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MULTI-CRITERIA APPROACH FOR THE EVALUATION OF THE SEISMIC-ENERGETIC RETROFIT SOLUTIONS FOR A PUBLIC RESIDENTIAL BUILDING

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Abstract

Sustainability and its application to the construction sector requires both the client and the designer to think holistically, considering not only economic aspects, but also environmental and social ones, while taking into account the entire life cycle of the building. In this regard, numerous types of multi-criteria analysis, and some examples of Life Cycle Analysis (LCA), have recently been developed for civil engineering. However, it would not be sufficient to focus on newly designed buildings, it is essential to undertake actions on the existing building stock, the majoritys of which requires energy renovation and seismic upgrading. In this work, a multicriteria analysis based on the MIVES method is implemented to evaluate different strategies for the combined/integrated seismic and energetic intervention for a real public residential building in Palombara Sabina (Italy). For this purpose, the Simple Lateral Mechanism Analysis (SLaMA) a mechanical-based analytical procedure developed in the NZSEE20017 Seismic Assessment Guidelines, has been carried out to assess the vulnerability of the structure and obtain the Safety Index (demand-capacity ratio) and the Expected Annual Losses (EAL). At the same time, an energy audit allowed to assess the energy class of the building. Six alternatives rehabilitation strategies have then been considered, three for the energy refurbishment and other three for seismic upgrading. Following a multi-criteria approach, the values of a sustainability index were calculated for the combined interventions, taking into account social, economic, and environmental aspects. The proposed procedure could be significantly useful for the decision making process of different stakeholders, not only with regard to the specific case study building, but to archetypes representing the Italian public housing building stock.

Keywords: Sustainability, Retrofit, Decision Making, Life Cycle Analysis, Low-damage exoskeleton, existing buildings.

1 INTRODUCTION

Italy's building stock is predominantly old and often affected by structural degradation. Its energy inefficiency and seismic vulnerability are primarily the result of outdated construction practices and widespread non-compliance with modern standards—issues that are further exacerbated by physical deterioration and the natural ageing of materials. These problems have made building retrofitting a critical priority for the civil engineering sector, particularly within the context of the European Green Deal and the United Nations 2030 Agenda. According to the International Energy Agency, the construction industry is responsible for 27% of global greenhouse gas emissions, 30% of annual non-renewable energy consumption, and 15% of water use. Furthermore, approximately 75% of the European building stock is energy inefficient, contributing to 40% of EU energy demand and 36% of total CO_2 emissions as highlighted by the Buildings Performance Institute Europe (BPIE). On the other hand, the numerous disasters caused by recent earthquakes have pointed out the significant impact in terms of economic losses due to the seismic vulnerability of buildings constructed according to pre-seismic codes.

To support informed decision-making in this complex context, Multi-Criteria Decision Analysis (MCDA) methods have emerged as powerful tools. MCDA enables the integration of diverse factors — including technical, economic, environmental, and social parameters — into a unified evaluation framework. In recent years, significant efforts have been made by research groups worldwide to integrate environmental and social perspectives into decision-making processes. First, as highlighted in Chen et al. (2019) [1], most existing studies tend to rely on LCA-based methods for conducting Sustainable Building Material Selection (SBMS). However, these methodological advancements often fall short in assessing the economic, social, and technical performance of building materials as a whole, without considering social aspects related to the construction itself. MCDA proposed by Caterino et al. (2008) [2] is one of the first applications of the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [3], to compare alternative structural retrofit solutions for buildings. This method evaluates the performance of different seismic and energy retrofitting strategies across a broad range of decision variables, identifying the best option as the one with the shortest distance to an ideal solution, with criteria being weighted accordingly. Later, Menna et al. (2013) [4] proposed a method for calculating the environmental impact of a building subjected to a potential seismic event throughout its lifespan, from a life cycle perspective, emphasizing the importance of integrated retrofitting interventions. Building on this work, Menna et al. (2021) [5] further developed this concepts by focusing on the integration of seismic and energy retrofitting strategies. Recently, Passoni et al. (2022) [6-7] presented a new and comprehensive perspective on the issue, by redefining the concept of Life Cycle Thinking (LCT) in structural engineering, and emphasizing the importance of renovating existing buildings through integrated approaches. Clemett et al. (2023) [8] applied a similar approach, using a weighted average method to identify the optimal retrofitting solution, further advancing the use of multi-criteria decision-making in this context. Finally, Caruso et al. (2023) [9] explored multiple case-study procedures to identify optimal retrofit solutions and proposed an end-to-end procedure for the integrated assessment and retrofitting of buildings [10-12]. This approach is not only limited to earthquake-induced impacts into life cycle evaluations, but also enables for the identification of optimal seismic and energy retrofitting solutions, considering economic, environmental, and social decision variables. Among the others, "Modelo Integrado de Valor para una Evaluacion Sostenible" (MIVES, integrated value-based model for sustainable evaluation) stands out for its versatility, as a tool to assess and compare the sustainability of construction and retrofit solutions and it was also adopted in *fib* TG6.3 [13-15]. MIVES methodology integrates multiple criteria such as cost, environmental impact, and social implications, through the incorporation of value functions, which allow for the transformation of qualitative and quantitative criteria into comparable values, allowing for a more holistic evaluation of building interventions.

The present work proposes a streamlined methodology for evaluating building retrofit options in the preliminary design phase. This procedure is intended for use by public housing agencies and other stakeholders seeking effective and manageable tools for decision-making. The strength of this approach lies in its ability to account for a high number of variables while remaining accessible to practitioners. By leveraging the MIVES framework, it supports a balanced analysis of energy efficiency, seismic safety, architectural impact, execution costs, and social acceptance, which represents crucial aspects in the pursuit of sustainable and resilient urban development.

2 METHODOLOGY

The proposed methodology is briefly illustrated in Figure 1 and consists mainly of three phases: integrated seismic and energy assessment, preliminary design, and decision-making. In the first phase, the structure is analyzed to determine both the seismic risk index and the energy performance. Subsequently, retrofit interventions are designed, and finally, a multi-criteria analysis is used to identify the most sustainable retrofit solution. Further details and assumptions can be found in the application to the selected case study. In general, the attempt to develop a user-friendly procedure is made possible by applying simplified, yet rigorous, methodologies used for the assessment and retrofit of the structure.

