APPLICATION OF A MULTI-CRITERIA DECISION-MAKING APPROACH FOR OPTIMAL BUILDING RETROFITTING

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Abstract: *The present work describes the application of a life-cycle multi-criteria decision-making approach aimed at identifying the optimal building retrofitting strategy based on economic, environmental, and social parameters, including earthquake-induced impacts. The case-study building is an existing reinforced concrete (RC) structure built in 1970 in Northern Italy, which is assessed in both its as-built configuration, as well as following the application of four different integrated retrofitting strategies involving the use of RC walls, steel walls, steel diagrid, and timber shell solutions. Some of these strategies were designed according to life cycle thinking (LCT) principles, and one of the aims of this study is thus to demonstrate the advantages of such solutions also in terms of seismic risk protection. The seismic assessment of both as-built and retrofitted configurations is carried out through the employment of 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 among the four retrofitting alternatives.*

1. Introduction

It is well-acknowledged that the existing building stock is significantly vulnerable to seismic shaking, as well as to other natural hazards, including climate change related ones (e.g. floods, heat waves), which are becoming more and more frequent and intense. The poor structural behaviour of existing buildings is generally due to insufficient structural detailing and quality of construction materials, and susceptibility to critical failure mechanisms (e.g. soft storey). At the same time, those buildings are amongst the largest contributors to energy and material resources consumption, due to the poor performances of the envelope's components and of the mechanical equipment.

Buildings' retrofitting techniques should thus be mostly intended to reduce their vulnerability against natural hazards, including earthquakes, as well as to limit their operational energy consumption, by adopting integrated retrofitting techniques (e.g. Marini et al., 2017; Baek et al., 2022; Bournas, 2018; Ferrante et al., 2018). However, a more holistic point of view, referred to as life cycle thinking (LCT), is also essential to address buildings' sustainable renovation. As described in more detail in Passoni et al. (2022b), examples of LCT principles that can be embraced throughout the design of retrofitting measures are, for instance, the use of recycled/recyclable materials, the choice of cost-effective retrofits, the limitation of potential earthquake-induced casualties and/or injuries, the improvement of indoor air quality, amongst others.

In this context, multi-criteria decision-making (MCDM) approaches are useful tools to support the identification of the optimal retrofitting strategies for buildings, accounting for several sustainability facets, including environmental, economic, and social aspects (e.g. Caruso et al. (2023); Clemett et al. (2023)). Notably, Passoni et al. (2021, 2022a) also introduced a more comprehensive LCT-based design framework for the design of holistic and sustainable retrofit interventions, whose main steps are: (i) multi-performance assessment of the building; (ii) pre-screening of retrofitting solutions based on sustainable performance targets; (iii) preliminary design of the candidate retrofitting techniques; (iv) selection of the optimal retrofitting measure for the given building based on meaningful performance metrics; (v) design development of the retrofitting solution; (vi) use of classification schemes that facilitate the accessibility to potential financial incentives; (vii) final design of the retrofitting solution and construction; and (viii) management of the building's operational life. MCDM approaches for the selection of optimal retrofitting strategies can thus be easily integrated in step (iv).

In this paper, an updated version of the MCDM approach proposed recently by Caruso et al. (2023) is applied to a case-study building, retrofitted with four different types of integrated exoskeletons, made of timber, steel and concrete, which were conceived according to either LCT principles or traditional ones. The application showed that the introduction of sustainable decision criteria favours LCT-based retrofitting interventions over traditional ones, thus representing a valuable supporting tool for the sustainable renovation of buildings.

2. Multi-criteria decision-making (MCDM) approach

The MCDM approach originally proposed by Caruso et al. (2023) is based on four decision-making parameters, and on the use of the so-called radar plots to visually aid the process of identification of optimal retrofitting strategies in an integrated manner. This methodology was developed with a view to define meaningful economic, environmental, and social quantitative metrics to compare alternative retrofitting solutions for a given building, while accounting for both its seismic and energy performances. The four decision variables considered in the original version of the MCDM are the following:

- post-retrofit life cycle costs (C), accounting for the contributions of the retrofit (namely, installation, and end of life), expected seismic economic losses, and costs for energy consumption;
- post-retrofit life cycle carbon emissions (CE), expressed in terms of equivalent carbon dioxide emissions (kg eCO_2), accounting for the contributions of the retrofit (namely, installation, and end of life), expected seismic environmental losses, and impact due to energy consumption;
- payback period (PB) of the retrofit economic investment;
- average annual loss of life (AALL) due to seismic risk, expressed in terms of expected fatalities per year.

