



An updated multi-criteria decision-making method for the sustainable renovation of buildings including environmental, economic and social life-cycle metrics

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ABSTRACT

The ambitious targets of carbon emission reduction set worldwide for the coming years entail the commitment of structural engineers towards the sustainable renovation of existing buildings. The life cycle thinking (LCT) approach offers a holistic perspective for the design of sustainable retrofitting strategies. It envisages the reduction of the environmental impact at all building life cycle phases, while also addressing economic and social issues. Multi-criteria decision-making (MCDM) approaches support the choice of optimal retrofitting solutions, thus being relevant tools for boosting the actual adoption of LCT in current practices. In this study, a previously proposed MCDM approach is enriched with additional LCT-inspired decision parameters (module D beyond-life impacts, environmental payback period, invasiveness), and is then scrutinised and discussed through its application to a case-study building. Four integrated retrofitting scenarios are investigated using state-of-art seismic loss and energy performance assessment methods, including four different types of exoskeletons, made of timber, steel, and concrete. The end-to-end integrated assessment shows that the inclusion of additional LCT-inspired decision criteria effectively favours LCT-based retrofitting interventions over more traditional ones.

1. Introduction

Structural engineers are expected to play a pivotal role in the transition towards a greener built environment. This will happen only if they entirely switch to a life cycle thinking (LCT) perspective [1]. Such a holistic approach for designing sustainable retrofitting measures envisages a gamut of building performance objectives and design principles [2], which address multifaceted building deficiencies in an integrated manner. Those targets can be attained only by conceiving new retrofitting techniques or reengineering the existing ones. Moreover, they should be set already during the preliminary design phase. To the purpose, a pre-screening process of available retrofitting techniques would avoid choosing unsustainable solutions right from the early stages of design. Embracing the LCT approach would allow an effective minimisation of environmental, economic, and social impacts at all building life cycle phases.

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Existing buildings are extremely vulnerable to seismic events, as well as to other natural hazards, including those directly correlated to climate change (e.g., floods, heat waves). Their poor structural behaviour is typically related to insufficient structural detailing and quality of materials, susceptibility to unfavourable failure mechanisms, e.g., soft storey, and lack of preparedness [3–6]. At the same time, the inadequate performance of the building's opaque and transparent envelope components, as well as the presence of obsolete mechanical equipment, make the existing building stock one of the largest contributors to energy resources consumption [3–6]. These structural and energy deficiencies translate into large environmental impacts throughout the operational life of such buildings. Those impacts are not only in terms of fossil fuels consumption, use of energy and material resources, but also include the potential need of repair, retrofitting and reconstruction activities after severe hazardous events like earthquakes. Simultaneously, such building deficiencies also have relevant economic and social consequences, including, e.g., expensive energy bills for heating and/or cooling, poor indoor air quality, potential fatalities and injuries during earthquakes [2], amongst others. For these reasons, building retrofitting interventions should be simultaneously aimed at (i) minimising building vulnerability against earthquakes and other natural hazards, including climate change-related ones, (ii) reducing the operational energy needs, as well as (iii) using low-impact construction materials for retrofitting.

Selection and design of such triple-objective retrofitting strategies, aimed at reducing the impacts of buildings all along their life cycle, require the support of multi-criteria decision-making (MCDM) approaches. Such tools, accounting for all the sustainability multiple facets (environmental, economic, social), represent relevant means for fostering the actual adoption of LCT principles in current practices.

In this context, the research community has made several scientific contributions in the field of environmental impact assessment, design of integrated seismic/energy retrofitting solutions and MCDM methods. Earthquake-induced damage and repair activities are now recognised as having a large impact in life cycle evaluations, especially in geographic locations with high seismic risk (e.g. Refs. [7–16]). The potential need for demolition and reconstruction is a significant contributor as well, as demonstrated, for instance, by the carbon cost of concrete buildings demolition and life-for-like replacement after the 2010–2011 Canterbury earthquake sequence [17].

At the same time, the importance of simultaneously addressing multiple building deficiencies (e.g., structural, energy, architectural, etc.), while also accounting for LCT principles, encouraged the development and application of integrated retrofitting techniques (e.g. Refs. [18–23]). Comprehensive reviews of available integrated techniques can be found in Refs. [24–26]. A specific focus on LCT-inspired retrofitting techniques is discussed in Ref. [27].

Lastly, environmental, economic, and social decision criteria have been explored as potential supports to MCDM procedures (e.g. Refs. [28–30]), focusing on those that are considered the most of interest to decision makers (e.g., retrofit costs, construction time, invasiveness, operational energy consumption, etc.). Comparative assessments of alternative MCDM procedures have also been recently carried out by Refs. [31,32]. Namely, in such latest research work, the influence of the considered decision-making parameters and assigned weights, the procedures to rank retrofitting options and to identify optimal retrofitting strategies are extensively discussed. Notably, some researchers proposed sustainability-oriented decision-making approaches applicable at a building portfolio level ([33,34]).

Recently, Passoni et al. [2,35] also introduced a more comprehensive perspective, referred to as Life Cycle Structural Engineering (LCSE) (Fig. 1), where the use of LCT principles is envisioned from the early design steps. A pre-screening phase of candidate retrofits (step 2) is envisaged before the preliminary design, based on the compliance with qualitative LCT criteria. Specific restrictions or decision-maker/owner requirements (e.g., economic budget, duration of works, etc.) should also drive such a preliminary screening of candidates. Following the preliminary design, the final choice of the optimal strategies (step 4) can be carried out based on quantitative decision-making (environmental, economic, social) parameters via MCDM approaches. Integrated classification and rating systems (step 6) should be standardised to have access to dedicated incentives, premiums and certificates. Sustainability and LCT-oriented tools are thus necessary within those steps to ensure the adoption of LCT-compliant retrofits allowing for an effective minimisation of impacts at all building life cycle phases.

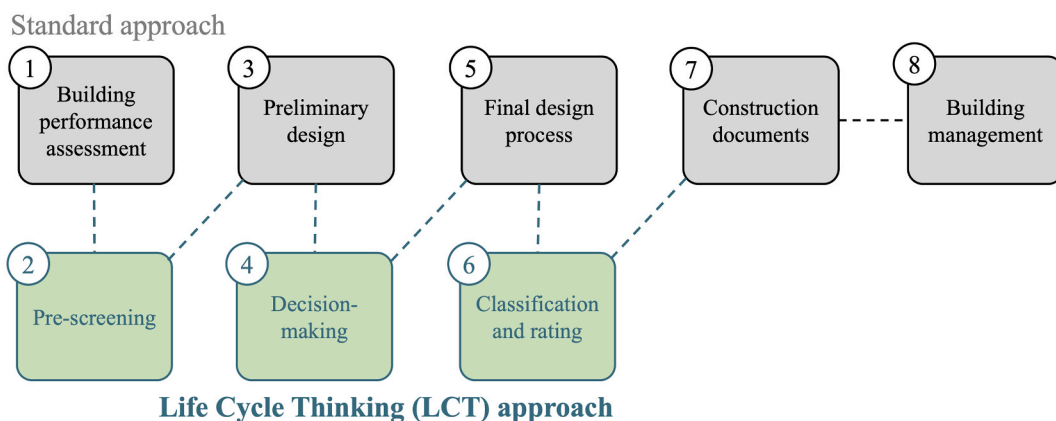


Fig. 1. Life Cycle Structural Engineering (LCSE) design process, including sustainability and LCT-oriented tools, as opposed to the standard design approach.

In this work, an updated version of the MCDM approach proposed in Ref. [28] is discussed throughout its application to a case-study building located in Northern Italy. Four different types of integrated exoskeletons, made of timber, steel and concrete, are investigated, some of which designed following an LCT-based conceptualisation, some others according to more traditional engineering practices. The case-study building, discussed in Ref. [1] for the environmental impact assessment of the four retrofits only, is analysed here using state-of-art seismic loss assessment methods. A fully integrated assessment of the as-built and retrofitted configurations is in turn carried out. The four retrofitting alternatives are compared using the original and updated versions of the MCDM approach. The main novelty of the proposed version lies in the adoption of additional LCT-inspired decision-making criteria (i.e., module D beyond-life impacts, environmental payback period, invasiveness). This makes it a suitable candidate tool for LCSE decision-making step 4 (Fig. 1). The introduction of sustainable criteria in the decision process proves indeed to favour and prioritise LCT-based retrofitting interventions over traditional ones, thus representing a valuable supporting tool for the sustainable renovation of buildings.