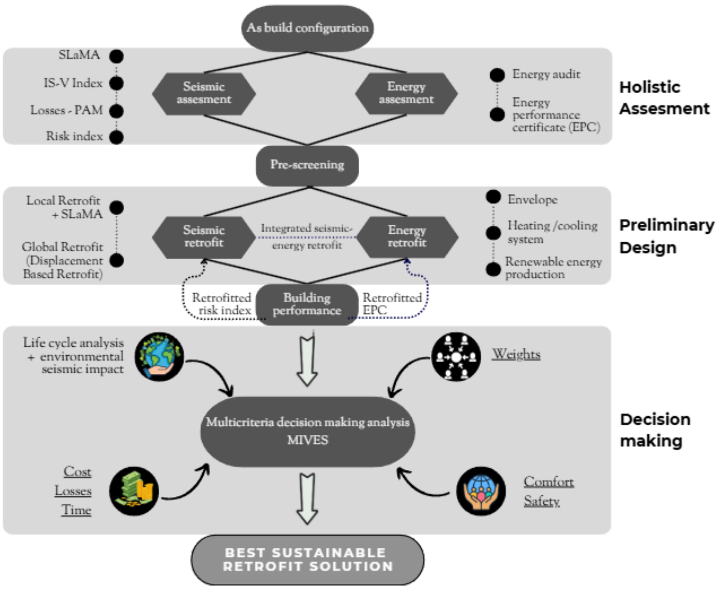


Figure 1 – Proposed workflow

3 CASE-STUDY APPLICATION

3.1 As-built configuration

The case-study building consists of a real four-story Reinforced Concrete frame building located in a moderate seismicity zone in Center Italy (i.e. Palombara Sabina, Rome, Italy). The building was built in 1986 for gravity loads only, in the absence of modern seismic code provisions, including "*capacity design principles*". The structure has a regular plan and elevation, with a gradual reduction of the cross-sections of the columns between the basement and the upper floor (Figure 2). Since it was not possible to obtain the structural design drawings, a simulated design procedure has been undertaken based on the standards in force at the time of constructions and following an "elastic design approach" based on "working stresses".

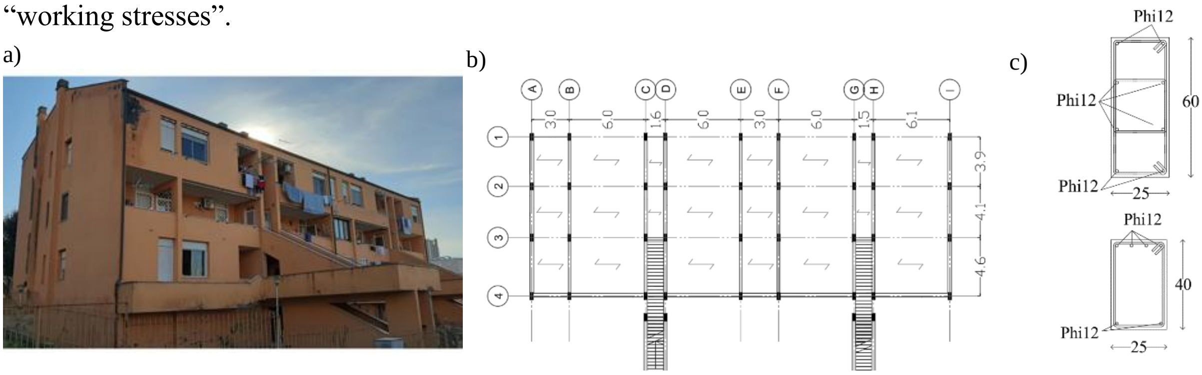
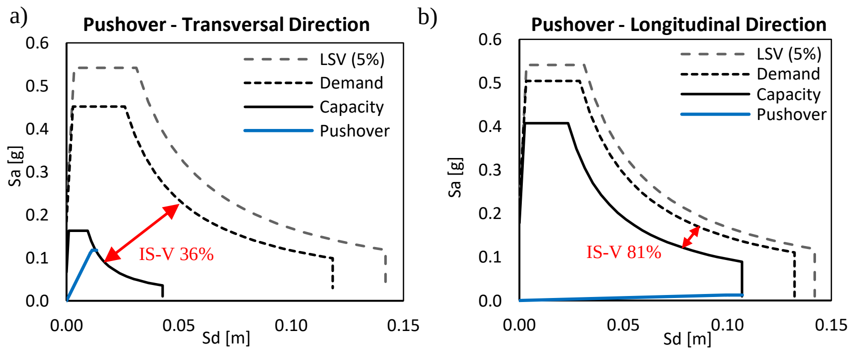


Figure 2 – a) Case-study building, b) typical floor plan, c) beam and columns cross-sectional area properties and reinforcement

3.2 Integrated (seismic/energy) assessment for the as built configuration

In this paragraph the results from the seismic and energy assessment of the existing building are discussed. Concerning seismic assessment, the SLaMA analytical procedure [16-18], was used to define the analytical pushover curves for each frame, while also providing essential information related to the sequence of events and hierarchy of strength in each beam-column joint sub-assembly. By summing in parallel the pushover of the individual frames, it was possible to define the global analytical pushover curve of the structure in each direction (i.e., longitudinal, and transversal). This methodology immediately identifies the "weakest link of the chain" (i.e., which element reaches failure within each beam-column joint sub-assembly), thus supporting targeted retrofit interventions if necessary. In particular, in the transverse direction collapse is due to shear failures at the base of several internal columns in almost all frame alignments. In the longitudinal direction, the absence of beams (since the floor is framed longitudinally) results in very low shear capacity at the base and high displacement capacity. For this reason, the second-order effects cannot be neglected and has been considered both in the analysis. Numerical model was then developed to validate the results. To account for the nonlinear behavior of the elements, lumped plasticity models were defined with mono-dimensional elastic elements equipped with plastic hinges at their end sections [19]. The beam-column joint is modeled using rigid links connected by rotational springs that represent the capabilities of the joint itself [20]. Finally, the Safety-Index (i.e., the IS-V defined as the demand/capacity ratio by DM65/2017 [21], and analogous to the %NBS defined in the NZSEE 2017 [16]) and the Economic Index related to the Expected Annual Losses (EAL, or PAM in Italian, DM65/2017 [21-22]) have been evaluated (Figure 3).



c)

	X		Y	
PAM	3.6%	G	2.9%	D
IS-V	80.8%	B	36.0%	D
Risk class	**E**		**D**	

Figure 3 - a), b) Pushover in ADRS domain, c) Risk class for the as-build

An energy diagnosis was carried out by using the "Termus-Bim" software [23]. The model was implemented with the stratigraphy of the infill walls and floors, windows and the information known about the heating system. The comparison with the utility bills yielded positive results. A consistency factor is defined as the ratio between estimated and actual natural gas consumption. According to current regulations, the error must remain within 10%. In the case study, the factor is equal to C = 0.906, and the model is therefore considered validated. The greatest heat loss occurs in the transparent surfaces, due to single-glazed windows without thermal breaks. Of course, when considering the heat-loss areas, the greater contribution comes from the infill walls. Moreover, the ground floor slab has a much higher heat loss than the attic slab, which is insulated with a thick layer of insulation. The building's theoretical energy consumption is based on UNI/TS 11300 and Italian regulations [24]. The building has a global Energy Performance Index (EPI), corresponding to the total primary energy consumption from non-renewable sources, equal to: $EP_{gl,nren} = 134.0306\ kWh/m^2year$, that corresponds to energy class "G".

