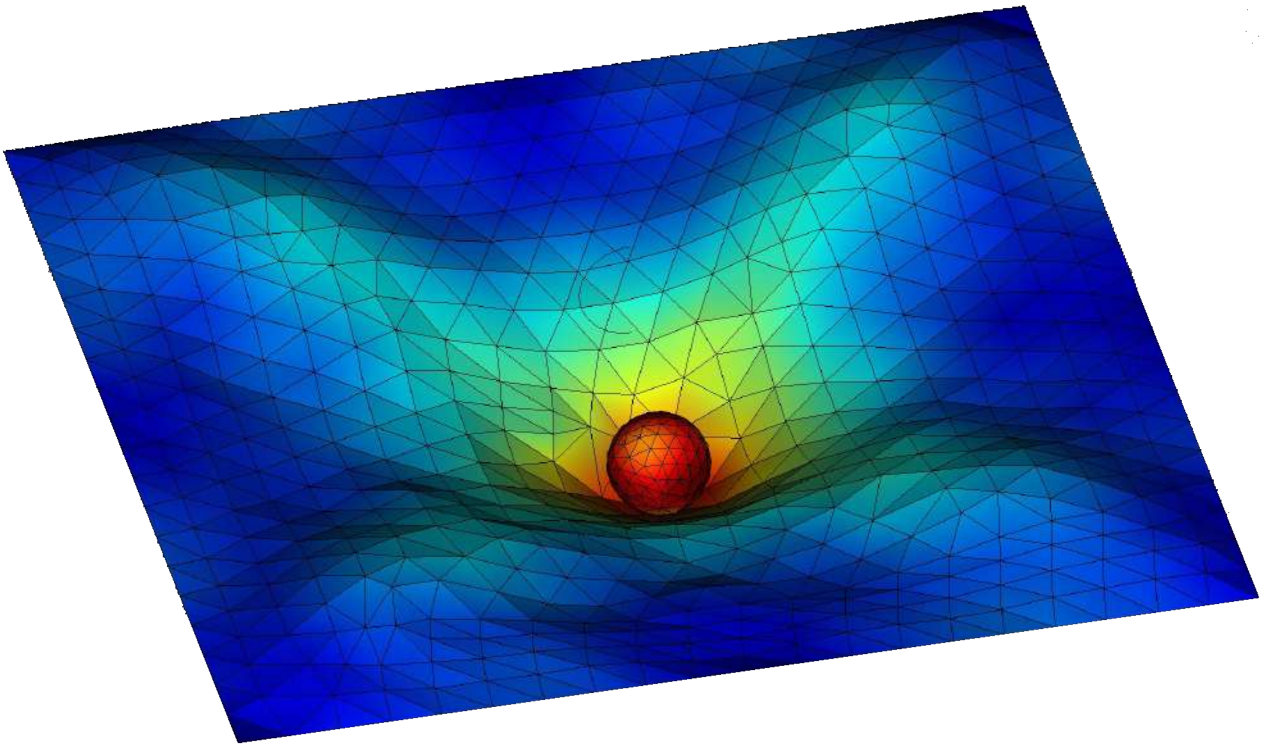

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MULTI-CRITERIA DECISION-MAKING APPLICATION FOR SUSTAINABLE BUILDING RENOVATION

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Abstract

The Life Cycle Thinking (LCT) approach offers a holistic perspective for designing sustainable retrofitting strategies, by minimising environmental impact throughout all phases of the building's life cycle, while also addressing economic and social issues. This work presents a multi-criteria decision-making (MCDM) application aimed at identifying the best retrofitting strategy for a building, considering economic, environmental, and social aspects, including earthquake-induced impacts. The case-study building is an existing reinforced concrete (RC) structure built in 1970 in Northern Italy, which is analysed and assessed in its as-built configuration, as well as in four integrated retrofitting scenarios, implying the adoption of new RC walls, steel walls, steel diagrid, and timber shell, respectively. Some of these strategies were designed according to LCT principles, and one of the aims of this study is to demonstrate the advantages of such solutions also in terms of seismic risk protection. The seismic assessment of the configurations is carried out through the FEMA P-58 approach. The results are compared in terms of the expected economic, environmental, and social impacts, leading to the identification of the timber shell solution as the best strategy.

Keywords: Integrated building renovation, Multi-criteria decision-making, Optimal retrofitting strategies, Seismic risk assessment, Life cycle analysis (LCA), Life cycle thinking (LCT).

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1 INTRODUCTION

The existing building stock is highly vulnerable to seismic events, as well as to other natural hazards, including those related to climate change (e.g., floods, heat waves). The inadequate structural performance of these buildings is typically a result of insufficient structural detailing, poor construction material quality, and susceptibility to critical failure mechanisms (e.g., soft storey). At the same, these buildings are among the largest contributors to energy and material resource consumption, owing to the poor performance of their envelope components and mechanical systems.