2. Decision-making supporting tool

As mentioned above, existing tools for the selection of optimal retrofitting strategies, including the MCDM approach proposed by Ref. [28], can be integrated in step 4 of the LCT-based framework proposed by Refs. [2,35] (Fig. 1). Four decision-making parameters were considered as a first attempt in Ref. [28], and radar plots were proposed as a powerful tool to select the best retrofitting option. The decision variables considered in such a first version are the following:

- post-retrofit life cycle costs (C), summing up the costs of the retrofit materials and installation, seismic economic losses, and costs for energy consumption, all normalised by the building's floor area and the post-retrofit service life;
- post-retrofit life cycle carbon emissions (CE), expressed in terms of equivalent carbon dioxide emissions (CO_{2e}), accounting for the contribution of retrofit components, earthquake-induced damage and repair, and energy consumption, all normalised by the building's floor area and the post-retrofit service life;
- payback period (PB) of the retrofit's economic investment;
- average annual loss of life (AALL), or fatalities, due to potential earthquakes.

Life cycle costs and carbon emissions are defined based on existing life cycle assessment and life cycle costing analysis procedures. The optimal retrofitting solution for a given building is determined as the one minimising all four considered variables at the same time. This results in the smallest ensuing area in the radar plots, as shown in an illustrative example in Fig. 2. It is noted that, for a suitable representation of radar charts, the payback period is normalised by the building's service life after retrofitting, while the other parameters are normalised by the as-built counterparts.

This method was initially developed with the prior objective of defining environmental, economic, and social quantitative performance metrics to compare alternative retrofitting solutions, accounting for both its seismic and energy performance assessments ([28,36,37]). Nonetheless, the approach was conceived in such a way that it would have been possible to include any additional performance metric of interest. In this work, an updated version of this MCDM approach is indeed proposed, 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 [38]: (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, instead, the benefits of the possible reuse, recycle and

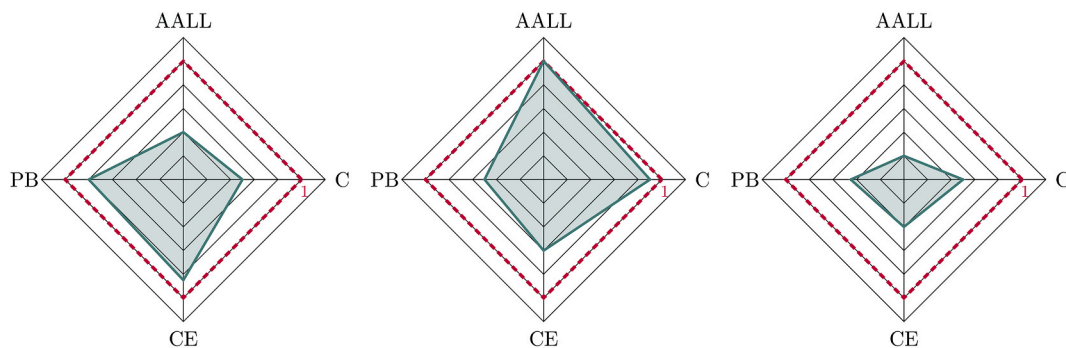


Fig. 2. Radar plots of three hypothetical retrofitting options, i.e., seismic strengthening (left), energy efficiency upgrade (centre), integrated solution (right): normalised post-retrofit costs (C), post-retrofit carbon emissions (CE), payback period (PB), and average loss of life (AALL).

recovery of salvaged materials after the end of life of the product considered. It can indeed be interpreted as the difference between the impact of the recycling/reuse/recovery processes and that of the primary production. For this reason, a negative value of module D corresponds to a saving in terms of environmental impacts, while a positive value indicates an additional burden. Module D represents potential future scenarios that extend beyond the current life cycle and, therefore, its impacts should be reported separately from those of other modules.

Operational impacts quantify the greenhouse gas (GHG) emissions and removals due to building operational energy and water use (modules B6-B7). The impacts associated to all remaining modules are typically referred to as embodied. Retrofit measures, as well as seismic damage and repair activities, can be seen as additional sources of embodied impact during a building use phase. However, it is necessary to distinguish between the embodied impact of the repair or retrofit components (e.g., modules A1-A3, C1-C4), which should be added to the building use embodied impact (i.e., in modules B3-B5), and the operational impact (module B6) of the building that is affected by the retrofit type (if it includes energy efficiency upgrades). In this study, equivalent carbon dioxide is used as an environmental impact metric, hereinafter referred to as simply 'carbon'. Both the embodied carbon of retrofits and seismic repair activities and the operational carbon due to the building energy use are considered in the life cycle parameter CE. The same contributions are considered in economic terms in the life cycle costs C.

Module D beyond-life carbon is included among the decision-making parameters to favour retrofitting techniques that are designed with recyclable and/or reusable materials and components to minimise the use of new raw materials and the impact of manufacturing processes. To be included in the radar plots (shown in Section 3.3), the value of module D can be normalised by calculating: $1 + (\text{module D}/|\text{modules A1-A3}|)$, 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 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) is defined similarly to the economic one, but in terms of environmental impact. It quantifies the number of years that allow to pay back the cradle-to-gate embodied carbon of the retrofit components (i.e., modules A1-A3) through the environmental savings generated year by year after retrofitting (e.g., the reduction of the energy consumption environmental impact achieved through an energy efficiency upgrade intervention). It is thus calculated by dividing the initial embodied carbon of the retrofit by such yearly environmental savings. This parameter is considered as relevant to prioritise retrofitting techniques with limited initial carbon footprint (typically the largest contributor to whole life cycle embodied carbon). 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 installation is considered as well, to account for the limitation not only of the impact of the retrofit itself on the building, but also of the disturbance to building's occupants. Quantifying numerically invasiveness is clearly not straightforward, given its inherently subjective nature. However, an attempt at doing so is nonetheless made here, by assigning values from 0 to 5 to three different criteria: (i) the need to build new foundations, (ii) the invasiveness of the retrofit installation, and (iii) the



Fig. 3. Blocks A and B elevation and plan (top), and prospects (bottom) (adapted from Ref. [1]).

invasiveness of the potential repair activities on retrofit components in case of a damaging seismic event. Criteria (ii) and (iii) could, at a first sight, appear as correlated. However, the former refers to the retrofit installation activities only, while the latter addresses instead the maintenance of the retrofit components during their service life, and their eventual need of being repaired or replaced in case of a damaging 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. A maximum value of 15 is attained for the most invasive retrofitting configurations. Such scores are assumed to be assigned by the building engineer, and not by the decision-maker/owner. This is because ideally specific requirements and needs of the decision-maker/owner are to be accounted for in the previous pre-screening phase (LCSE step 2 in Fig. 1). Finally, and in order to facilitate the introduction and consideration of invasiveness in the normalised radar plots presented in Section 3.3, the parameter I 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

3.1. Building's description

The case-study building at hand is a three-storey reinforced concrete (RC) structure, built in the 70s and located in the city of Brescia (Northern Italy). The region features a medium to high level of seismic hazard (with soil type C and topographic class T1, according to the Italian building code classification [39]) and a mild climate. The building plan is L-shaped and is made of two rectangular units, referred to as 'block A' and 'block B', respectively. The blocks are connected in correspondence to the stairwell, for a total area of approximately 230 m² per floor (Fig. 3).

Block A is characterised by a 12.28 × 8.12 m² floor area and inter-story heights of approximately 3 m. Block B, which is instead located over a 1.05 m-high RC basement, has a 13.60 × 9.80 m² floor area and inter-story heights ranging between 3 and 4 m. Thus, the two blocks have slabs at different heights. The structures are composed of one-way RC frames designed for gravity loads only, with floors made of unidirectional concrete/hollow clay blocks slabs and external infills characterised by double clay brick layers with a 7-cm air cavity. Further details on the building's geometries and characteristics are discussed in Refs. [1,40]. The end-to-end integrated seismic/energy assessment of the case-study building is described in the following sections. Namely, the FEMA P-58 assessment procedure was used to quantify the expected seismic losses with the support of the PACT tool [41–43]. The energy performance assessment leveraged upon the work already described in Ref. [40], using the Transient System Simulation tool (TRNSYS) [44].

3.1.1. Seismic loss estimation of the as-built configuration

It is recalled that the FEMA P-58 approach for seismic loss assessment is characterised by four relevant steps, according to the workflow shown in Fig. 4: (1) definition of the seismic input at the site of interest, (2) structural analysis of the building's response under seismic loads, through engineering demand parameters (EDPs) and collapse mechanisms, (3) quantification of damage in all building's vulnerable components, and (4) calculation 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 dedicated consequence functions.