Life cycle costs (C) and carbon emissions (CE) are evaluated throughout the post-retrofit life of the building by summing up the economic and environmental contributions of the retrofitting intervention, earthquake-induced losses, and operational energy consumption, 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 monetary savings provided by the adopted retrofitting option. Finally, the average annual fatalities can be estimated through the preferred casualty model (e.g., ATC, 2018a, Coburn et al., 1992). The optimal retrofitting option can then be determined through the use of radar plots, where all the four variables are normalised by the as-built corresponding values (except for the PB that is normalised by the building's expected post-retrofit life). The solution that at the same time minimises all the four considered parameters is the one that corresponds to the smallest area in the radar charts. It is noted that, differently from other MCDM approaches proposed in literature, any weighting factor is on purpose assigned to the decision variables considered, assuming all the four parameters to be equally important.

This method, however, was conceived in such a way it would have been possible to include additional performance metrics of interest (Caruso et al., 2020, 2021, 2023). In this work, indeed, an updated version of this MCDM approach is proposed, by including three additional decision-making parameters:

- module D of life cycle assessment of retrofit components (D);
- payback period (PB-env) of the retrofit environmental burden;
- level of invasiveness of the retrofit measure (I).

Life cycle assessment (LCA) procedures (ISO 14040, ISO 14044, 2006) typically consider the environmental impact of several life cycle phases of a product (or a building) (UNI EN 15978, 2011): (i) production (modules A1-A3), including raw materials extraction, transportation to factory and manufacturing, (ii) construction (modules A4-A5), including transportation to the construction site and installation processes; (iii) use (modules B1-B7), including use, maintenance, repair, replacement, refurbishment, energy and water use; and (iv) end-of-life (modules C1-C4), including demolition, transportation to landfill, processing and disposal of waste materials. Module D, referred to as beyond-life phase, is used instead to measure the benefits that can be produced beyond the life boundaries of the product considered through the possible reuse, recycle and recovery of salvaged materials. In other words, the net impact of module D can thus be obtained as the difference between the impact of the reuse/recycle/recovery process and that of the primary production activity. Consequently, a saving of environmental impacts is achieved when module D is negative, on the contrary an additional burden is expected when it is positive. By including this parameter amongst the decision-making parameters, retrofitting measures that are designed with recyclable and/or reusable materials and components would be favoured.

The environmental payback period (PB-env), similarly to the economic one, quantifies the number of years needed to “pay back” the embodied carbon of the retrofit components’ production (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). PB-env can thus be calculated in a simplified manner, by dividing the cradle-to-gate embodied carbon of the retrofit by the yearly environmental savings. By also considering this parameter, retrofitting techniques with limited initial carbon footprint would be prioritized. For clearness, the economic payback will be referred from now on as PB-econ.

Lastly, the level of invasiveness of the retrofit is considered as well, in terms of not only limitation of the impact on the building, but also minimization of the disturbance to the building’s occupants. A simplified way is proposed here to quantify invasiveness, 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. Retrofitting configurations, where a new foundation system is needed, or where the occupants’ relocation during the retrofit installation or during potential post-retrofit repair activities is needed, are assigned the highest scores.

As done for the variables of the original version of the MCDM approach, to be included in radar charts, module D, PB-env and I need to be normalised as well. Module D can be normalised by calculating: 1 + (module D/|modules A1-A3|). If the result of the normalization is negative, it is considered equal to zero. In such a way, large negative D-values, indicating larger environmental savings, are prioritized, by leading to smaller areas in radar charts. It is noted that not all the negative D-values 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. Similarly to the PB-econ, the PB-env is normalised by the building’s expected post-retrofit life. Lastly, for what concerns the I-parameter, it can instead be divided by 10, in such a way it is in the range between 0 and 1.5.