For these reasons, building retrofitting techniques should focus on (i) minimizing the vulnerability against earthquakes and other natural hazards, including those related to climate change, (ii) reducing operational energy demands, and (iii) utilizing low-impact construction materials and components for the retrofits. Multi-criteria decision-making (MCDM) approaches can support the choice of optimal retrofitting strategies, aimed at reducing the environmental, economic, and social impacts of buildings throughout their life. These tools, considering multi-faceted aspects of sustainability, are essential for promoting the effective adoption of life cycle thinking principles in current practices (e.g., Refs. [1], [2]). In addition to this, Passoni et al. (2021, 2022a) ([3], [4]) proposed a more comprehensive design framework based on Life Cycle Thinking (LCT) specifically aimed at the design of holistic and sustainable retrofitting solutions, referred to as Life Cycle Structural Engineering (LCSE). The main steps of this framework (Figure 1) include: (i) multi-performance assessment of the building; (ii) pre-screening of retrofitting techniques based on sustainable performance targets; (iii) preliminary design of candidate retrofitting techniques; (iv) selection of the optimal retrofitting solution for the specific building based on relevant performance metrics; (v) design development of the retrofitting solution; (vi) use of classification schemes to access potential financial incentives; (vii) final design and construction of the retrofitting solution; and (viii) management of the building's operational life. MCDM approaches for selecting optimal retrofitting strategies can thus be seamlessly integrated into step (iv).

In this paper, an updated version of the MCDM approach proposed in Ref. [5] is proposed, focusing on its application to a case-study building located in Northern Italy. Four different types of integrated exoskeletons, made of timber, steel, and concrete, are examined; some of these solutions were designed based on an LCT-inspired conceptual framework, while others followed more traditional engineering practices. The main innovation of the updated version lies in the inclusion of additional LCT-inspired decision-making criteria (such as module D - beyond-life impacts, environmental payback period, and invasiveness). These additions make it a suitable tool for step (iv) of the LCSE framework (Figure 1). The integration of sustainable criteria into the decision-making process clearly favors and prioritizes LCT-based retrofitting interventions over traditional ones, demonstrating its value as a supportive tool for the sustainable renovation of buildings.

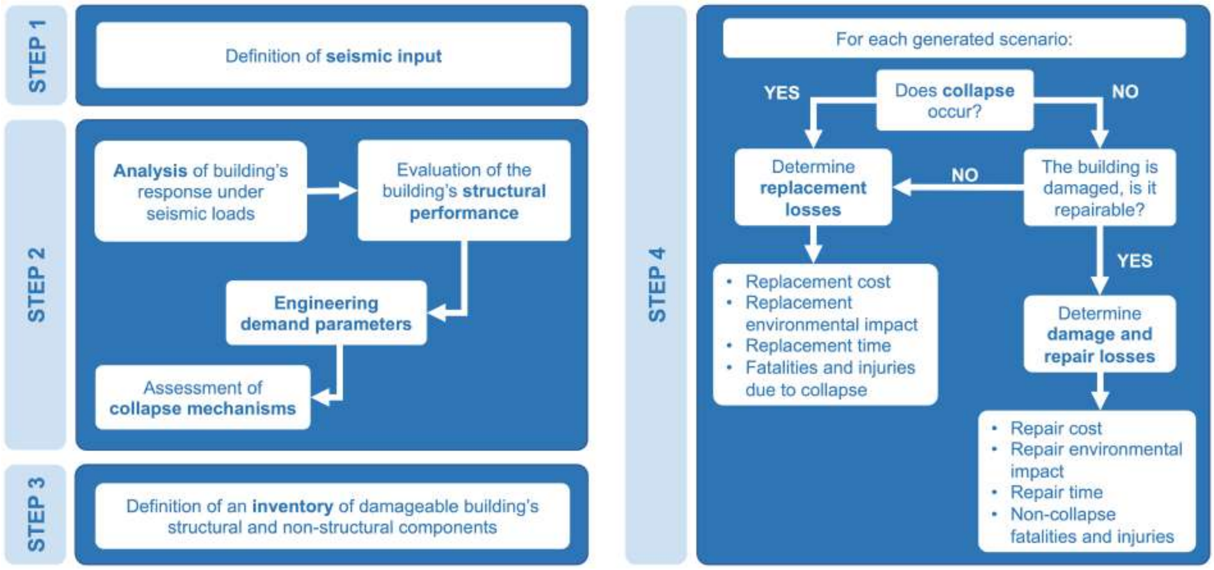

Figure 1: FEMA P-58 workflow for seismic loss assessment.