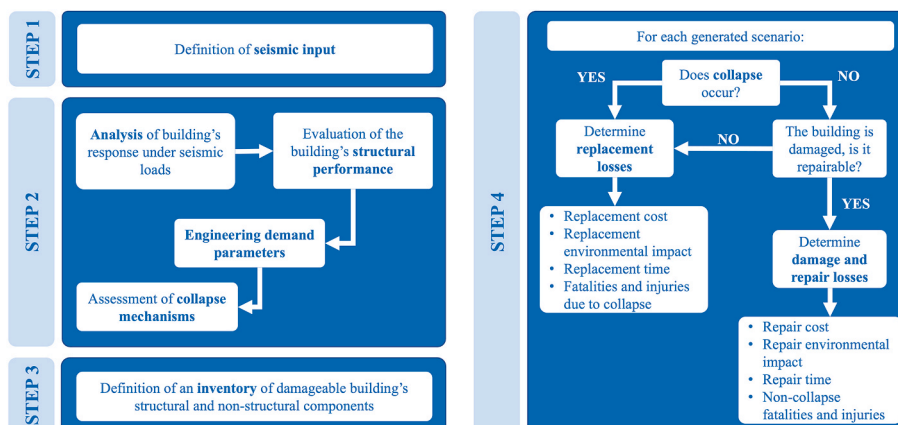


Fig. 4. FEMA P-58 workflow for seismic loss assessment.

As previously mentioned, the building is located in the city of Brescia (Northern Italy). Based on the Italian building code classification [39], 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 (30, 50, 475, and 2475-year return periods). The conditioning period was assumed as equal as the arithmetic mean of the building's vibration periods in the two horizontal directions [41,42], that is 0.49 s.

For the seismic performance analysis of the building, a numerical 3D model was developed with the support of the Midas Gen software [45]. Nonlinear static analyses were carried out according to the Italian building code requirements [39]. Blocks A and B, considering the different floor heights, were assumed as having an independent seismic response, thus modelled separately. Structural members were modelled using beam elements with end plastic hinges. Infills were considered through the use of compression-only struts converging into structural nodes. Floors were assumed as rigid diaphragms. Further information on the structural modelling and analysis of the case-study building can be found in Ref. [40]. From the structural analysis, the EDPs of interest were extracted in terms of interstorey drift ratios (IDRs) for each seismic intensity level, floor, and direction (Fig. 5). Large drifts were observed at the ground floor in the X direction, and at first and second floors in the Y direction.

Based on the capacity curves obtained, the vulnerability modellers toolkit (VMTK) [46] was employed to derive the collapse fragility function of the building, relating the probability of structural collapse to seismic intensity. The VMTK is an open-source platform for the derivation of analytical fragility and vulnerability models. The collapse fragility function and the possible incurring structural collapse modes at different floors (e.g., single-storey or multi-storey collapse, partial floor collapse, etc.) are necessary inputs to assess the average annual loss of life as well. At the same time, the population model according to the building occupancy (i. e., the number of occupants that are expected to be in the building at different times) is also relevant. Based on the randomly generated time of earthquake occurrence, for each PACT simulation, the number of people either dead or injured due to the collapse of the building or to parts of it can be estimated.

The inventory of structural and non-structural components of the case-study building (shown in Fig. 6), which may experience damage during seismic events, was then compiled. Each component was assigned a set of fragility functions indicating the conditional probability of achieving discrete damage states (DSs) given certain values of EDP (i.e., interstorey drift ratio). Also, sets of consequence functions are needed to translate each damage state into potential repair or replacement costs, repair time, fatalities, or environmental impacts. The PACT library contains a wide range of fragility and consequence functions, which are however mostly applicable to North American building components. Fragility and repair cost functions for RC structural components and masonry non-structural elements, developed by Refs. [47,48] specifically for Italian and European RC frame buildings built before the 70s, were thus used. The components considered include 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), and 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). The consequence functions in terms of equivalent carbon dioxide for these components were instead taken from Ref. [28]. Lastly, the fragility and consequence functions for the slender RC shear walls were taken from the PACT library, in the absence of more specific references for Italy. Further information on the component that was adopted for walls can be found in Appendix A (Table A. 3).

It is noted that this inventory of structural and non-structural elements includes drift-sensitive components only. This is due to two main reasons: (i) the lack of proper acceleration-based fragility functions specific for Italian building components, to the best of authors' knowledge; (ii) the extraction of EPDs from nonlinear static analyses, instead of nonlinear dynamic ones.

As rendered clear in the workflow in Fig. 4 as well, the cost and environmental impact of building replacement (intended as demolition plus reconstruction) are required to consider possible reconstruction scenarios. A reconstruction cost of 1350 €/m² was used [49], and an additional cost of 44 €/m³ for demolition and disposal was herein assumed [50], leading to an overall replacement cost of the building, referred to as ReC, of €1.4 million. The demolition-triggering loss ratio threshold was set equal to 0.6 [50]. The building replacement carbon was instead evaluated through the support of the US EIO-LCA web-tool [51,52], which translates sector-specific costs into cradle-to-gate environmental impacts, leading to around 561,700 kg CO_{2e}.

An average annual loss ratio (AALR) equal to 0.26 % was obtained as the fraction between the area underneath the economic loss exceedance curve (approximately equal to 3641 €) and the total replacement cost (approximately equal to € 1.4 million). An average

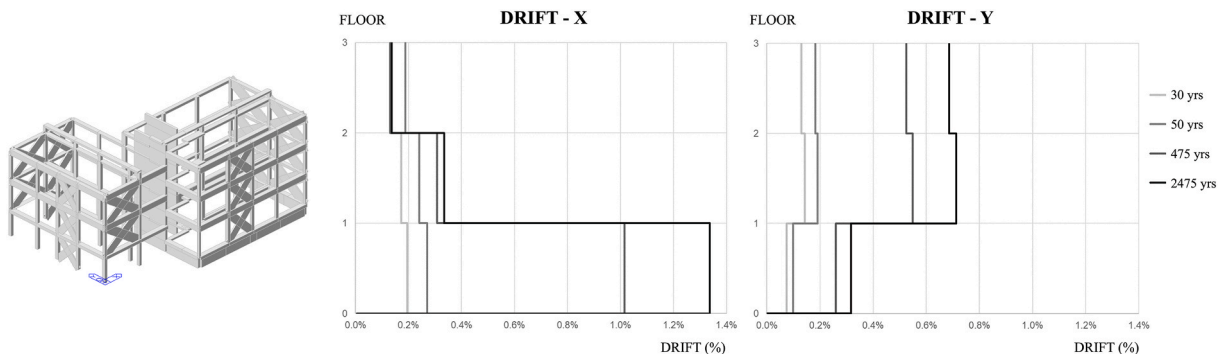


Fig. 5. IDR profiles of the as-built configuration in the directions X and Y at the four seismic intensity levels considered.

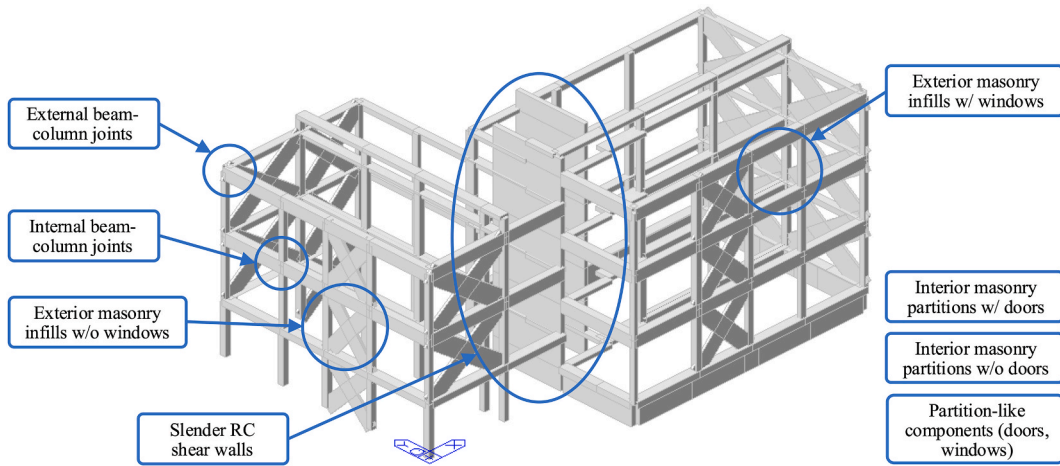


Fig. 6. Inventory of damageable structural and non-structural building's components.

annual emission ratio (AAER) equal to 0.27 % was instead calculated as the fraction between the area underneath the environmental loss exceedance curve (approximately equal to 1516 kg CO₂e) and the total replacement environmental impact (equal to 561,700 kg CO₂e). Finally, the average annual number of fatalities (AALL) was estimated as 0.0034. All these results are summarised in Appendix B (Table B. 1).