3.3 Pre-screening of combined/integrated renovation alternatives

This phase, previously proposed also by Passoni et al. (2021) [25], is crucial as it allows for the definition of minimum requirements that interventions must meet, both from a technical and sustainability perspective. This pre-screening phase is important as it helps to consider the technical, economic, and prioritization requirements for supporting the decision-making in the subsequent selection process. In this study, the minimum requirement was set to be an increase of at least two seismic and energy risk classes for the building.

3.4 Preliminary design

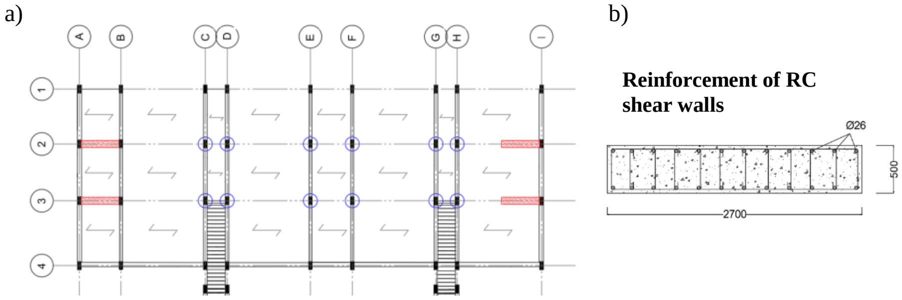
In the Table 1 below, the three seismic retrofit solutions designed for the case study are summarized.

Table 1 - Summary of the seismic retrofit solutions

Scheme	Interventions	Effect
S1	CFRP wraps of columns + RC walls	Increases shear resistance and confinement of the columns at the first floor, increases strength in direction x and reduces displacement demand on Moment Resisting Frames.
S2	RC Jacketing of columns + isolation	Increases stiffness in the columns (Jacketing) and reduces force on MRF (Isolation).
S3	Pres-Lam exoskeleton: 2 timber frames in x direction + 4 shear walls in y direction	Increases stiffness and resistance of the global system.

The first solution (Figure 4) involves a local and partial retrofit in the transverse direction, aimed at eliminating shear failures in the ground-floor columns only, and a global retrofit in the longitudinal direction, with the addition of reinforcement elements to limit drift and increase the stiffness and strength of the system. The design of the reinforced concrete shear walls was carried out using the Displacement Based Retrofit (DBR) method [26]. Overall, this solution enables the structure to improve only from 36% to 51%. of the IS-V index, due to the decision to intervene only partially on the transverse frames.

a) b) c)

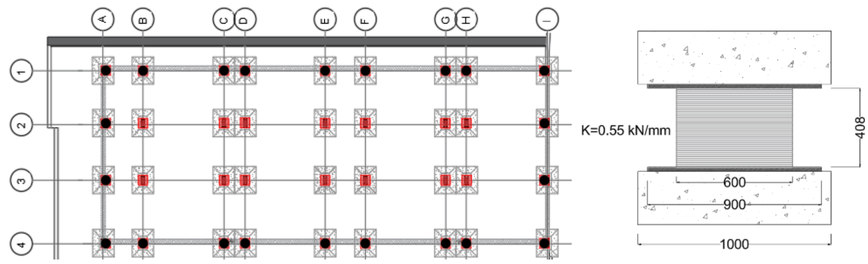


	S1	
	X	Y
PAM	1.0%	2.15%
IS-V	82.2%	51.3%
Risk	**C**	

Figure 4 – a) Placement of reinforced concrete shear walls and FRP, b) Section of the shear wall, c) risk class for S1

The second solution involves installing a seismic isolation system between the basement and the ground floor to reduce seismic demand. This approach is particularly suitable for the studied building due to the presence of exposed basement columns that can be enlarged to accommodate isolation devices and the absence of nearby structures. The isolation system is placed at the top of the basement columns, making the ground floor slab act as the rigid base of the superstructure. To support this, the foundation will be stiffened with reinforced concrete tie beams connecting all footings, and the basement columns will be strengthened to limit horizontal displacements and increase cross-sectional area to accommodate the isolation devices. It's also noted that seismic isolation is generally designed to keep the superstructure within the elastic range. This often makes it unsuitable for existing buildings, which typically have stiffness coefficients between 3% and 5% [27]. For this reason, it was necessary to stiffen the superstructure. To this end, it was decided to carry out jacketing of the internal columns. The isolation system design followed the methodology outlined in Cardone et al. (2010) [28].

a) b) c)



	S2	
	X	Y
PAM	0.54%	0.55%
IS-V	101.2%	97.9%
Risk	**A**	

Figure 5 - a) Placement of the isolation devices, b) characteristic of the isolators, c) risk class for S2

The third solution involves a global retrofit in both directions, addressing the need to increase strength and stiffness in both directions. To this end, an external exoskeleton implementing the Pres-Lam technology [29-32] has been designed, consisting of two longitudinal frames (one attached to the facade and one separated, connected through newly designed slabs) and four walls, paired two by two, in the transverse direction (Figure 6).

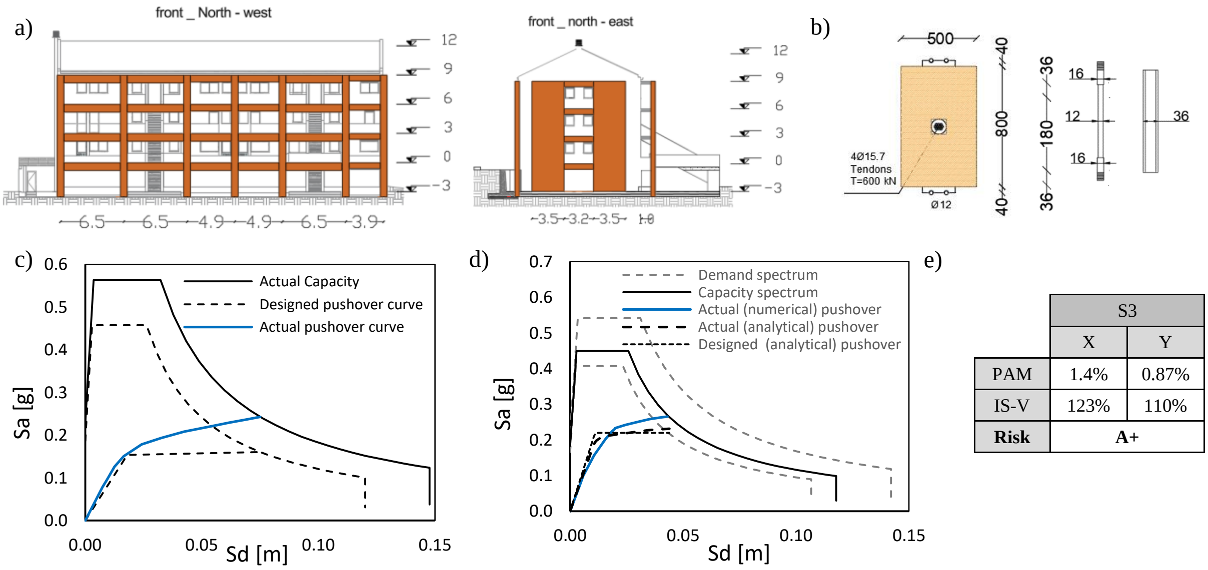
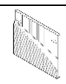
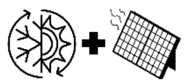