2 MULTI-CRITERIA DECISION-MAKING (MCDM) APPROACH

The MCDM approach originally proposed by Caruso et al. (2023) [1] is based on four decision-making parameters, and on the use of the so-called radar plots as a powerful tool to identify the best retrofitting option in an integrated fashion. This methodology was developed with a view to define meaningful economic, environmental, and social quantitative metrics allowing for the comparison of alternative retrofitting solutions for a given building, considering its seismic and energy performances at the same time. The decision variables considered in the original version of the MCDM are the following:

- post-retrofit life cycle costs (C), summing up the costs of the retrofit components, seismic economic losses, and costs for energy consumption;
- post-retrofit life cycle carbon emissions (CE), expressed in terms of equivalent carbon dioxide emissions (kg CO_2e), accounting for the environmental contributions of the retrofit components, earthquake-induced damage and repair, and energy consumption;
- payback period (PB) of the retrofit's economic investment;
- average annual loss of life (AALL) due to potential earthquakes, expressed in terms of expected fatalities per year.

Life cycle costs (C) and carbon emissions (CE) are calculated for the building's post-retrofit lifespan by summing up the economic and environmental contributions of the retrofitting intervention, earthquake-induced losses, and operational energy consumption. These values are then normalised by the total floor area of the building and its expected post-retrofit life. The payback period of the retrofit investment indicates the number of years needed to fully pay back the initial investment through the yearly monetary savings provided by the adopted retrofitting option. Finally, the average annual number of fatalities can be estimated through a dedicated casualty model (e.g., ATC, 2018a [6], Coburn et al., 1992 [7]). The optimal retrofitting solution can then be determined through the support of radar plots, where all the four variables are normalised by the corresponding as-built values (except for the PB that is normalised by the building's expected post-retrofit life). The solution resulting in the smallest area in radar charts is the one that, at the same time, minimises all the four considered parameters.

This method was initially designed to allow for the inclusion of any additional performance metrics of interest. In this work, indeed, an updated version of this MCDM approach is presented, by including the following additional decision-making parameters, which are inspired by LCT principles:

- beyond-life phase carbon of retrofit components (D);
- payback period (PB-env) of the retrofit environmental cost;
- level of invasiveness of the retrofit measure (I).

It is briefly recalled that life cycle assessment (LCA) procedures of buildings typically account for the environmental impact associated to the following life cycle phases [8]: (i) production (modules A1-A3), including raw materials supply, transportation to factory and manufacture, (ii) construction (modules A4-A5), including transportation to and installation in the construction site; (iii) use and maintenance (modules B1-B7); and (iv) end-of-life (modules C1-C4), including deconstruction and demolition, waste transportation, processing and disposal. The beyond-life phase (module D) quantifies the benefits of the potential reuse, recycle and recovery of salvaged materials after the end of life of the building. It can indeed be interpreted as the difference between the impacts of the recycling/reuse/recovery processes and that of the primary production. Therefore, a negative value of module D indicates an environmental saving, while a positive value represents an additional burden. This parameter highlights retrofitting techniques with high potentials of beyond-life use. To be included in radar plots, module D values can be normalised by calculating: 1 + (module D/|modules A1-A3|), considering null all the negative values that may result. In such a way, large negative D-values are prioritised. It is noted that not all the negative D-values will result as null, indeed they may also be in the range between 0 and 1 when the absolute value of module D is lower than that of modules A1-A3. Module D is not considered in absolute terms in the normalisation in order to maintain a distinction between potentially beneficial and burdensome scenarios.

The environmental payback period (PB-env), can be defined similarly to the economic one, as it quantifies the number of years needed to “pay back” the cradle-to-gate embodied carbon of the retrofit components (i.e., LCA modules A1-A3) by means of the environmental savings generated by the adopted retrofitting measure (e.g., the reduction of the environmental impact due to energy consumption achieved through an energy efficiency upgrade intervention). It can be calculated in a simplified manner, by dividing the cradle-to-gate embodied carbon of the retrofit by the yearly environmental savings offered by the retrofit considered. This parameter is considered as relevant to prioritise retrofitting techniques with limited initial carbon footprint. The PB-env is normalised by the building's post-retrofit life, as done for the economic PB that from now on will be referred to as PB-econ.