The economic losses estimated herein seem to differ significantly from the values that may be expected by using the Italian Guidelines on obtaining relative seismic risk classification [53]. However, some studies (e.g. Ref. [37]) already discussed that loss estimates derived from the Italian guidelines are conspicuously high when compared with the results obtained by the Italian Department of Civil Protection [54] or by the Global Earthquake Model (GEM) Foundation [55]. In addition, in the context of this application, the economic loss estimates result of the same order of magnitude of AAL values ranging from 0.1 to 0.9 % estimated by other researchers (e.g. Refs. [56–59]) for RC buildings in the Italian territory. AAE ratios are also comparable with the estimates of [60] for low-code Italian residential RC buildings. The strong correlation between repair cost and carbon loss ratios is also confirmed by Ref. [60].

3.1.2. Energy performance assessment of the as-built configuration

Energy performance analyses allow the quantification of the building operational energy needs, as well as the corresponding energy annual costs and carbon emissions. Any insulation coating was found to be present in the case-study building, as proved by

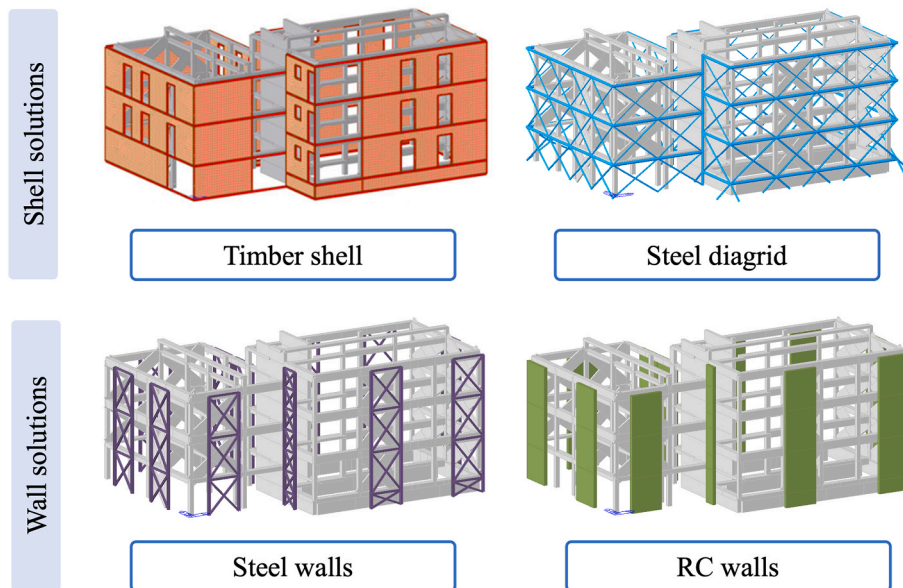


Fig. 7. Four integrated exoskeletons: cross-laminated timber (CLT) panels (solution 1 – timber shell), diagrid frame of tubular steel profiles (solution 2 – steel diagrid), steel (solution 3 – steel walls) or reinforced concrete shear walls (solution 4 – RC walls).

architectural drawings and in-situ inspections. Both opaque and transparent components showed a very poor performance, leading to the presence of several thermal bridges. The mechanical equipment was mostly obsolete.

As mentioned earlier, the TRNSYS tool was employed for the energy performance assessment of the building in its as-built configuration, considering both the aforementioned characteristics of the building’s envelope, as well as its equipment [40]. The total annual energy consumption for heating and cooling was thus estimated as 84,000 kWh (150 kWh/m² yr) and 4100 kWh (7 kWh/m² yr), respectively. Assuming a cost for methane equal to 0.80€ per standard cubic meter (which is equal to 10.69 kWh), the annual cost for energy consumption resulted as equal to around 6593€. Assuming instead 0.19 kg CO₂e/kWh, the annual carbon emissions for energy consumption were estimated as equal to approximately 16,739 kg CO₂e. All these results are summarised in Appendix B (Table B. 1).

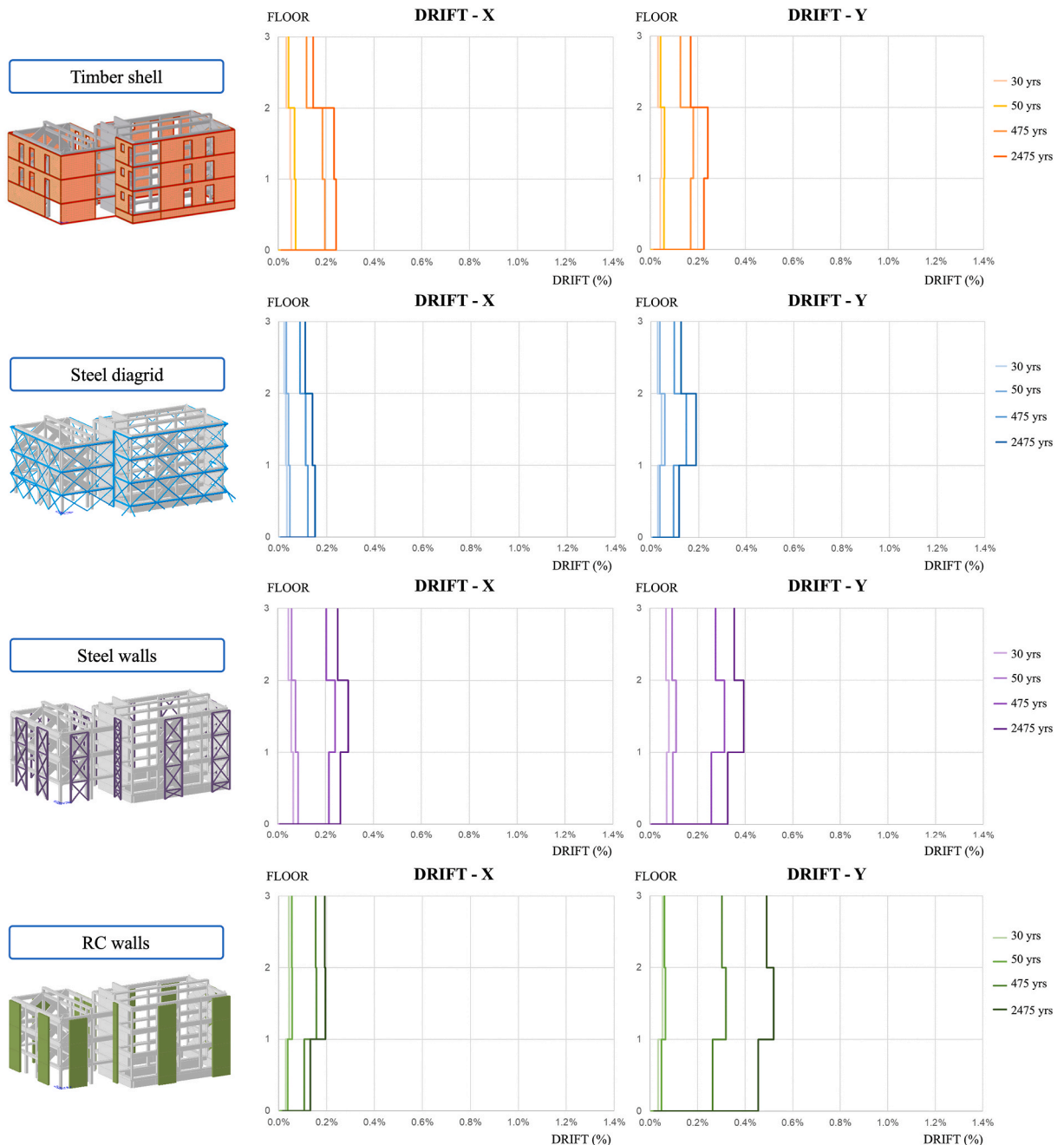


Fig. 8. IDR profiles of the iso-performance structural solutions in directions X and Y at the four seismic intensity levels considered.