Figure 6 – a) Design of the exoskeleton, b) Example of a cross-section of the beam and details of the plug-and-play dissipaters, c) Analytical vs numerical pushover comparison in ADRS domain for S3, d) risk class for S3

The DBR method was used to calculate the required moment and shear at the base of the exoskeleton. Subsequently, the exoskeleton sections were designed using the *Modified Monolithic Beam Analogy* [33]. A recentering ratio $\lambda = 1.75$ was considered, meaning that 64% of the resistant moment is assigned to the recentering component and 36% to the dissipative component. This choice stems from the need to minimize residual displacements in the existing structure, ensuring its usability after an earthquake through a strongly recentering system. At the end of the design, the results were compared with those obtained from the numerical modeling. For this purpose, beam-column joints of the low-damage Pres-Lam exoskeletons are modeled with two links working in parallel: first one is a Multilinear plastic link representing the external Plug & Play dissipaters, while the second is a Multilinear elastic link related to post-tensioned cables [34-35]. Assuming a rigid connection between the structure and the exoskeleton, end-pinned rigid links have been used to connect the two structures [36].

On the other hand, three energy retrofit solutions were developed for the case study, as summarized in the table below.

Table 2 - Summary of the energy retrofit solutions

Scheme	Interventions	
E1	External wall insulation with timber panels + Replacement of windows + Insulation of the 1st floor	
E2	Replace existing boiler with new generations heat pump + Installations of fan coil + Centralization of the hot water distribution + Install photovoltaic panels	
E3	E1+E2 interventions	

Solution E1 consists of a passive intervention on the vertical building envelope, specifically targeting the perimeter walls and external windows. Prefabricated lightweight cladding panels made of wood were used for the opaque surfaces. The stratigraphy of the panel is based on a prototype developed in the

"LegnAttivo" research project, coordinated by "Eurac Research Centre", which aims to promote the renovation of residential buildings in terms of both internal comfort and high energy performance [37]. Regarding the transparent surfaces, the windows were replaced with frames made of polyurethane with a metal core, equipped with thermal breaks, and double glazing with a thickness of 5 mm. Finally, an insulation layer of double-density rock wool with a thickness of 6 cm and thermal conductivity λ = 0.035 W/mK was added on the first floor. The new energy index is $EP_{gl,nren} = 59.5207\ kWh/m^2year$ which corresponds to an energy class E. However, the result is good, considering that the value has been reduced by more than 50%. From the comparison with the existing building, it can be observed that the heat loss through the elements has decreased significantly, particularly concerning the heat loss due to opaque vertical closures (Figure 7). This is also reflected in the transmission loss value of the building, which has been more than halved.

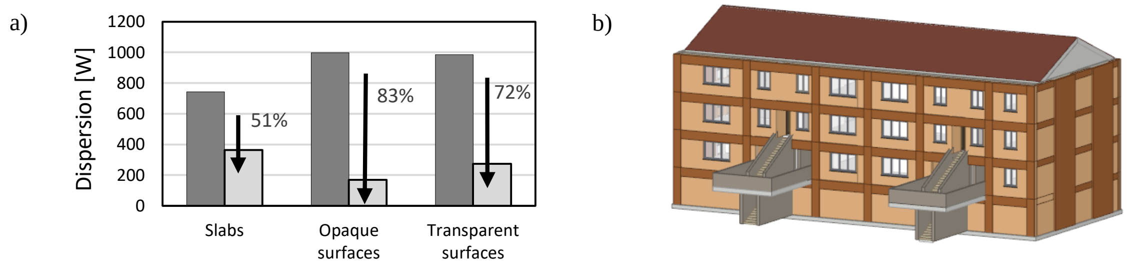


Figure 7 – a) External heat loss surface, pre and after retrofit , b) 3D rendering of the building with the cladding façade panels connected to the exoskeleton.

The second intervention (E2) essentially involves the replacement of the heating and cooling system with a new high-performance unit. For this solution, the resulting Energy Performance Index is $EP_{gl,nren} = 9.8978\ kWh/m^2year$, corresponding to an A3 energy class. The great improvement in energy class is due to the contribution of photovoltaic panels, which significantly reduce the building's reliance on non-renewable energy sources. Since the EPI accounts solely for the consumption of non-renewable energy, the integration of renewable energy systems such as photovoltaics leads to a notable enhancement in the overall energy rating. Finally, the third design alternative (E3), in terms of energy efficiency, consists simply of combining the two interventions described previously. Therefore, improvements are expected both in terms of heat loss reduction and in terms of emissions and energy savings. The EPI obtained is $EP_{gl,nren} = 9.8978\ kWh/m^2year$, that corresponds to an A4 class.

3.5 Fragility curves

At the end of the design and numerical modeling phase of the proposed interventions, it is useful to compare them through fragility curves [38]. The resulting curves will then play a role in the LCA to correlate the losses associated with reaching a certain limit state with environmental impact values. In this study, the construction of the fragility curves was carried out using the Capacity Spectrum Method [39]. More specifically, given the capacity curve of the structure in the ADRS domain, the performance points of the structure are defined based on the associated limit states (Damage States, DS). Therefore, the spectrum can be scaled until it intersects the performance point. This gives the Peak Ground Acceleration (PGA) associated with reaching a certain limit state [18]. Thus, the limit states were expressed in terms of displacement, as proposed by Martin and Silva (2021) [40]: $d_{DS1} = 0.75d_y$; $d_{DS2} = 0.5d_y + 0.3d_u$; $d_{DS3} = 0.25d_y + 0.67d_u$; $d_{DS4} = d_u$. The PGA values obtained in this way are the mean values of the fragility curves, to which, in order to account for the use of simplified analyses, a dispersion β = 0.5 was associated. In Figure 8 below, fragility curves obtained for each solution are compared for DS1 and DS4.