Lastly, the invasiveness of the retrofit is considered in terms of limitation of its impact on the building, as well as of minimization of the disturbance to building’s occupants. Quantifying numerically invasiveness is clearly not straightforward, however a simplified way is proposed here, by assigning values from 0 to 5 to three different criteria and summing them up, those being: (i) the need to build new foundations, (ii) the invasiveness of the retrofit installation, and (iii) the invasiveness of the potential repair activities on retrofit components in case of a destructive seismic event. Attributing a score of 5 to a given criterion implies a high level of invasiveness, such as e.g., a new foundation system is constructed (criterion i), the need of occupants’ relocation and/or of restoring the finishing layers of the building during the retrofit installation (criterion ii) or during potential post-event repair activities (criterion iii). An overall invasiveness score between 0 and 15 can thus be obtained, after summing the scores for each of the three individual criteria. This parameter exploits low-invasive retrofitting techniques. Finally, the parameter I for radar charts is obtained by dividing the aforementioned score by a factor of 10, thus implying that it may vary between 0 and 1.5.

In conclusion, the updated version of the MCDM proposed herein considers three environmental (life cycle carbon emissions (CE), beyond-life carbon (D), environment payback period (PB-env)), two economic (life cycle costs (C), economic payback period (PB- econ)), and two social parameters (annual average loss of life (AALL), invasiveness (I)). It is noted that, in both versions (original and updated) of the MCDM, all the decision-making parameters are considered as equally important, thus any weighting factor is assigned to the different criteria. The following section describes the application of both versions of the MCDM to a case-study building.

3 CASE-STUDY BUILDING APPLICATION

The case-study building is a three-storey reinforced concrete structure built in the 70s and located in the city of Brescia (Northern Italy) (Figure 2). This region is characterised by a medium to high level of seismic hazard (with soil type C and topographic class T1, according to the Italian building code classification [9]) and mild climate conditions. The L-shaped building plan is made of two rectangular blocks, referred to as 'block A' and 'block B', respectively, which are connected by a stairwell, for a total area of approximately 230 m^2 per floor.

The block A has floor dimensions of 12.28 m × 8.12 m, with an inter-story height of 3.06 m on the ground floor and 3.15 m on the upper floors. The block B, located over a 1.05 m-high RC basement, has floor dimensions of 13.60 m × 9.80 m, with an inter-story height of 3.10 m on the ground floor and 3.95 m on the upper floors. The two blocks have thus slabs at different heights. Both structures are composed of one-way RC frames designed for gravity loads only, with floors made of unidirectional mixed concrete and hollow clay block slabs and double-leaf masonry infills (with a 7-cm air cavity between two solid brick layers). For a more detailed description of the building's geometries and characteristics, the reader is referred to Passoni et al. (2022b) [10] and Labò et al. (2022) [11].

Figure 2: Blocks A and B views (adapted from Passoni et al., 2022b).

3.1 Integrated assessment of the as-built configuration

3.1.1. Seismic loss estimation of the as-built configuration

The FEMA P-58 component-based approach for seismic loss assessment is characterised by four main steps, according to the workflow shown in Figure 1: (1) definition of the seismic input at the site of interest, (2) structural performance analysis of the building's response under seismic loads, through engineering demand parameters (EDPs) and collapse mechanisms, (3) evaluation of damage in all building's vulnerable components, and (4) assessment of losses due to repair of damaged components or to building's collapse. The results are expressed in terms of annual loss exceedance curves, showing the annual probability of exceeding different values of a decision variable (DV), such as, e.g., repair cost, repair time, repair environmental impacts and fatalities, by combining the hazard curve with the building vulnerability.

Based on the Italian building code classification [9], the hazard curve of the site of interest was obtained in terms of spectral acceleration at a conditioning period T* at four seismic intensity levels (i.e., 30, 50, 475, and 2475-year return periods). The conditioning period was taken, as suggested in ATC (2018a, b) [6], [12], as the arithmetic mean of the building's periods of vibration in the two horizontal directions, that is 0.49 s.

A 3D numerical model of the case-study building (Figure 3) was created by using Midas Gen software (1989) [13] to perform the structural analysis of the building under seismic loading through nonlinear static analyses. Beam elements with lumped plastic hinges were used to model structural components, while compression-only struts converging into structural nodes were employed to model external infills. Floors were modelled as rigid diaphragms. For further details on the structural modelling assumptions and the analysis of the case-study building, the reader is referred to Labò et al. (2022) [11] . From the nonlinear static analyses, the inter-storey drift ratios (IDRs) were extracted for each seismic intensity level, floor, and horizontal direction of the building. The vulnerability modellers toolkit (VMTK) [14] was then employed to derive the building's collapse fragility function from the capacity curves, relating the probability of incurring structural collapse to ground motion intensity.