3.2. Integrated retrofitting solutions

The building under scrutiny presented most of the vulnerabilities typical of post-WWII infilled RC buildings, such as in-plane and vertical irregularities or monodirectional resisting frames conceived for gravity loads only. The structure resulted as non-compliant with capacity-demand checks at the collapse prevention (CPLS) and the life safety limit state (LSLS) prescribed by the Italian seismic assessment building code [39]. Four different iso-performance exoskeleton solutions (Fig. 7) were thus investigated, all allowing for the same seismic performance improvement [40]. Namely, all exoskeletons were designed to be over-resistant at the LSLS and dissipative at the CPLS, i.e., to maintain the retrofitted building's response in the elastic range for seismic demand values with a return period lower than 475 years and to develop a ductile mechanism for stronger seismic demand levels. Ad-hoc connections all along floor perimeters were designed in each retrofitted configuration to provide an effective transition of seismic horizontal loads from the existing structure to the new structural system. Additional details on the design of exoskeleton solutions are provided in Ref. [61]. As shown in the structural 3D models in Fig. 7, the first two retrofitting solutions are shell exoskeletons composed of engineered continuous façades. The first one is made of cross-laminated timber (CLT) panels (solution 1 – timber shell), the other one consists in a diagrid frame of tubular steel profiles (solution 2 – steel diagrid). Two wall exoskeletons are also considered, composed of discrete shear walls, made of steel (solution 3 – steel walls) or reinforced concrete (solution 4 – RC walls). Fig. 8 shows the IDR profiles of the four iso-performance structural solutions investigated herein, in the directions X and Y at the four intensity levels. It should be noted that the adoption of different structural schemes (i.e., walls or shell exoskeletons) and material technologies (i.e., timber, steel, RC) for the four solutions led to some differences in the drift distributions along the building height. Despite this, interstorey drifts were kept below 0.3 % at the LSLS and 0.5 % at the CPLS in all configurations (Fig. 8). The choice of adopting such target drifts was aimed at responding to the LCT criteria of reducing damage after a potential seismic event, as described in Refs. [1,40].

Each one of the four possible seismic interventions was coupled with the installation of a thermal insulation layer and of a new architectural finishing to address both the building's energy performance and its architectural appearance. The new thermal coating is a combination of expanded polystyrene (EPS) panels for the vertical envelope and the ground floor, and rock wool panels for the roof. In the case of steel diagrid only, the vertical thermal insulation layer is interposed between the existing envelope and the diagrid system. In all the other retrofitting scenarios it is located externally with respect to the structural retrofitting system, as the most external new envelope layer. It is noted as well that all solutions were designed in such a way to keep all the original envelope openings unchanged.

The first solution is a timber shell exoskeleton, featuring relevant potential benefits of future recycling and reuse of components at the building's end of life. Its installation at the construction site consists in a dry assembly of prefabricated components, i.e., modular elements and standardised connections, where the potential seismic damage is expected to be concentrated solely in the connections, allowing easy reparability or replacement after severe seismic events. These characteristics also make the exoskeleton system easy demountable and reusable. Additional insights on the design of such kind of innovative exoskeleton structure can be found in Ref. [62].

Solutions 2 and 3 are made of a steel diagrid structure of tubular profiles spanning building floors and of walls with HEA commercial steel profiles, respectively. The advantages of using steel as structural material are multifaced. Typically, such profiles are made of recycled or reused steel, which can in turn be recycled or reused at the end of life of the exoskeleton. In addition, both steel solutions are conceived as dry, prefabricated, modular and standardised, provided with ad-hoc connections to the existing structure. Such connections are the locations where seismic damage is expected to be concentrated, as well as allowing for practical demountability and replacement of unusable components.

RC cast-in-place walls were explored as Solution 4, which represents a traditional retrofitting strategy for RC buildings. Concrete is not necessarily a recycled material; however, it can be recycled at its end of life generating new aggregates and/or steel rebars. The installation activity, which is not dry in this case, may render the end of life of such an exoskeleton much more impactful, also given the amount of demolition waste that is expected to be disposed in 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 unreparability they would need to be fully replaced.

It is noted that all the exoskeletons considered herein require the construction of new RC foundations, with wall systems requiring a larger share of reinforced concrete if compared to shell exoskeletons. A detailed description of the new foundation systems for all solutions can be found in Ref. [40]. Lastly, based on the results of the environmental impact assessment of the four alternative retrofitting solutions described in Ref. [1], considering LCA modules A1-A3 and C3-C4, the LCT-based solutions proved to have reduced embodied carbon at all life cycle phases if compared to the more traditional ones.

3.2.1. Seismic loss estimation of the retrofitted configurations

The FEMA P-58 procedure and the PACT tool were employed for the seismic loss assessment of all the four retrofitted configurations described above. To this purpose, it was necessary to make some additional considerations and modifications to the as-built inventory of damageable components, so as to include the retrofit components 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 performance models. In addition, the replacement cost and carbon emissions of each retrofitted building were increased of a 10%-value with respect to the corresponding estimates for the as-built configuration, leading to approximately €1.5 million and 620,000 kg CO_{2e}, respectively.

Table 1 shows 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 (AALR) and carbon emissions ratios (AAER), and average annual loss of life (AALL). The as-built configuration is, as expected, characterised by the highest environmental, economic, and social impacts due to seismic damage and

repair activities. All the retrofitting solutions investigated herein do provide a significant reduction of earthquake-induced consequences. Among the four exoskeleton options explored, the one providing the highest benefits, in terms of all the three earthquake-related performance parameters, is the timber shell solution. 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.

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 reason for the observed difference is undoubtedly related to the fragility and consequence models used for each exoskeleton's components. 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 in the PACT library. Those components, for instance, 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, though considering the complete damage of the component itself. The localisation of seismic damage is instead one of the major advantages of the LCT-based solutions presented herein. For the interested readers, the components used for each exoskeleton's members, together with the description of the damage states and related repair activities, along with the repair costs and carbon emissions, are collected in [Appendix A](#).

3.2.2. Energy performance assessment of the retrofitted configurations

As mentioned above, all the exoskeleton structures were provided with a new thermal insulation coat and a new architectural layer, thus leading to the same energy efficiency improvement in all retrofitted configurations. The new energy performance was assessed using the TRNSYS software tool, as described in some detail in Ref. [40]. Owing to the energy efficiency upgrade, the total annual energy consumption for heating and cooling of the retrofitted structure was estimated as 38,169 kWh (68 kWh/m² yr) and 3930 kWh (7 kWh/m² yr), respectively. The annual cost and carbon emissions for energy consumption resulted as equal to around 3151€ and 7999 kg CO_{2e}, respectively, which correspond to around a halving of the as-built estimates. All these results are summarised in [Appendix B](#) (Table B. 1).

3.3. Choice of the optimal integrated retrofitting strategy

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 employed for selecting the optimal retrofitting strategy. For comparison, both the first version of the MCDM approach [28] 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 to the case-study building. The comparison aims at investigating the influence on the results of the introduction of additional sustainability-related decision-making criteria.

Post-retrofit life cycle economic (C) and environmental impacts (CE) were obtained by summing up the (i) economic and environmental costs of the retrofit intervention itself (taken from the work of [1]), (ii) seismic losses (collected in Sections 3.1.1 and 3.2.1) and (iii) operational energy consumption (collected in Sections 3.1.2 and 3.2.2), all normalised by the total useable floor area of the building (i.e., around 700 m²) and its post-retrofit life (i.e., 50 years). The economic payback period (PB-econ) of the retrofit investment was calculated as dividing the cost of retrofit by the economic benefits due to the reduction of annual costs for both energy and seismic risk after retrofitting. The average annual loss of life due to seismic risk, expressed in terms of expected number of fatalities per year, was instead obtained from the FEMA P-58 loss analysis (as reported in [Table 1](#)). All these data are collected in [Appendix B](#) (Table B. 1).

[Fig. 9](#) shows the radar plots that would result from the application of the original version of the MCDM. It is recalled that, to draw radar plots, the PB is normalised by the building's post-retrofit service life (i.e., 50 years). Life cycle costs, carbon emissions, and average annual fatalities are instead normalised by the as-built corresponding values. The optimal solution, which is the one corresponding to the smallest resulting area and thus minimising all the four variables considered, is the timber shell solution. It is followed, in ascending order, by RC walls, steel diagrid and steel walls. It is observed that, according to this MCDM version, RC walls would result overall very efficient, coherently with the observations derived from the seismic loss analysis, more than the alternative steel solutions, notwithstanding the fact that these are the result of an LCT-based design.

It is noted that the variation of prices observed in the latest months/years has been relevant, even for different geographic locations within the same country. However, this work does not aim at the evaluation of the actual costs and economic feasibility of specific retrofitting endeavours, but rather at the application of the updated MCDM approach to highlight its relative differences with respect to a previously proposed method.