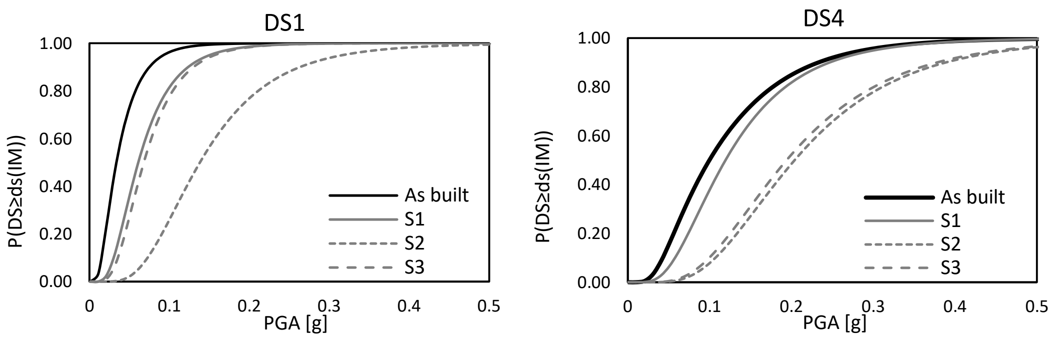
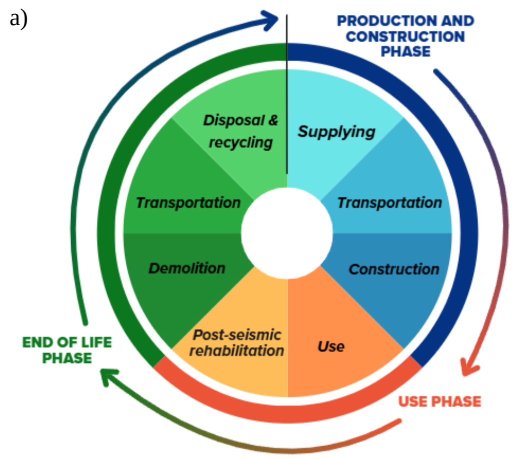


Figure 8 – Examples of fragility curves for the seismic designed interventions (S1, S2, S3) for two different Limit State.

3.6 Life Cycle Analysis

A Life Cycle Assessment (LCA) was conducted to evaluate the environmental impacts of each option across the entire lifespan of the structure. The LCA for the case study encompassed all life cycle stages of the building, as illustrated in Figure 9, including the likelihood of seismic events during its assumed 50-year post-retrofit service life. A "cradle to cradle" perspective was adopted, accounting for the entire life cycle from raw material extraction to end-of-life disposal or recycling. The assessment focused on CO_2-equivalent emissions and non-renewable primary energy consumption.

First, the production and construction phase assessed the environmental impacts associated with material extraction and production, employing the ICE V2.0 database [41] and Eco-cost [42] to quantify CO_{2eq} emissions and energy consumption relative to material usage. For steel components, the databases differentiate based on application (e.g., bars, plates, pipes) and material origin (virgin or recycled). A 59% recycled material usage was assumed based on European standards. For timber elements, emissions were disaggregated into fossil and biomass contributions. Biomass emissions were excluded under the assumption that the wood was sourced from sustainably managed forests. The study did not consider carbon release from wood at end-of-life, acknowledging ongoing debate in this area. Given the "cradle-to-gate" scope of the reference databases, carbon neutrality was assumed by accounting for the biogenic carbon cycle—i.e., CO_2 absorbed during tree growth is released upon combustion, yielding a net-zero balance. Material transportation from production sites to the construction site was also analyzed. Emissions were estimated based on ton-kilometers (TKM) and vehicle type (28-ton and 16-ton trucks), following Mineral Products Association (MPA) guidelines [43]. Air transport impacts, including CO_2 emissions and primary energy use, were calculated using conversion factors from the Sustainable Energy Authority of Ireland (SEAI) [44-45]. For the construction process, the different uses of machinery and equipment necessary to implement the various solutions (e.g., cranes, concrete mixers, etc.) were considered, along with the various construction site activities that result in emissions and consumption. Specifically, Tar et al. (2022) [46] was used as a reference to assess the impact per hour of use for each piece of equipment. As a result, the speed of construction and installation of each solution significantly influences the impact assessment in the construction phase. However, the overall savings and impact values associated with this phase are quite modest compared to others.



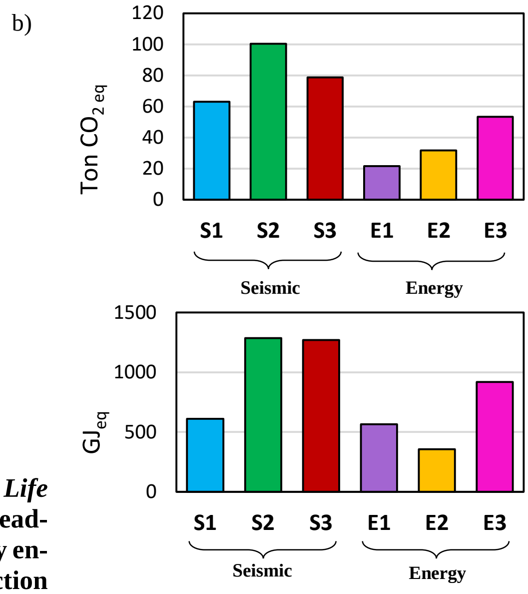


Figure 9 – a) Phases of building life cycle. Modified after *Life Cycle Assessment of Buildings: A Practice Guide* (Carbon Leadership Forum, 2019), b) total CO_2eq emissions and primary energy consumption during the production and construction phase

The use phase is the most impactful and is naturally the most influenced by the type of intervention, both from an energy perspective regarding the actual use phase, as well as from a structural perspective concerning post-seismic rehabilitation. To assess CO_{2eq} emissions and primary energy consumption, the results obtained during the diagnosis and design phases of the interventions were used directly. As illustrated in Figure 10, solution E1 reduces consumption and emissions of 50%, while the E2 achieves reductions of up to 80%, primarily due to the installation of photovoltaic panels, which lower non-renewable energy consumption. The combination of both solutions makes the building almost zero-impact.