It is thus seen that, in the proposed version of the MCDM approach, two economic (life cycle costs and PB-econ), three environmental (life cycle carbon emissions, module D, PB-env), and two social parameters (AALL, invasiveness) are considered, by including multiple facets of buildings’ sustainability.

3. Case-study building application

The case-study building is a three-storey reinforced concrete (RC) structure built in the 70s (Figure 1). It is located in the city of Brescia (Northern Italy), which is a region that is characterised by a medium to high level of seismic hazard and a mild climate. 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 features floor dimensions equal to 12.28 m × 8.12 m and inter-story height of 3.06 m at the ground floor and 3.15 m at the upper floors. The block B, which is located over a 1.05 m-high RC basement, is instead characterized by floor dimensions equal to 13.60 m × 9.80 m and inter-story height of 3.10 m at the ground floor and 3.95 m at the upper floors. The two building blocks have thus slabs at different heights.

The structure is composed of one-way RC frames designed for gravity loads only, with unidirectional mixed concrete and hollow clay block slabs and double-leaf masonry infills (with a 7-cm air cavity between two solid brick layers). A more detailed description of the building’s geometries and characteristics can be found in Passoni et al. (2022b) and Labò et al. (2022).

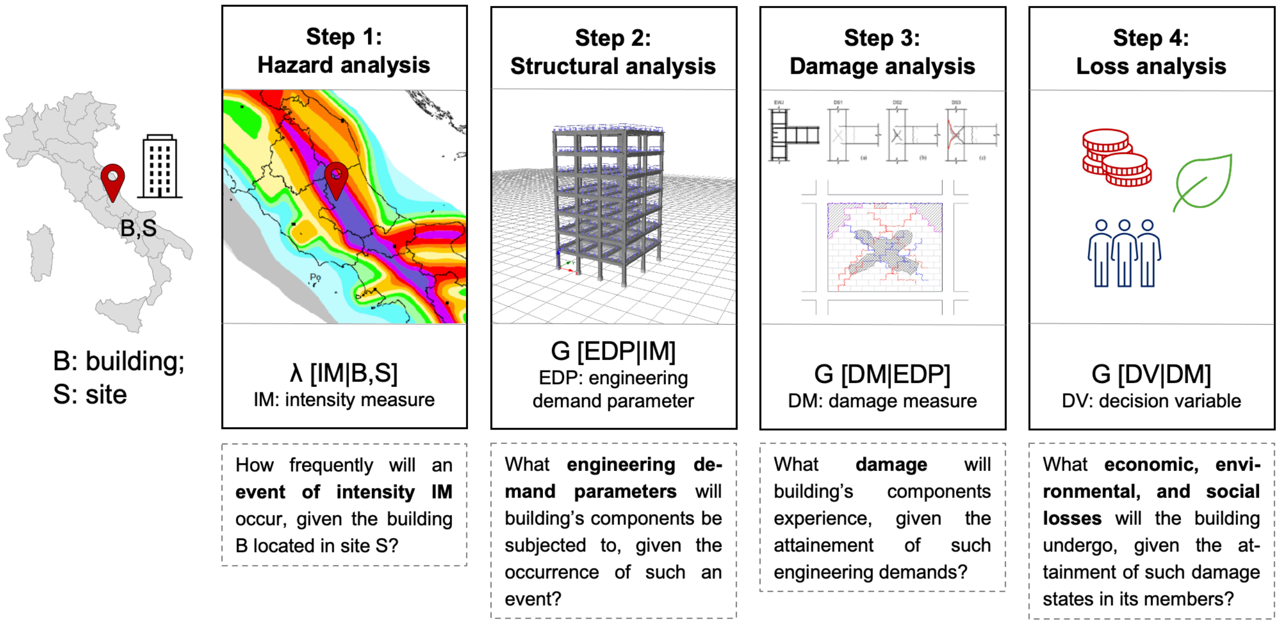
The following sections are dedicated to the description of the integrated assessment of both seismic and energy performances of the case-study building in its as-built configuration. The FEMA P-58 approach was adopted for the seismic loss assessment of the structure with the support of the PACT tool (ATC, 2018b), while for the energy performance assessment the Transient System Simulation Tool (TRNSYS) (2006) was employed.