For what concerns the updated version of the MCDM proposed herein, the other variables were calculated as follows for each retrofitted configuration. Module D carbon of each solution was taken from the work of [1]. Given that the normalisation with respect

Table 1
Results of the seismic loss assessment of as-built and retrofitted configurations.

	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

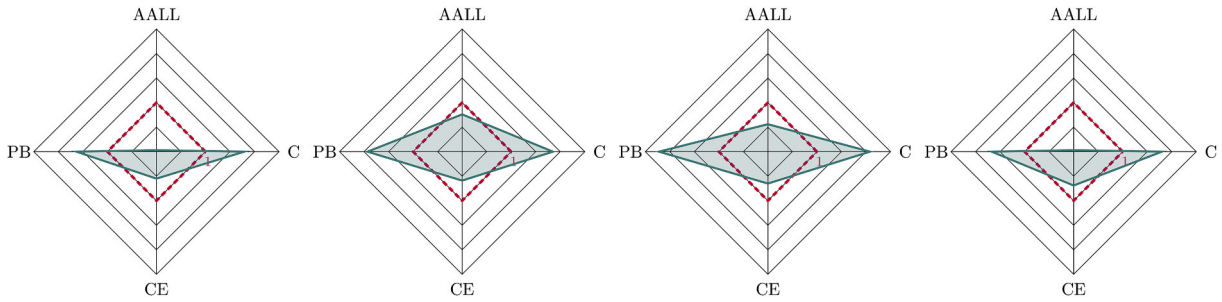


Fig. 9. Radar plots of the four retrofitted configurations (from left to right, timber shell, steel diagrid, steel walls, RC walls): normalised post-retrofit costs (C), post-retrofit carbon emissions (CE), payback period (PB), and average annual loss of life (AALL).

to the as-built configuration was not feasible (because $D_{as-built}$ is null), then module D was normalised as follows: $1 + (\text{module D} / \text{modules A1-A3})$, considering null all the resulting negative values. The environmental payback period (PB-env) was, as described previously, obtained as the ratio between the initial embodied carbon of the retrofit (modules A1-A3) and the annual environmental savings produced by the retrofitting solution adopted. It was then normalised by the building's post-retrofit life (i.e., 50 years), as done for PB-econ as well. Lastly, the level of invasiveness (I) was calculated as the sum of the scores assigned from 0 to 5 to three different criteria: (i) the construction of new foundations, (ii) the invasiveness of the retrofit installation, and (iii) the invasiveness of the potential repair activities on retrofit components after a strong seismic event. Concerning foundations, a score of 2 was assigned to both timber shell and steel diagrid solutions. A 5-score was assigned to steel walls and RC walls, instead. The difference between shell and wall exoskeleton solutions was assumed based on the fact that the shell types require a reduced amount of reinforced concrete foundations (almost 6-times lower) if compared to the wall ones. Regarding instead the invasiveness of the retrofit installation, given that all solutions are designed to be applied from the outside avoiding the need of residents' 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; so, a score of 4 was assigned. All the parameters' values used for both the original and the updated versions of the MCDM method discussed herein are collected in [Appendix B](#).

Based on these seven parameters, the optimal solution resulting from the updated radar charts, shown in [Fig. 10](#), is still the timber shell solution (with a very large advantage if compared to the other solutions). It is now followed, in ascending order, by steel diagrid, RC walls, and steel walls. Steel diagrid and RC walls solutions are now inverted in the new ranking. This highlights the advantage of including LCT-inspired and sustainability parameters amongst the decision-making variables.

4. Conclusions

In this work, an update to a multi-criteria decision-making (MCDM) approach that had been previously developed to support the process of identification of optimal retrofitting strategies [28] is proposed. The updated version of the MCDM method was applied to a case-study residential building for demonstrative purposes. Four different integrated exoskeletons, made of timber, steel and concrete, were investigated. The comparison of results obtained with the original and updated versions of the MCDM procedure demonstrated that the introduction, in the latter, of sustainability and LCT-inspired criteria assists in the consideration and quantification of the benefits of LCT-based retrofitting interventions over traditional ones. In the context of a LCSE approach, such an MCDM approach represents a valuable supporting tool for decision-making fostering the adoption of life cycle thinking principles in current practice.

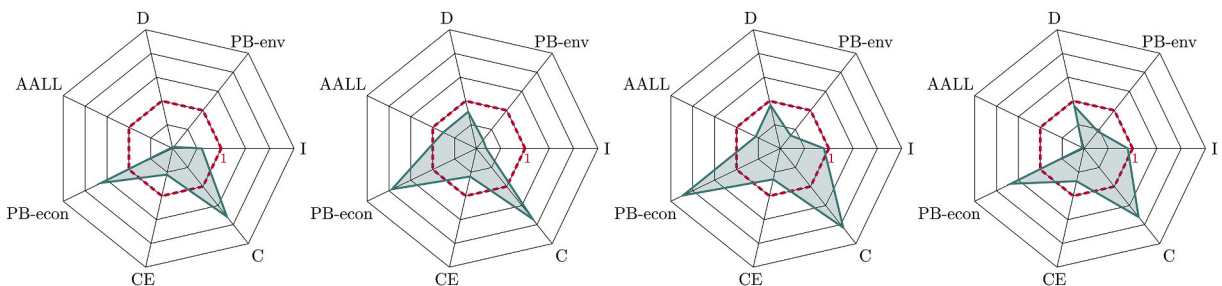


Fig. 10. Radar plots of the four retrofitted configurations (from left to right, timber shell, steel diagrid, steel walls, RC walls): normalised post-retrofit costs (C), post-retrofit carbon emissions (CE), economic payback period (PB-econ), average annual loss of life (AALL), module D (D), environmental payback period (PB-env), and level of invasiveness (I).

The trends in the rankings observed herein are not expected to be limited to the case-study building investigated. However, further applications of the updated MCDM approach to additional building typologies are envisaged to confirm that it prioritises LCT-compliant retrofitting solutions. This would ensure the choice of solutions that are effectively able to minimise building life cycle environmental, economic, and social impacts at the same time.

The case-study application efforts described in this work also highlighted the pressing need for further developments regarding, e.g., specific fragility and consequence functions for exoskeleton components (which in this work were approximately considered equivalent to non-exoskeleton components present in the PACT library), including the different type of connections that the installation of these systems entails. In addition, the development of fragility and consequence functions for acceleration-sensitive components typically found in existing Italian and European buildings was also found to be required. Lastly, the design of new retrofitting techniques or the process of reengineering the available ones, also for other building typologies, is certainly of interest with a view to boost the application of LCT-based solutions in real case studies.

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CRedit authorship contribution statement

Martina Caruso: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Margherita Buttazzoni:** Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Chiara Passoni:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simone Labò:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Data curation. **Alessandra Marini:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Rui Pinho:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available upon request.

Appendix A

Table A. 1

Timber shell: B1071.031 - Wood walls with diagonal let-in bracing.

Damage state	Description	Repair activity	Repair cost (€/unit)	Emissions (kg CO ₂ e/unit)
DS1	Failure of diagonal bracing.	Remove and replace sheathing studs, plates and bracing and replace with new stud wall construction of plywood, hold-downs, etc. Provide shoring as required.	3793–6164	2184

Table A. 2

Steel diagrid and steel walls: B1033.111a - Steel Buckling Restrained Brace (BRB), Single Diagonal Brace, Weight of brace <40 plf.

Damage state	Description	Repair activity	Repair cost (€/unit)	Emissions (kg CO ₂ e/unit)
DS1	Fracture of brace or gusset. Buckling of gusset. Severe yielding of beams and columns adjacent to the gusset with possibility of local buckling and cracking in the yielded areas. Severe loss of lateral resistance.	Brace and gusset are severely damaged with significant loss in stiffness and resistance, and both likely require replacement. Yielding and local buckling of beams and columns may be repaired by heat straightening, stiffeners or reinforcement, if there is no cracking or tearing. If cracking or tearing has initiated more substantial repair is needed.	33,226–53,993	8800

Table A. 3

Concrete walls: B1044.091 - Slender Concrete walls, 0.3 m thick, 3.6 m high, 4.5 m long.

(continued on next page)

Table A. 3 (continued)

Damage state	Description	Repair activity	Repair cost (€/unit)	Emissions (kg CO ₂ e/unit)
DS1	Spalling of cover, vertical cracks greater than 1/16 inch.	Epoxy inject cracks and patch spalled concrete	4808 - 7070	1488
DS2	Exposed longitudinal reinforcing.	Shore wall, remove all concrete in damaged regions, replace concrete	18,157 - 26,702	8519
DS3	Core concrete damage, buckled reinforcing, fractured reinforcing, shear failure, web failure, bond slip.	Replace wall or reinforce with R/C jacket if possible. Shore floor and wall, remove damaged concrete and steel within one development length of damaged region, replace removed concrete and steel.	34,517 - 50,760	8021

Appendix B

Table B. 1

Variables used in the original version (first four rows only) and the updated one (all rows) of the MCDM method discussed herein, for all four retrofitting strategies.