A crucial step in the seismic loss assessment process is the creation of a comprehensive inventory of structural and non-structural components (Figure 3), which are expected to incur damage during seismic events. Each of these components is associated with a fragility function and a set of consequence functions. The fragility function defines the conditional probability of reaching a certain damage state (DS) given a specific level of seismic demand, typically measured in terms of an EDP, such as inter-storey drift ratio, peak floor acceleration, or peak velocity. Consequence functions are used to translate the damage state of each component into tangible outcomes, including repair costs, repair time, repair environmental impacts, and fatalities. The inventory includes a range of components that are critical to understanding the building's overall vulnerability. The components considered for the case-study building are the following: RC external beam-column joints (EWJs), RC internal beam-column joints (IWCs), exterior masonry infills with and without windows (EIW_ws and EIWs, respectively), interior masonry partitions with and without doors (IP_ds and IPs, respectively), windows and doors, which are categorized as partition-like components (PLs; i.e., non-structural components whose damage and repair are considered to be directly related to the damage states of the infills or partitions in which they are integrated), and RC shear walls.

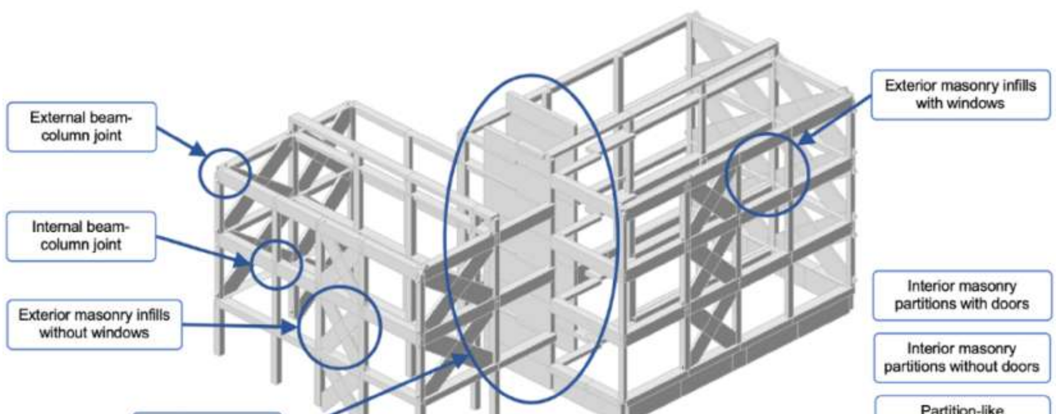

Figure 3: Inventory of damageable structural and non-structural building's components.

This study employed the fragility and repair cost functions for RC structural components and masonry non-structural elements developed by Cardone (2016) [15] and Cardone and Perrone (2015) [16]. These functions are representative of RC frame buildings in Italy and Europe built prior to 1970. The consequence functions, quantified in terms of equivalent carbon dioxide emissions, were obtained from Caruso et al. (2023) [1]. For the RC shear walls, the fragility and consequence functions were directly taken from those available in the PACT library.

Further to the consequence functions for damageable components, it is essential to estimate the economic and environmental cost of the building's replacement (including demolition plus reconstruction activities) to fully account for the potential contributions of building collapse or non-repairable scenarios in the calculation of average earthquakes-induced losses. The replacement economic cost of the building was estimated as equal to €1.4 million, based on a reconstruction cost of €1,350 per square meter, as recommended in the Italian National Risk Assessment (DPC, 2018) [17], along with an additional cost of €44 per cubic meter for demolition and disposal, as noted in Cardone et al. (2017) [18]. A total loss threshold of 0.6 was assumed, meaning that if the damage exceeds 60% of the reconstruction cost, demolition would be considered to be more cost-effective than repair. To assess the replacement environmental cost of the building, the economic input output (EIO) method for life cycle assessment (LCA) was adopted employing the US EIO-LCA web tool (CMUGDI, 2023) [19]. This tool translates sector-specific costs into cradle-to-gate environmental impacts, expressed in terms of equivalent carbon dioxide (CO_2e). Based on this approach, the equivalent carbon emissions associated with demolition and reconstruction were estimated to be approximately equal to 561,700 kg of CO_2e.

Finally, it was possible to estimate the average annual losses for the building in economic, environmental, and social terms. The economic average annual loss ratio (AALR) was determined to be equal to 0.26%, as the ratio between the area under the monetary exceedance loss curve (approximately €3,640) and the total replacement economic cost (approximately €1.4 million). The environmental loss analysis yielded an average annual embodied carbon ratio (AAECR) of 0.27%, derived from the ratio between the area under the environmental exceedance loss curve (approximately 1,515 kg CO_2e) and the total replacement environmental cost (561,700 kg CO_2e). Lastly, the average annual loss of life (AALL) was estimated as equal to 0.0034 fatalities per year.