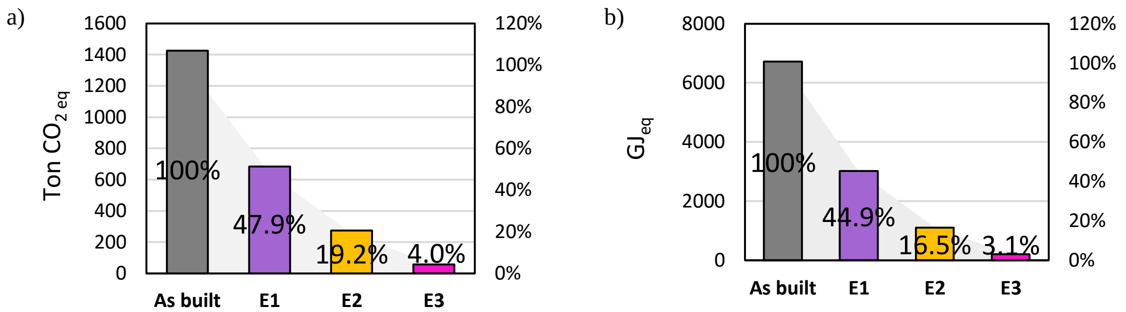
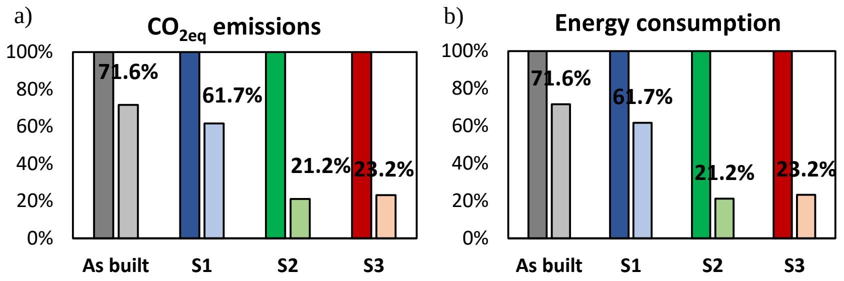


Figure 10 – a) total CO_{2eq} emissions and b) primary energy consumption during the use phase

The phase of post-seismic rehabilitation was included to assess the consequences of earthquakes during the building's life span. The evaluation is based on the levels of damage the structure may sustain, which are associated with environmental impacts due to potential repairs or replacements of structural and non-structural components, and depend on the fragility curves obtained for the various solutions [5]. Environmental indices were estimated based on Biswas (2014) [47]. The procedure estimates environmental impacts during the rehabilitation phase as a fraction of those from the original construction and production stages. Environmental loads are assigned to specific limit states, differentiating between structural and non-structural components, and expressed as a percentage of the original load based on the severity of the limit state. The percentages used are those proposed for cast-in-place elements, while for the prefabricated solution, the values suggested by Peng (2016) [48], based on the drift associated with each limit state, were used (Figure 11).



c)

%	Struct	Non struct
SLO	0	0
SLD	0.05	0.15
SLV	0.38	0.58
SLC	0.6	0.8

d)

%	Struct	Non struct
SLO	0	0.15
SLD	0.15	0.35
SLV	0.6	0.8
SLC	1	1

Figure 11 – a) total CO_{2eq} emissions and b) primary energy consumption during the rehabilitation phase. Percentage of material components required for the building retrofit according to the limit state level for (c) prefabricated solutions and (d) cast-in-place solutions.

For the demolition phase, reference was made to Peng (2016) [48]. For a reinforced concrete building, the energy consumption for demolition is estimated equal to 107.7 kWh/m². Therefore, energy consumption can be derived by knowing the gross area. CO_{2eq} emissions can be calculated using the emission factor in tCO_{2eq}/MWh. For prefabricated elements, the approach is similar to the construction phase, although the values will be lower due to the reduced time required for the operations.
For evaluating the impacts during the recycling phase, reference was made to [49] and [41]. Recycling plays a crucial role in LCA, though no universal method exists to assess its impacts, as recycling can be viewed as either the beginning or end of a production process. Annex B of the ICE V2.0 [41] outlines three simplified reference approaches. The selection of the method depends on the LCA boundaries (e.g., cradle-to-gate, cradle-to-grave), each having distinct advantages. This study adopted the 50:50 method for steel elements, which are assumed to follow a closed recycling loop, replacing virgin steel production. In sustainable construction, in fact, the ideal strategy combines the use of recycled materials during construction with design provisions for future reuse. For timber elements, the end-of-life scenario involves dismantling and energy recovery through incineration, rather than landfill disposal. The CO_{2eq} emitted is excluded from the analysis under the assumption of carbon neutrality. However, the energy recovered is considered: it is assumed that 60% of the heat generated is converted into primary energy, with a heat-to-electricity ratio of 1:3 [49]. This electricity is expected to offset fossil-fuel-based grid electricity, allowing for an estimation of energy and CO_2 savings. For these reasons the contribution in the recycle phase are negative, as shown in Figure 12.

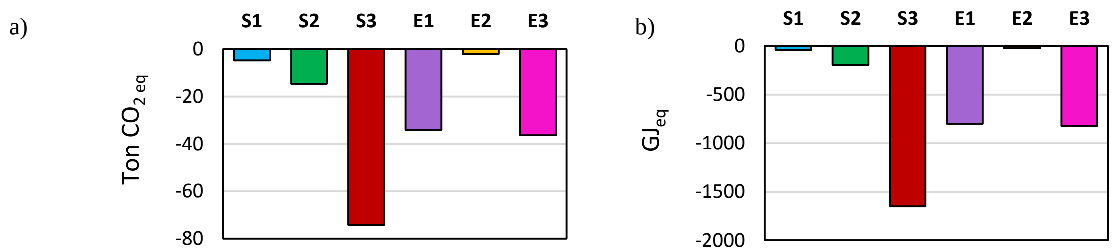


Figure 12 – a) total CO_{2eq} emissions and b) primary energy consumption during the recycle phase

The results obtained at the end of the analysis are shown in Figure 13. From the comparison between the graphs, it can be seen that structural interventions, without simultaneous energy efficiency improvements, result in very high values of emissions and energy consumption. Among these, the solution with FRP and reinforced concrete shear walls is the most impactful, followed by base isolation, and finally the exoskeleton. The energy efficiency solutions primarily reflect the results of the usage phase.

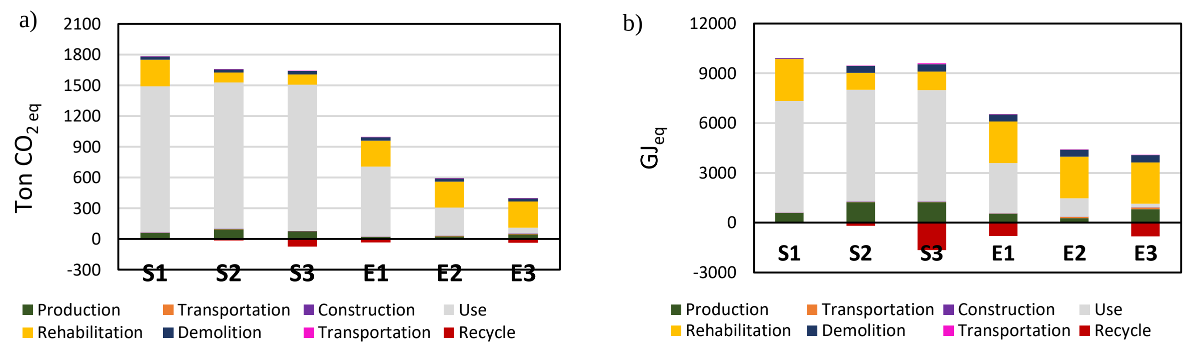


Figure 13 – a) total CO_{2eq} emissions and b) total primary energy consumption

It is evident that the phase that most influences the environmental impact indices is the usage phase, which is entirely due to the energy efficiency interventions. Following this, the rehabilitation phase assumes considerable importance, which is lower for S2 and for solution S3. Finally, the recycling phase is more significant for the two solutions that involve the use of wood.