Variable	As-built	Timber shell	Steel diagrid	Steel walls	RC walls
Post-retrofit costs (C) (€/m ² yr)	11.46	20.52	21.20	23.89	20.67
Retrofit (modules A1-A3) (€)	0	547,502	520,366	614,652	544,959
Annual energy consumption (€)	6593	3151	3151	3151	3151
Average annual seismic losses (€)	3641	353	1696	1544	544
Retrofit (modules C3-C4) (€)	0	54,750	52,037	61,465	54,496
Total floor area (m ²)	700	700	700	700	700
Post-retrofit life (yr)	50	50	50	50	50
Post-retrofit carbon emissions (CE) (kg CO ₂ e/m ² yr)	26.08	14.25	15.34	17.03	17.99
Retrofit (modules A1-A3) (kg CO ₂ e)	0	20,616	107,243	164,021	227,372
Annual energy consumption (kg CO ₂ e)	16,739	7999	7999	7999	7999
Average annual seismic losses (kg CO ₂ e)	1516	201	692	711	233
Retrofit (modules C3-C4) (kg CO ₂ e)	0	68,270	-5012	-3541	-9437
Total floor area (m ²)	700	700	700	700	700
Post-retrofit life (yr)	50	50	50	50	50
Economic payback period (PB-econ) (yr)	0	81	97	111	83
Average annual loss of life (AALL) (p)	0.0034	0.0001	0.0026	0.0019	0.0001
Module D (D) (kg CO₂e)	0	-83,555	-25,010	-14,742	-25,879
Economic payback period (PB-env) (yr)	0	2	11	17	23
Level of invasiveness (I) (-)	0	6	2	9	9

References

- [1] C. Passoni, E. Palumbo, R. Pinho, A. Marini, The LCT challenge: defining new design objectives to increase the sustainability of building retrofit interventions, *Sustainability* 14 (14) (2022) 8860.
- [2] C. Passoni, M. Caruso, A. Marini, R. Pinho, R. Landolfo, The role of life cycle structural engineering in the transition towards a sustainable building renovation: available tools and research needs, *Buildings* 12 (8) (2022) 1107.
- [3] A. Marini, C. Passoni, A. Belleri, F. Feroldi, M. Preti, G. Metelli, P. Riva, E. Giuriani, G. Plizzari, Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: a proof of concept, *European Journal of Environmental and Civil Engineering* 26 (7) (2022) 2475–2495.
- [4] C. Menna, L. Felicioni, P. Negro, A. Lupíšek, E. Romano, A. Prota, P. Hájek, Review of methods for the combined assessment of seismic resilience and energy efficiency towards sustainable retrofitting of existing European buildings, *Sustain. Cities Soc.* 77 (2022) 103556.
- [5] D.A. Pohoryles, D.A. Bournas, F. Da Porto, G. Santarsiero, T. Triantafyllou, D. Oliveira, B.P. Jelle, Technologies for the Combined Seismic and Energy Upgrading of Existing Buildings, *European Commission Joint Research Centre*, 2022.
- [6] A. Marini, C. Passoni, P. Riva, P. Negro, E. Romano, F. Taucer, Technology Options for Earthquake Resistant, Eco-Efficient Buildings in Europe: Research Needs, *European Commission, Joint Research Centre scientific and policy reports*, 2014.
- [7] A. Belleri, A. Marini, Does seismic risk affect the environmental impact of existing buildings? *Energy Build.* 110 (2016) 149–158.
- [8] J.P. Chhabra, V. Hasik, M.M. Bilec, G.P. Warn, Probabilistic assessment of the life-cycle environmental performance and functional life of buildings due to seismic events, *J. Architect. Eng.* 24 (1) (2018) 04017035.
- [9] Y. Dong, D.M. Frangopol, Performance-based seismic assessment of conventional and base-isolated steel buildings including environmental impact and resilience, *Earthq. Eng. Struct. Dynam.* 45 (5) (2016) 739–756.
- [10] C. Feese, Y. Li, W.M. Bulleit, Assessment of seismic damage of buildings and related environmental impacts, *J. Perform. Constr. Facil.* 29 (4) (2015) 04014106.
- [11] B. Gencturk, K. Hossain, S. Lahourpour, Life cycle sustainability assessment of RC buildings in seismic regions, *Eng. Struct.* 110 (2016) 347–362.
- [12] K.A. Hossain, B. Gencturk, Life-cycle environmental impact assessment of reinforced concrete buildings subjected to natural hazards, *J. Architect. Eng.* 22 (4) (2016) A4014001.
- [13] M. Huang, K. Simonen, Comparative environmental analysis of seismic damage in buildings, *J. Struct. Eng.* 146 (2) (2020) 05019002.
- [14] J.E. Padgett, Y. Li, Risk-based assessment of sustainability and hazard resistance of structural design, *J. Perform. Constr. Facil.* 30 (2) (2016) 04014208.