Figure 1. Blocks A and B of the case-study building: pictures of two prospects (adapted from Passoni et al., 2022b).

3.1. As-built integrated assessment

Seismic loss estimation of the as-built configuration

The FEMA P-58 approach for seismic loss assessment of buildings is characterised by four main steps, according to the workflow shown in Figure 2: (i) seismic hazard quantification at the site, (ii) structural performance analysis under seismic loads, (iii) estimation of damage level in building's vulnerable components, and (iv) calculation of losses due to repair of damaged components or to building's collapse. The results are expressed in terms of annual loss exceeding curves, showing the annual probability of exceeding different values of a decision variable (DV), those being, for example, expected repair cost, repair time, repair environmental impacts and casualties.



How frequently will an **event of intensity IM** occur, given the building B located in site S?

What **engineering demand parameters** will building's components be subjected to, given the occurrence of such an event?

What **damage** will building's components experience, given the attainement of such engineering demands?

What **economic, environmental, and social losses** will the building undergo, given the attainment of such damage states in its members?

Figure 2. FEMA P-58 seismic loss assessment of buildings (ATC, 2018a, 2018b): (i) hazard analysis, (ii) structural analysis, (iii) damage analysis, and (iv) loss estimation (adapted from Passoni et al. (2022a)).

According to the Italian building code classification (MIT, 2018), the hazard curve for the city of Brescia (Northern Italy) was obtained in terms of spectral acceleration at a conditioning period T*, corresponding to four different seismic intensity levels with return periods of 30, 50, 475, and 2475-year, respectively. The conditioning period was taken, as suggested in ATC (2018a), as the arithmetic mean of the building's periods of vibration in the two horizontal directions, and it is equal to 0.49 s.

A numerical 3D model of the case-study building at hand (Figure 3) was created with the support of the Midas Gen software (1989) to carry out the structural analysis of the building under seismic loads employing nonlinear static analyses. Beam elements with lumped plastic hinges were used to model structural members, while compression-only struts converging into structural nodes were employed to model external infills. Floors were assumed as rigid diaphragms. A more detailed description of the structural modelling assumptions and of the structural analyses of the case-study building can be found in Labò et al. (2022). From the nonlinear static analyses, the engineering demand parameters (EDPs) of interest were extracted in terms of inter-storey drift ratios (IDRs) for each considered seismic intensity level, floor, and direction of the building. The vulnerability modellers toolkit (VMTK) (Martins et al., 2021) was then employed to get, from the capacity curves, the collapse fragility function of the building, relating the probability of incurring in structural collapse to ground motion intensity.

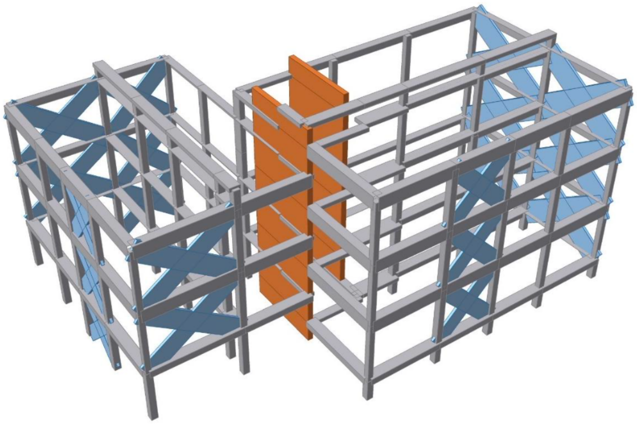


Figure 3. 3D numerical model of the case-study building created with the support of the Midas Gen software.

One fundamental step of the seismic loss assessment procedure is the creation of an inventory of structural and non-structural components, which are expected to experience damage during seismic events. Each of these components features a component-based fragility function and a set of consequence functions. The fragility functions indicate the conditional probability of reaching a damage state (DS) given a certain value of seismic demand, expressed in terms of an EDP, e.g. inter-storey drift ratio, peak floor acceleration or velocity. Consequence functions are instead used to translate each damage state into potential repair or replacement costs, repair time, casualties, or environmental impacts. The components included in the inventory of the case-study building are: RC external beam-column joints (EWJs), RC internal beam-column joints (IWCs), exterior masonry infills with and without windows (EIWws, and EIWs, respectively), interior masonry partitions with and without doors (IPds, and IPs, respectively), windows and doors, referred to as partition-like components (PLs; i.e. non-structural components whose damage and repair are assumed to be related to the DSs of the infills or partitions in which they are inserted), and RC shear walls.