3.1.2. Energy performance assessment of the as-built configuration

The energy performance model of the case-study building was developed using architectural drawings and in-situ inspections in the TRNSYS tool. The building lacked a thermal insulation layer and had poor opaque and transparent envelope components, as well as outdated mechanical equipment. As a result, the total annual energy consumption for heating and cooling was estimated to be 84,000 kWh and 4,100 kWh, respectively (Labò et al., 2022) [11]. With a methane cost of € 0.80 per standard cubic meter (that is equivalent to 10.69 kWh) and 0.19 kg CO_2e emitted per 1 kWh, the annual cost of energy consumption was calculated to be approximately €6,600, and the annual carbon emissions from energy use were estimated to be around 16,700 kg CO_2e. It is noteworthy that the annual cost for energy is nearly double the average annual economic losses due to potential earthquakes, and the annual carbon due to energy consumption is almost one order of magnitude greater than the corresponding impact from seismic risk.

3.2 Integrated retrofitting solutions

Four different structural retrofitting solutions were designed for the case-study building, each achieving the same structural performance (i.e., those being iso-performance targeted), through the use of four different exoskeleton systems (Figure 4). Each solution also included the addition of a thermal insulation layer and a new architectural finish to enhance both the building's energy efficiency and its architectural aesthetics. As a result, while the energy performance of all four retrofitted configurations remains the same, their structural performances vary based on the retrofit type.

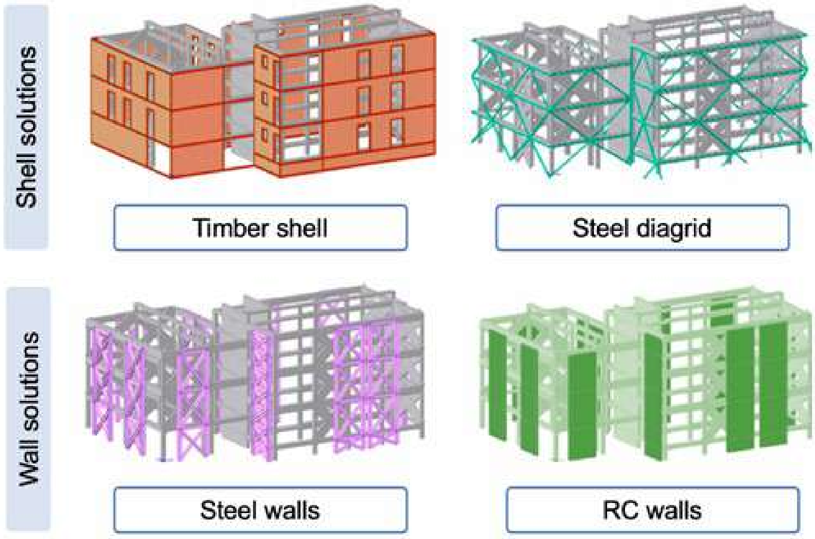

Figure 4: Four alternative iso-performance structural solutions: shell and wall exoskeletons.

The exoskeleton systems examined in this study include both shell and wall exoskeletons. Solutions 1 and 2 are shell exoskeletons, made of cross-laminated timber (CLT) panels and a diagrid frame of tubular steel profiles, respectively. In contrast, the wall exoskeletons include one with steel walls (solution 3) and another with reinforced concrete walls (solution 4). All systems are connected to the building's floors via continuous steel chords and custom-designed connections along the perimeter, ensuring efficient transfer of seismic loads from the existing structure to the new one. Solutions 1 to 3 follow LCT principles, while solution 4 is based on traditional design rules (Passoni et al., 2022b) [10].

The first solution is a timber shell exoskeleton, offering significant potential for recycling and reuse of components at the building's end of life. Its installation involves dry assembly of prefabricated components, including modular elements and standardized connections, as well as sacrificial elements where the potential seismic damage is expected to be concentrated. For more details on the design of this innovative exoskeleton structure, refer to Zanni et al. (2021) [20].

Solutions 2 and 3 consist of a steel diagrid structure made of tubular profiles spanning the building's floors and walls with HEA commercial steel profiles, respectively. The use of steel as a structural material offers multiple advantages: these profiles are typically made of recycled or reused steel, which can also be recycled or reused at the end of the exoskeleton's life. Additionally, both steel solutions are designed as dry, prefabricated, modular, and standardized systems, with custom connections to the existing structure.

Lastly, solution 4 is the traditional RC cast-in-place wall solution. The installation process for this solution is not dry, which could result in a more significant environmental impact at the exoskeleton's end of life, especially considering the amount of demolition waste that is likely to be transported to landfills. Moreover, this type of structure does not concentrate seismic damage but rather distributes it across the walls, particularly at their base. While RC walls are known to enhance the seismic performance of retrofitted buildings during seismic events, if they become irreparable, they would require complete replacement.