- [15] H.H. Wei, M.J. Skibniewski, I.M. Shohet, X. Yao, Lifecycle environmental performance of natural-hazard mitigation for buildings, *J. Perform. Constr. Facil.* 30 (3) (2016) 04015042.
- [16] S.J. Welsh-Huggins, A.B. Liel, A life-cycle framework for integrating green building and hazard-resistant design: examining the seismic impacts of buildings with green roofs, *Structure and Infrastructure Engineering* 13 (1) (2017) 19–33.
- [17] R.E. Gonzalez, M.T. Stephens, C. Toma, D. Dowdell, The estimated carbon cost of concrete building demolitions following the Canterbury earthquake sequence, *Earthq. Spectra* 38 (3) (2022) 1615–1635.
- [18] E. Baek, D.A. Pohoryles, S. Kallioras, D.A. Bournas, H. Choi, T. Kim, Innovative seismic and energy retrofitting of wall envelopes using prefabricated textile-reinforced concrete panels with an embedded capillary tube system, *Eng. Struct.* 265 (2022) 114453.
- [19] D.A. Bournas, Concurrent seismic and energy retrofitting of RC and masonry building envelopes using inorganic textile-based composites combined with insulation materials: a new concept, *Compos. B Eng.* 148 (2018) 166–179.
- [20] A. Ferrante, G. Mochi, G. Predari, L. Badini, A. Fotopoulou, R. Gulli, G. Semprini, A European project for safer and energy efficient buildings: pro-get-one (proactive synergy of integrated efficient technologies on buildings' envelopes), *Sustainability* 10 (3) (2018) 812.
- [21] M. Margani, G. Evola, C. Tardo, E.M. Marino, Energy, seismic, and architectural renovation of RC framed buildings with prefabricated timber panels, *Sustainability* 12 (12) (2020) 4845.
- [22] M.R. Valluzzi, E. Saler, A. Vignato, M. Salvalaggio, G. Croatto, G. Dorigatti, U. Turrini, Nested buildings: an innovative strategy for the integrated seismic and energy retrofit of existing masonry buildings with CLT panels, *Sustainability* 13 (3) (2021) 1188.
- [23] S.S. Zuluaga, S. Kallioras, A. Tsiavos, Optimization of synergetic seismic and energy retrofitting based on timber beams and bio-based infill panels: application to an existing masonry building in Switzerland, *Buildings* 12 (8) (2022) 1126.
- [24] N. Ademovic, A. Formisano, L. Penazzato, D.V. Oliveira, Seismic and energy integrated retrofit of buildings: a critical review, *Frontiers in Built Environment* 8 (2023) 963337.
- [25] C. Menna, C. Del Vecchio, M. Di Ludovico, G.M. Mauro, F. Ascione, A. Prota, Conceptual design of integrated seismic and energy retrofit interventions, *J. Build. Eng.* 38 (2021) 102190.
- [26] D.A. Pohoryles, D.A. Bournas, F. Da Porto, A. Caprino, G. Santarsiero, T. Triantafyllou, Integrated seismic and energy retrofitting of existing buildings: a state-of-the-art review, *J. Build. Eng.* 61 (2022) 105274.
- [27] C. Passoni, M. Caruso, L. Felicioni, P. Negro, The evolution of sustainable renovation of existing buildings: from integrated seismic and environmental retrofitting strategies to a life cycle thinking approach, *Bull. Earthq. Eng.* (2024) 1–35.
- [28] M. Caruso, R. Pinho, F. Bianchi, F. Cavalieri, M. Lemmo, Multi-criteria decision-making approach for optimal seismic/energy retrofitting of existing buildings, *Earthq. Spectra* 39 (1) (2023) 191–217.
- [29] N. Clemett, W.W. Carofilis Gallo, G. Gabbianelli, G.J. O'Reilly, R. Monteiro, Optimal combined seismic and energy efficiency retrofitting for existing buildings in Italy, *J. Struct. Eng.* 149 (1) (2023) 04022207.
- [30] L. Giresini, F. Stochino, M. Sassu, Economic vs environmental isocost and isoperformance curves for the seismic and energy improvement of buildings considering Life Cycle Assessment, *Eng. Struct.* 233 (2021) 111923.
- [31] W. Carofilis, G. Gabbianelli, R. Monteiro, Assessment of multi-criteria evaluation procedures for identification of optimal seismic retrofitting strategies for existing RC buildings, *J. Earthq. Eng.* 26 (11) (2022) 5539–5572.
- [32] M. Caruso, R. Couto, R. Pinho, R. Monteiro, Decision-making approaches for optimal seismic/energy integrated retrofitting of existing buildings, *Frontiers in Built Environment* 9 (2023) 1176515.
- [33] G. Mucedero, R. Monteiro, An integrated regional prioritisation framework for seismic and energy-efficiency performance upgrading of residential buildings, *Int. J. Disaster Risk Reduc.* 103 (2024) 104341.
- [34] G.A. Anwar, M. Hussain, M.Z. Akber, et al., Sustainability-oriented optimization and decision making of community buildings under seismic hazard, *Sustainability* 15 (2023) 1–21, <https://doi.org/10.3390/su15054385>.
- [35] C. Passoni, A. Marini, A. Belleri, C. Menna, Redefining the concept of sustainable renovation of buildings: state of the art and an LCT-based design framework, *Sustain. Cities Soc.* 64 (2021) 102519.
- [36] M. Caruso, R. Pinho, F. Bianchi, F. Cavalieri, M.T. Lemmo, A life cycle framework for the identification of optimal building renovation strategies considering economic and environmental impacts, *Sustainability* 12 (23) (2020) 10221.
- [37] M. Caruso, R. Pinho, F. Bianchi, F. Cavalieri, M.T. Lemmo, Integrated economic and environmental building classification and optimal seismic vulnerability/energy efficiency retrofitting, *Bull. Earthq. Eng.* 19 (9) (2021) 3627–3670.
- [38] EN 15978:2011. Sustainability of Construction Works — Assessment of Environmental Performance of Buildings—Calculation Method. Brussels: European Committee for Standardization (CEN).
- [39] Ministero delle Infrastrutture e dei Trasporti (MIT), Aggiornamento delle Norme Tecniche per le costruzioni (Gazzetta Ufficiale della Repubblica Italiana No. 42), Ministry of Infrastructures and Transport, Rome, 2018.
- [40] S. Labò, C. Passoni, J. Zanni, M. Milesi, A. Belleri, A. Marini, P. Riva, G. Brumana, M. Preti, V. Bolis, et al., Applicazione di Interventi Condotti Dall'esterno ad un caso Studio—Edificio Residenziale in Calcestruzzo Armato Report Reluis—WP5: Interventi di Rapida Esecuzione a Basso Impatto ed Integrati 2022, Available online: www.reluis.it. (Accessed 3 June 2022) (In Italian).
- [41] Applied Technology Council (ATC), Seismic Performance Assessment of Buildings— Methodology (Rep No FEMA P-58-1), vol. 1, Federal Emergency Management Agency (FEMA), Washington, DC, 2018.
- [42] Applied Technology Council (ATC), Seismic Performance Assessment of Buildings— Implementation Guide (Rep No FEMA P-58-2), vol. 2, Federal Emergency Management Agency (FEMA), Washington, DC, 2018.
- [43] Applied Technology Council (ATC), Seismic Performance Assessment of Buildings— Supporting Electronic Materials and Background Documentation (Rep No FEMA P-58-3), vol. 3, Federal Emergency Management Agency (FEMA), Washington, DC, 2018.
- [44] TRNSYS. A Transient System Simulation Tool, TRNSYS Reference Manual: Mathematical Reference, 2006.
- [45] MidasGen 2020 V11; Copyright © SINCE 1989 MIDAS Information Technology Co, Ltd, Beijing, China, 1989.
- [46] L. Martins, V. Silva, H. Crowley, F. Cavalieri, Vulnerability modellers toolkit, an open-source platform for vulnerability analysis, *Bull. Earthq. Eng.* 19 (2021) 5691–5709.
- [47] D. Cardone, Fragility curves and loss functions for RC structural components with smooth rebars, *Earthquakes and Structures* 10 (5) (2016) 1181–1212.
- [48] D. Cardone, G. Perrone, Developing fragility curves and loss functions for masonry infill walls, *Earthquakes and Structures* 9 (1) (2015) 257–279.
- [49] Dipartimento della Protezione Civile (DPC), National risk assessment - overview of the potential major disasters in Italy: seismic, volcanic, tsunamis, hydro-geological/hydraulic and extreme weather. Droughts and Forest Fire Risks, Italian Civil Protection Department, Rome, Italy, 2018.
- [50] D. Cardone, G. Perrone, Damage and loss assessment of pre-70 RC frame buildings with FEMA P-58, *J. Earthq. Eng.* 21 (1) (2017) 23–61.
- [51] Carnegie Mellon University Green Design Institute (CMUGDI), Free economic input-output life cycle assessment. <http://www.eiolca.net/>, 2008. April 2023.
- [52] C. Weber, D. Matthews, A. Venkatesh, C. Costello, H. Matthews, The 2002 US benchmark version of the economic input-output life cycle assessment (EIO-LCA) model. Green Design Institute at Carnegie Mellon University, Pittsburg, PA, USA, 2009. <http://www.eiolcanet/docs/index.html>. April 2023.
- [53] Ministero delle Infrastrutture e dei Trasporti (MIT), Linee Guida per la Classificazione del Rischio Sismico delle Costruzioni: Decreto Ministeriale 65 del 7 Marzo, 2017.
- [54] Dipartimento della Protezione Civile (DPC), National risk assessment: overview of the potential major disasters in Italy: seismic, volcanic, tsunamis, hydro-geological/hydraulic and extreme weather, droughts and forest fire risks, Italian Civil Protection Department (2018). Rome, Italy.
- [55] V. Silva, A. Calderon, M. Caruso, C. Costa, J. Dabbeek, M.C. Hoyos, Z. Karimzadeh, L. Martins, N. Paul, A. Rao, M. Simonato, C. Yepes-Estrada, H. Crowley, K. Jaiswal, Country/territory seismic risk profiles of the GEM foundation, GitHub (2023), <https://doi.org/10.5281/zenodo.8431824>. <https://github.com/gem/risk-profiles/>.
- [56] D. Cardone, G. Perrone, Damage and loss assessment of pre-70 RC frame buildings with FEMA P-58, *J. Earthq. Eng.* 21 (1) (2017) 23–61.

- [57] L. Sousa, R. Monteiro, Seismic retrofit options for non-structural building partition walls: impact on loss estimation and cost-benefit analysis, *Eng. Struct.* 161 (2018) 8–27.
- [58] G.J. O'Reilly, D. Perrone, M. Fox, R. Monteiro, A. Filiatrault, Seismic assessment and loss estimation of existing school buildings in Italy, *Eng. Struct.* 168 (2018) 142–162.
- [59] G.J. O'Reilly, T.J. Sullivan, Probabilistic seismic assessment and retrofit considerations for Italian RC frame buildings, *Bull. Earthq. Eng.* 16 (3) (2018) 1447–1485.
- [60] K. Aljawhari, R. Gentile, C. Galasso, Earthquake-induced environmental impacts for residential Italian buildings: consequence models and risk assessment, *J. Build. Eng.* 84 (2024) 108149.
- [61] C. Passoni, J. Guo, C. Christopoulos, A. Marini, P. Riva, Design of dissipative and elastic high-strength exoskeleton solutions for sustainable seismic upgrades of existing RC buildings, *Eng. Struct.* 221 (2020) 111057.
- [62] J. Zanni, S. Cademartori, A. Marini, A. Belleri, C. Passoni, E. Giuriani, P. Riva, B. Angi, G. Franchini, G. Brumana, Integrated deep renovation of existing buildings with prefabricated shell exoskeleton: the AdESA case study, *Sustainability* 13 (2021) 11287.