Fragility and repair cost functions for RC structural components and masonry non-structural elements developed by Cardone (2016) and Cardone and Perrone (2015), respectively, were employed herein, since they are representative of Italian and European RC frame buildings built before 1970. The consequence functions in terms of equivalent carbon dioxide for those components were instead taken from Caruso et al. (2023). On the other side, the fragility and consequence functions for the RC shear walls were taken directly from the PACT library.

In addition to the consequence functions of damageable components, estimates of the cost and environmental impact of building's replacement (demolition + reconstruction) are necessary, to include the potential contribution of building collapse in the estimation of average losses due to earthquakes. The replacement cost of the building, referred to as ReC, was estimated equal to €1.4 million, by considering a reconstruction cost of 1,350 €/m^2, as suggested in the Italian National Risk Assessment (DPC, 2018), and an additional cost of 44 €/m^3 for demolition and disposal, as indicated in Cardone et al. (2017). A total loss threshold value equal to 0.6 was assumed as the percentage of the reconstruction cost for which demolition would be preferable to repair. On the other side, the US EIO-LCA web-tool (CMUGDI, 2008) was used to estimate the replacement environmental impact of the building, expressed in terms of equivalent carbon dioxide (eCO_2), translating sector-specific costs into cradle-to-gate environmental impacts. The equivalent carbon emissions associated to demolition and reconstruction were thus estimated to be approximately equal to 561,700 kg eCO_2.

Finally, it was possible to estimate the average annual losses expected in the building, in economic, environmental, and social terms. An economic average annual loss (AAL) ratio equal to 0.26% was obtained as the fraction between the area underneath the monetary exceedance loss curve (approximately equal to 3,640 €) and the total replacement cost (approximately equal to € 1.4 million). The environmental loss analysis resulted instead in an average annual emission (AAE) ratio equal to 0.27%, as the fraction between the area underneath the environmental exceedance loss curve (approximately equal to 1,515 kg eCO_2) and the total replacement environmental impact (equal to 561,700 kg eCO_2). Finally, 0.0034 fatalities per year resulted as the average annual loss of life (AALL).

Energy performance assessment of the as-built configuration

The architectural drawings and the in-situ inspections were used as a basis to build the energy performance model of the case-study building in the TRNSYS tool. The structure was found to lack of a thermal insulation layer and to feature poor opaque and transparent envelope's components, as well as obsolete mechanical equipment. The total annual energy consumption for heating and cooling was thus estimated equal to 84,000 kWh and 4,100 kWh, respectively (Labò et al., 2022). Assuming a cost for methane equal to 0.80€ per standard cubic meter (equal to 10.69 kWh) and 0.19 kg eCO_2 emitted per 1 kWh, the annual cost for energy consumption resulted as equal to around 6,600€, and the annual carbon emissions for energy consumption were estimated as equal to around 16,700 kg eCO_2. It is noted that the annual cost of energy is almost double the corresponding seismic economic losses, and that the annual environmental impact due to energy consumption is almost one order of magnitude higher than that due to seismic risk.

3.2. Integrated retrofitting solutions

Four alternative structural retrofitting solutions, achieving the same structural performance (i.e. being iso-performance targeted), were designed for the case-study building, namely four different exoskeleton systems (Figure 4). Each of those solutions was coupled with the introduction of an additional thermal insulation layer and of a new architectural finishing to improve the energy performance as well as the architectural appearance of the building at hand. For such a reason, the structural performances of the four retrofitted configurations differ, while they have the same upgraded energy performance.