3.2.1. Seismic loss estimation of the retrofitted configurations

The seismic loss assessment of all four retrofitted configurations was carried out through the FEMA P-58 procedure and with the support of the PACT Tool (ATC 2018a, 2018b) [6], [12], following the same steps indicated for the as-built structure in the previous section. To this purpose, additional considerations and modifications were made to the as-built inventory of damageable components to include the retrofit components. Specifically, fragility and consequence functions for CLT panels, steel diagrids, and steel and RC shear walls were selected from the PACT library and included into the performance models for each new system. Furthermore, the replacement economic and environmental costs of each retrofitted building were increased by 10% compared to the estimates for the as-built configuration, resulting in approximately €1.5 million of replacement economic cost and 620,000 kg of CO_2e of environmental cost.

Table 1 presents the results of the seismic loss assessment for each retrofitted configuration compared to those of the as-built one, in terms of average annual economic loss ratio (AALR), average annual embodied carbon ratios (AAECR), and average annual loss of life (AALL). All the retrofitting solutions explored in this study lead to a significant reduction in earthquake-induced consequences. Among the four exoskeleton options, the timber shell solution offers the greatest benefits across all three earthquake-related performance parameters. The steel diagrid option, while still effective, appears to be the least efficient, though it is comparable in terms of impact to the steel wall solution. RC walls also proved to be highly effective, though not as much as the timber shell solution.

It is important to note that the four retrofitting solutions were designed to be iso-performance, meaning that very similar, if not identical, loss estimates would be expected for all four scenarios. However, due to the current lack of specific fragility and consequence functions for these types of components, it was necessary to use those available for similar components in the PACT library. Those components, mostly representative of North American construction practices, do not account for the concentration of damage at the connections between the exoskeleton and the existing structure, though assuming the complete component failure.

	As-built	Timber shell	Steel diagrid	Steel walls	RC walls
AALR	0.26 %	0.02 %	0.11 %	0.10 %	0.04 %
AAECR	0.27 %	0.03 %	0.11 %	0.12 %	0.04 %
AALL	0.0034	0.0001	0.0026	0.0019	0.0001

Table 1: Summary results of the seismic loss assessment of as-built and retrofitted configurations.

3.2.2. Energy performance assessment of the retrofitted configurations

All four exoskeleton types were designed as coupled with a thermal insulation layer to improve the energy performance of the building. This new envelope configuration was incorporated into the TRNSYS energy performance model. As a result of this energy upgrade, the total annual energy consumption for heating and cooling of the upgraded structure was estimated to be equal to 38,169 kWh and 3,930 kWh, respectively (Labò et al., 2022) [11]. The annual costs and carbon emissions associated with energy consumption were thus estimated at approximately €3,150 and 8,000 kg CO_2e, respectively, reflecting a reduction of about 50% compared to the as-built estimates.

3.3 Choice of the optimal integrated retrofitting solution

Once the integrated assessment of both the seismic and energy performances of the building in all configurations is carried out, multi-criteria decision-making approaches can be used for selecting the optimal retrofitting solution for the building at hand. In this work, for comparison, both the first version of the MCDM approach [1] with four decision variables (referred from now on as 'original version') and the updated version proposed herein with seven variables (referred from now on as 'updated version') were applied. The purpose of this comparison is the investigation of the influence on the results of the introduction of additional sustainability-related decision-making criteria.

Figure 5 shows the radar plots derived from applying the original version of the MCDM. The optimal solution, identified by the smallest area, which minimizes all four considered variables, is the timber shell solution. The final ranking is as follows: timber shell, RC walls, steel diagrid, and steel walls. As anticipated, RC walls prove to be highly efficient, aligning with the results from the seismic loss analysis. For this reason, it ranks higher than the two steel solutions, which were instead designed based on LCT principles.

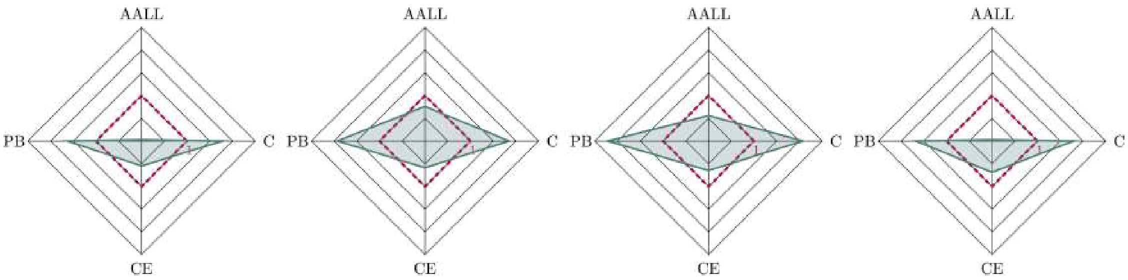

Figure 5: Radar plots of the four retrofitted configurations (from left to right, timber shell, steel diagrid, steel walls, RC walls): normalised post-retrofit costs (C), carbon emissions (CE), payback period (PB), and average annual loss of life (AALL).