Knowing the values for each solution, a matrix including all the possible combinations of interventions can be defined (Figure 14). For both indices, the solution with the least impact is the exoskeleton in Pres-Lam combined with the replacement of the system and the envelope in prefabricated wooden panels. The reduction in consumption and emissions is clearly visible from top to bottom, i.e., as the energy efficiency performance increases during the usage phase, and from left to right, with a marked decrease for the exoskeleton.

a)

Energetic	tonCO2eq	Seismic: As built	S1	S2	S3
	As built	1713	1776	1641	1569
	E1	960	1022	888	816
	E2	590	653	518	446
	E3	362	425	290	218

b)

Energetic	GJ	Seismic: As built	S1	S2	S3
	As built	9657	9851	9278	7958
	E1	5729	5923	5350	4030
	E2	4383	4577	4004	2684
	E3	3255	3856	2876	1556

Figure 14 - Matrices of results in terms of a) total CO_{2eq} emissions and b) primary energy consumption.

3.7 Decision Making

After the definition of the retrofit alternatives, the subsequent phase involves defining the decision tree and assigning weights to the evaluation indices. It is essential to consider that the case study building is owned by "*Ater*", a publicly funded economic entity with financial and accounting autonomy. Given that *Ater*'s funding originates primarily from public authorities, interventions must be evaluated primarily through the lens of cost-effectiveness to enable broader applicability across multiple buildings.

Within the economic domain, the time factor is particularly significant. Service disruption entails severe inconvenience for tenants, many of whom face socio-economic hardship and are unable to secure alternative housing. As such, for public residential housing, invasive interventions should be avoided in favor of solutions that maintain service continuity. In addition to economic considerations, environmental sustainability has become a growing priority for public entities. Environmental performance indices also carry indirect economic implications in this context: since utility costs (electricity and natural gas) are partially borne by *Ater*, reductions in energy consumption benefit both residents and the institution's financial sustainability. Finally, social criteria, although less emphasized, remain relevant. They encompass construction management factors and achievement of specific performance targets, which contribute to the overall effectiveness and acceptance of the retrofit strategy.

Based on these considerations and following a discussion with the technicians responsible for *Ater*, a set of evaluation indices and corresponding weights was established (Table 3).

Table 3 - List of requirements, criteria, indices and corresponding weights adopted in the MIVES evaluation

Requirement	%	Criteria	%	Index	%
R1. Economic	**43%**	C1. Cost	**75%**	I1. Direct cost	**58%**
				I2. Losses	**42%**
		C2. Time	**25%**	I3. Disruption	**100%**
R2. Environmental	**39%**	C3. Emission	**33%**	I4. CO_{2eq} emissions	**100%**
		C4. Energy	**67%**	I5. Energy consumption	**100%**
R3. Social	**18%**	C6. Safety	**60%**	I6. Risk index	**100%**
		C7. Comfort	**40%**	I8. Disturbances	**100%**

The total cost of each intervention refers to the sum of the costs that can be directly estimated in relation to the project, such as the costs for purchasing materials, equipment, and labor. In this case, simplified cost evaluations were made: pricing lists of the Lazio region [50] were used for S1 and S2, and regional pricing was combined with examples found in literature for the S3 [51]. For the energy part, in the case of the building envelope, the average price per square meter provided by the company "Marlegno" was used, while for the heating/cooling system, the pre-estimated costs for the intervention already approved by *Ater* were used. The cost of each solution was then normalized with respect to the most expensive solution, in order to be included in the value function (Figure 15a). The expected annual loss (PAM) due to earthquake-induced damage over the building's lifespan was incorporated as an indicator of economic resilience. This metric distinguishes conventional retrofit strategies from more advanced damage-minimization solutions. Since the focus is on retrofit interventions, PAM values are expected to remain within a similar range, with lower sensitivity for less risky configurations (Figure 15b).

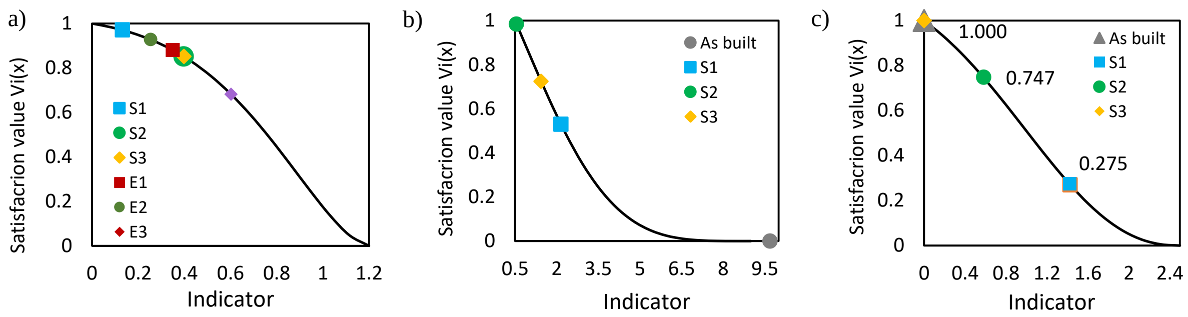


Figure 15 – Value function for a) Direct Cost, b) Losses, c) Disruption

Construction duration was also assessed by analyzing the sequence and complexity of tasks, labor availability, equipment needs, and estimated timeframes. Prefabricated solution results in a time savings of approximately 50% compared to the other two solutions. For the purposes of the analysis, however, only the days of service interruption are important. The disruption value function is reported in (Figure 15c) Finally, by weighting each of the three indices and combining them, the satisfaction matrix for the economic performance requirement is obtained (Figure 16a). It can be noted that the best solution, considering all the combinations, is the seismic isolation intervention without energy efficiency measures. This can be explained by the fact that in this first phase, seismic solutions take precedence, influencing the rehabilitation index, while any energy efficiency interventions entail additional costs that are not yet offset by other factors. In this specific case, narrowing the scope to the nine alternatives under comparison, the best intervention from an economic perspective would be S2+E2. Slightly after that follows the solution with the exoskeleton, which has comparable costs and no service interruption.

a)

Energetic \ Seismic	As built	S1	S2	S3
As built	0.69	0.66	0.86	0.85
E1	0.63	0.58	0.72	0.70
E2	0.65	0.61	0.77	0.75
E3	0.55	0.47	0.57	0.55

b)