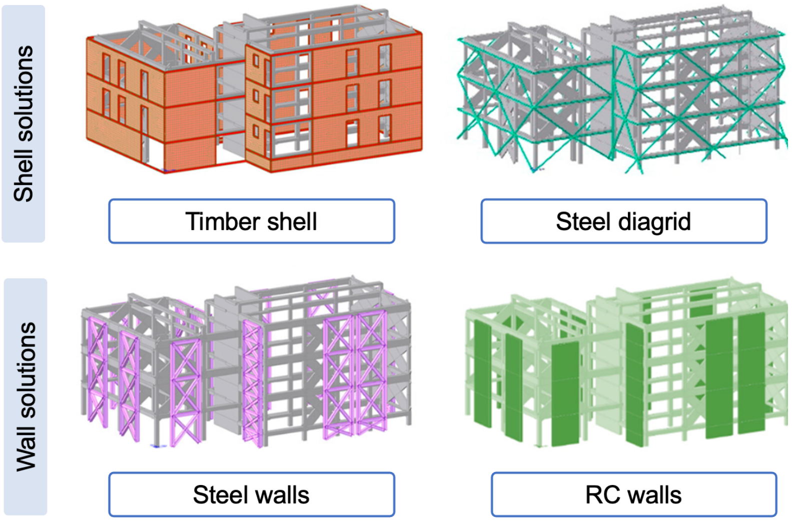


Figure 4. Four alternative iso-performance structural solutions: shell and wall exoskeletons.

The exoskeleton systems considered herein include both shell and wall exoskeletons. Solutions 1 and 2 are examples of shell exoskeletons, and are made of cross-laminated timber (CLT) panels and a diagrid frame of tubular steel profiles, respectively. On the opposite, the two wall exoskeletons include one with steel walls (solution 3) and another one with RC walls (solution 4). All these systems are connected to the building's floors through continuous steel chords and ad-hoc connections all along the perimeter to efficiently transfer seismic loads from the existing structural members to the new ones. Solutions 1 to 3 were designed according to LCT principles, while solution 4 was conceived according to traditional design rules (Passoni et al., 2022b).

Solution 1 is a timber shell exoskeleton made of renewable biomaterials that can be recycled and/or reused at the building's end of life. This kind of system features dry assembly processes, modular elements and standardised connections, as well as sacrificial elements in which seismic damage is expected to be concentrated. Additional insights on the design of such kind of innovative exoskeleton structures can be found in Zanni et al. (2021). Solution 2 is a shell exoskeleton, composed of a diagrid structure of tubular profiles spanning between floors, while solution 3 is made of steel walls with HEA commercial profiles. Steel is typically recycled and recyclable at its end of life. At the same time, steel components can be assembled though dry techniques, and are easy to repair and demount. Lastly, solution 4 is the typical RC cast-in-place wall solution. The installation activity, which is not dry in this case, may render the end of life of such an exoskeleton much more impactful, if compared to the others, also given that a share of the demolition waste will surely be transported to landfill. In addition, this kind of structure does not allow for the concentration of seismic damage, which instead is expected to be spread across the walls, especially at their base. RC walls are known to significantly improve the seismic performance of retrofitted buildings during seismic events, however in case of unrepairability they would need to be fully replaced.

Seismic loss estimation of the retrofitted configurations

The seismic loss assessment of all retrofitted configurations was carried out through the FEMA P-58 procedure and with the support of the PACT Tool (ATC 2018a, 2018b), following the same steps indicated for the as-built structure in the previous section. To the purpose, some additional considerations and modifications were introduced to the as-built inventory of damageable components to include the components of the retrofit as well. Indeed, the fragility and consequence functions for CLT panels, steel diagrid, steel and RC shear walls were selected amongst the available ones in the PACT library and included in each of the new corresponding inventories. Lastly, the cost and carbon emission for the replacement of the as-built structure were increased of a 10%-value to get the corresponding estimates for the retrofitted configurations, leading to approximately €1.5 million and 620,000 kg eCO_2, respectively. Table 1 reports the results of the seismic loss assessment of each retrofitted configuration compared to those of the as-built one, in terms of average annual economic loss (AAL) and carbon emissions (AAE) ratios, and average annual loss of life (AALL). All the retrofitting solutions adopted herein proved to provide a significant reduction of earthquake-induced economic, environmental, and social consequences. Among the four options explored, the one providing the highest benefits, in terms of all the three earthquake-related parameters, is the timber shell solution, while the least effective strategy amongst the four options appears to be the steel diagrid one (even if of the same order of magnitude of the steel wall solution). RC walls resulted to be very effective as well, even if not at the same level of the timber shell solution.