For the application of the updated version of the MCDM proposed here, the other variables for each retrofitted configuration were calculated as follows. Modules D of each solution were taken from the work of Passoni et al. (2022b) [10]. Module D was normalized as follows: 1 + (module D / |modules A1-A3|), with all resulting negative values treated as zero. The environmental payback period (PB-env) was calculated as the ratio between the initial embodied carbon of the retrofit (modules A1-A3) and the annual environmental savings produced by the adopted retrofitting solution. This was then normalized by the building's post-retrofit life (i.e., 50 years), similar to the normalization of PB-econ. Lastly, the level of invasiveness (I) was calculated by summing the scores (ranging from 0 to 5) assigned to three different criteria described in the previous section. Regarding foundations, a score of 2 was assigned to both the timber shell and steel diagrid solutions, while a score of 5 was given to the steel walls and RC walls. For the invasiveness of the retrofit installation, since all solutions are designed to be applied from the outside of the building, without occupants' relocation, a score of 0 was assigned to all options. In terms of repair activities following a strong seismic event, the steel diagrid solution, being the outermost layer of the retrofitted building with thermal insulation placed between the existing envelope and the diagrid system, is expected to be the least invasive, requiring minimal finishing work and occupant disturbance. Therefore, a score of 0 was given to this criterion for the steel diagrid solution. In contrast, the other three solutions, although repairable from the outside, would require the removal of exterior finishes and insulation layers to repair the structural retrofit components. As a result, a score of 4 was assigned to each of these three solutions.

Based on these seven parameters, the optimal solution derived from the updated radar charts, shown in Figure 6, remains the timber shell solution, which has a significant advantage over the other options. Following it, in ascending order, are the steel diagrid, RC walls, and steel walls solutions. Notably, the steel diagrid and RC walls solutions are now ranked in reverse order, reflecting the impact of including LCT-inspired and sustainability parameters in the decision-making variables.

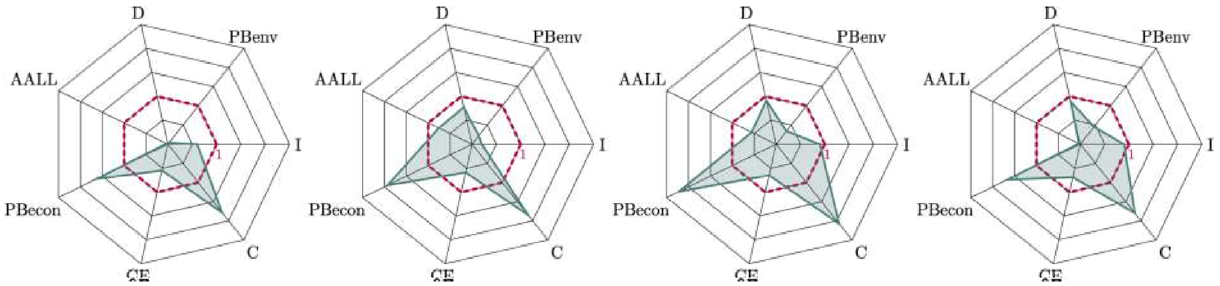

Figure 6: Radar plots of four retrofitted configurations (from left to right, timber shell, steel diagrid, steel walls, RC walls): normalised post-retrofit costs (C), carbon emissions (CE), economic payback period (PB-econ), average annual loss of life (AALL), module D (D), environmental payback period (PB-env), and level of invasiveness (I).

4 CONCLUSIONS

Multi-criteria decision-making (MCDM) methodologies typically include economic, social, environmental, and technical criteria that are of interest to decision-makers (e.g., retrofit installation costs, invasiveness, operational energy consumption, etc.). This study discusses an updated version of the MCDM approach proposed by Caruso et al. (2023) [1] through an application to a residential building located in Northern Italy. Four different integrated exoskeletons, made of timber, steel, and concrete, were designed as retrofit solutions for the building in question. Solutions 1 and 2 are shell exoskeletons, made of cross-laminated timber panels and a diagrid frame of tubular steel profiles, respectively. Solutions 3 and 4 are wall exoskeletons, made of steel and RC walls, respectively. Solutions 1 to 3 were designed according to LCT principles, while Solution 4 was designed following traditional design rules.

The results of both the original and updated versions of the MCDM approach demonstrated that introducing additional LCT-compliant criteria in the decision-making process effectively favours LCT-based retrofit interventions over traditional ones. This was evidenced by the reversal of ranking positions between the steel diagrid solution and the RC walls solution, favouring the steel diagrid, which is generally more sustainable than RC walls.

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