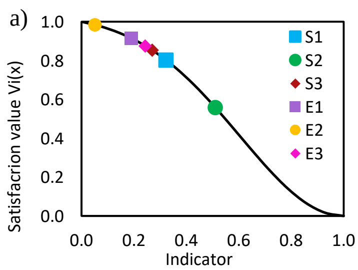
Energetic \ Seismic	As built	S1	S2	S3
As built	0.08	0.06	0.11	0.20
E1	0.49	0.46	0.54	0.65
E2	0.67	0.65	0.71	0.81
E3	0.79	0.74	0.82	0.91

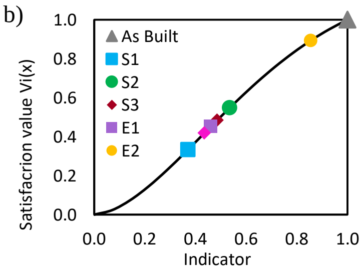
Figure 16 – a) Results matrix for economic requirement, b) Results matrix for environmental requirement

Regarding the environmental indices, the evaluation can start from the results obtained through the LCA. The indices evaluated are carbon dioxide emissions and energy consumption, where the latter clearly holds greater relevance and weight due to the economic and social impacts on tenants resulting from energy savings. The matrix of results for the environmental requirement can then be derived as for the economic one (Figure 16b). Results shows the strong impact of energy interventions in this phase, due to the significant reduction in impacts during the use phase of the structure. At the same time, the overall performance of the solution improves as it shifts towards low-damage seismic retrofit strategies (i.e., S2 or S3), since these approaches reduce not only direct impacts but also the environmental losses associated with potential post-earthquake repairs. This highlights the importance of accounting for seismic risk-related environmental impacts in the decision making process.

Social requirement integrates indicators that account for the well-being of all stakeholders over the structure's lifecycle. This analysis concentrates on safety and disturbance indices. The first is represented by Occupational Risk Index (ORI), that quantifies the level of occupational hazard to which construction workers are exposed, based on factors such as construction methods, tools, working environment, and task complexity [52]. For the case study, S3 showed the lowest overall hazard. This is mainly due to its fast execution, which reduces workers' exposure time. Energy-efficiency-focused interventions exhibit limited impact on worker safety, as risks are more closely tied to structural activities (Figure 17a).

The disturbance index evaluates the extent to which the construction process affects occupants and the local environment. This includes: noise pollution (quantified in decibels), pedestrian transit disruption, and traffic impact. Each parameter is rated on a 0–10 scale and weighted accordingly, with noise pollution receiving the highest weight (60%) due to its direct effects on health (e.g., earing loss, sleep disruption, stress), while for transit (15%) and traffic (25%) lower values have been considered as they have less impact on residents. Noise levels were assessed using INAIL guidelines [53]. Prefabricated solutions generate less noise due to off-site manufacturing, requiring only assembly operations on-site. In contrast, cast-in-place methods (S1 and S2) involve more intensive construction equipment use, resulting in higher noise levels. Transit and traffic-related disturbances depend on the construction site layout and logistics. Cast-in-place solutions require less transportation operation but require more raw-material deliveries. Prefabricated elements require fewer deliveries but involve more disruptive transport operations, sometimes necessitating special vehicles. Therefore, higher disturbance scores were given to cast-in-place solutions compared to the two solutions using prefabricated elements (Figure 17b).

a)


b)


c)

Energetic \ Seismic	As built	S1	S2	S3
As built	1.00	0.62	0.55	0.69
E1	0.73	0.39	0.26	0.63
E2	0.95	0.59	0.50	0.66
E3	0.70	0.34	0.21	0.59

Figure 17 – Value function for a) Risk index b) Disturbances; c) Results matrix for social requirement

3.8 Optimal sustainable retrofit solution

At the end of the procedure, combining all the requirements and indices with the defined weight, it is possible to obtain the optimal (in terms of sustainability) retrofit solution. In this study, to achieve the predefined requirement of improving both seismic and energy performance by at least two classes, the analysis focused on nine feasible design combinations (Figure 18). The optimal solution for the case-study application combines a low-damage timber external exoskeleton for seismic retrofitting with a heating/cooling system replacement for energy efficiency. The exoskeleton offers seismic performance comparable to base isolation, with lower environmental and social impacts. On the energy side, the inclusion of photovoltaic panels in solution E2 ensures substantial energy savings and emission reductions at relatively low cost.

Energetic \ Seismic	As built	S1	S2	S3
As built	0.51	0.42	0.51	0.57
E1	0.59	0.50	0.56	0.67
E2	0.71	0.62	0.70	0.76
E3	0.67	0.55	0.60	0.70

Figure 18 - Results matrix for sustainability index

4 CONCLUSIONS

This study developed and applied a multi-criteria analysis procedure to evaluate sustainability in public residential buildings. Although simplified for preliminary assessments, the procedure proved to be adaptable and reliable, offering comprehensive results that can be extended to the broader Italian building stock, especially for structures requiring retrofit interventions. The methodology was first defined and supported by literature to ensure robustness despite its simplified nature and then applied to a real case study of a pre-code residential building in Italy. Six design alternatives were proposed—three focused on seismic upgrades and three on energy refurbishment—each aimed at enhancing the building's performance by at least two rating classes. These alternatives were selected to represent a diverse range of materials, strategies, technologies, and intervention types. Life Cycle Assessment provided critical insight into environmental impacts across production, use, and end-of-life phases. It highlighted material selection, especially the sustainability of timber, which offers high recyclability and environmental benefits when sourced from responsibly managed forests. The possibility of seismic events during the building's lifespan was also integrated into the analysis, as post-earthquake rehabilitation can entail considerable environmental costs, in addition to unsustainable direct/indirect monetary losses. The exoskeleton, if constructed in reinforced concrete or steel, would have a significantly higher impact. From an economic point of view, although insulation and exoskeleton options involved higher initial costs, they offered long-term savings by reducing potential seismic damage. Energy solutions were more cost-sensitive, and downtime minimization was prioritized given the public residential context, where relocation costs are borne by the public sector. The environmental assessment focused on two key indicators: CO_2 emissions and non-renewable primary energy consumption. Energy-related interventions showed the greatest impact during the use phase, with sustainability increasing progressively from envelope upgrades to full-system replacements and integrated solutions. Even though less impactful overall, the rehabilitation phase remains environmentally significant, particularly when structural components are restored. Timber-based solutions, due to their recyclability, reusability and dry connections, emerged as the less-impact one. From a social perspective, priority was given to worker safety, minimal tenant disruption, and improved comfort—factors of particular relevance to public housing. Results shows that also in this context the timber exoskeleton was favored for its minimal disruption and safety. In conclusion, the analysis demonstrated that addressing seismic or energy improvements in a non-combined or non-integrated manner limits sustainable outcomes. Nonetheless, both the multi-criteria and LCA methods retain a degree of approximation due to data availability and the complexity of comparing multiple alternatives. Future research should refine these methodologies, moving beyond basic cost-benefit frameworks to capture the full scope of seismic and energy retrofitting implications.

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