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

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

It is recalled that the four retrofitting solutions were designed to be iso-performance, thus one could argue that very similar loss estimates, if not the same ones, would have been expected for all four scenarios. The current unavailability of specific fragility and consequence functions for such type of components, which are amongst the objectives of future developments of this work, made it necessary to use those of similar components from the PACT library. Those components, mostly representative of North American construction practices, do not account for the concentration of damage in the connections between the exoskeleton and the existing structure, which is instead one of the major advantages of the solutions presented herein, though considering the complete damage of the component itself.

Energy performance assessment of the retrofitted configurations

The energy efficiency upgrade considered for all the exoskeleton types herein consists in the introduction of an additional thermal insulation layer. The new envelope configuration was assembled in the TRNSYS energy performance model as well. Thanks to the energy upgrade, the total annual energy consumption for heating and cooling of the upgraded structure was estimated as 38,169 kWh and 3,930 kWh, respectively (Labò et al., 2022). The annual cost and carbon emissions for energy consumption resulted as equal to around 3,150€ and 8,000 kg eCO_2, respectively, which correspond to around a half-reduction of the as-built estimates.

3.3. Selection of the optimal integrated retrofitting technique

The two versions of the multi-criteria decision-making approach described in Section 2 were finally employed to identify the optimal retrofitting strategy for the given building. The original version of the MCDM approach (Caruso et al., 2023) considering four decision variables will be referred from now on as 'original version', while the updated one proposed herein as 'updated version'. The objective of this comparative application is the investigation of the influence on the outcomes of the introduction of additional sustainable decision criteria.

Figure 5 illustrates the radar plots resulting from the application of the original version of the MCDM. The optimal solution, which corresponds to the smallest resulting area and thus minimises at the same time all the four variables considered, is the timber shell solution. The final resulting ranking is thus: timber shell, RC walls, steel diagrid, and steel walls. As expected, RC walls are overall very efficient, coherently with the observations derived from the seismic loss analysis, and for that reason solution 4 lays in a higher-ranking position if compared to the other two steel solutions, which were instead conceived according to LCT principles.

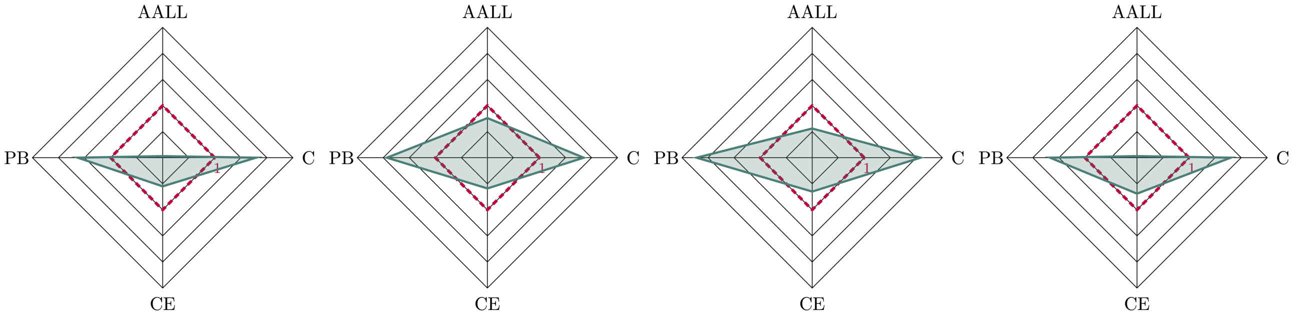


Figure 5. Radar plots of the four retrofitted configurations (from left to right, timber shell, steel diagrid, steel walls, RC walls): normalised post-retrofit costs (C), carbon emissions (CE), payback period (PB), and average annual loss of life (AALL).

With reference to the updated version of the MCDM, the other variables were calculated as follows for each retrofitted configuration. Module D of each solution, expressed in terms of GWP, was taken from Passoni et al. (2022b). The environmental payback period (PB-env), as stated above, was calculated as the ratio between the cradle-to-gate embodied carbon of the retrofit (i.e. module A) and the annual environmental savings produced by the retrofitting solution adopted (in terms of reduced energy and earthquake-induced environmental impacts). Lastly, the level of invasiveness (I) was calculated as the sum of the values assigned from 0 to 5 to three different criteria. Concerning the foundations, a value of 2 was assigned to both timber shell and steel diagrid solutions, while 5 was assigned to steel walls and RC walls, instead. Regarding the invasiveness of the retrofit installation, given that all four solutions are designed to be applied from the outside of the building, and to avoid occupants' relocation, a 0-value can be assigned equivalently. In case of repair activities needed after a strong seismic event, the steel diagrid, which is constructed as the most external envelope layer of the retrofitted building (with the thermal insulation layer being interposed between the existing envelope and the diagrid system), is expected to be the solution with the most limited invasiveness, in terms of both need of finishing activities and occupants' disturbance. For this reason, a score of 0 is assigned to this criterion for the steel diagrid solution. On the opposite, the other three solutions, though all repairable from the outside, would in any case require the removal of exterior finishing and insulation layers for repairing the structural retrofit components.

Figure 6 shows the radar plots resulting from the application of the updated version of the MCDM. The optimal solution is still the timber shell solution. However, the final resulting ranking is: timber shell, steel diagrid, RC walls, and steel walls. An interesting inversion of ranking positions was thus observed between steel diagrid and RC walls, highlighting the potentials of including LCT-compliant and sustainable parameters amongst the decision-making variables in favouring LCT-based retrofitting solutions, as the steel diagrid in this case.

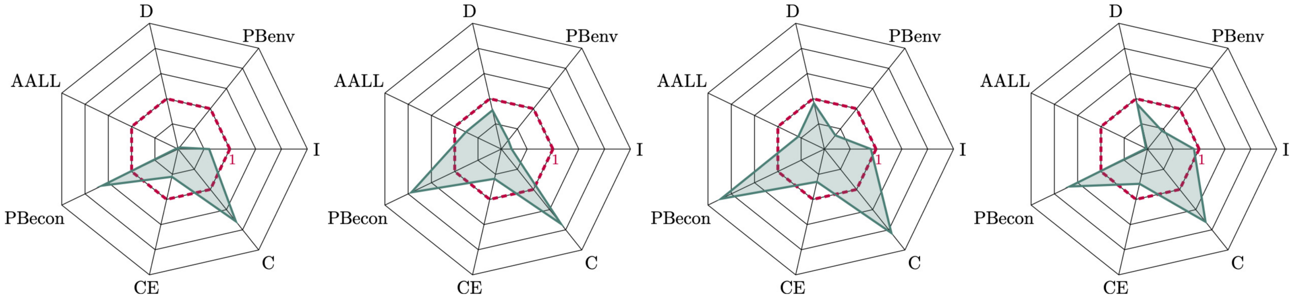


Figure 6. Radar plots of four retrofitted configurations (from left to right, timber shell, steel diagrid, steel walls, RC walls): normalised post-retrofit costs (C), carbon emissions (CE), economic payback period (PB-econ), average annual loss of life (AALL), module D (D), environmental payback period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

4. Conclusions

Multi-criteria decision-making procedures do typically include economic, social, environmental, and technical decision criteria that are considered of interest to decision makers (e.g., retrofit installation costs, invasiveness, operational energy consumption, etc.). In this work, an updated version of the MCDM approach proposed in Caruso et al. (2023) is discussed throughout its application to a case-study residential building located in Northern Italy. Four different integrated exoskeletons, made of timber, steel and concrete, were designed as retrofitting options for the building at hand. Solutions 1 and 2 are shell exoskeletons, and are made of cross-laminated timber panels and a diagrid frame of tubular steel profiles, respectively. Solutions 3 and 4 are instead wall exoskeletons, made of steel walls and RC walls, respectively. Solutions 1 to 3 were designed according to LCT principles, while solution 4 was conceived according to traditional design rules.

The results of the original and updated versions of the MCDM above demonstrated that the introduction of some additional LCT-compliant criteria in the decision-making procedure does effectively favour LCT-based retrofitting interventions over traditional ones. This was proved by the inversion of ranking positions between the steel diagrid and RC walls, in favour of the steel diagrid solution, which is in general more sustainable than RC walls.

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