



## A FRAMEWORK FOR THE SUSTAINABLE RENOVATION OF EXISTING STRUCTURES: APPLICATION TO A REFERENCE BUILDING

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### Abstract

The current dramatic environmental situation has emphasized the need to introduce sustainability issues into the construction sector to substantially reduce its large environmental impacts. Such impacts are mainly connected to raw material depletion during construction/renovation works, to the energy consumption and CO<sub>2</sub> emissions during operational phases, and to the waste disposal at the building dismissal and end-of-life. The most sustainable approach to the built environment should consider deep renovation rather than demolition-and-reconstruction, considering energy and structural upgrade of existing buildings to the modern standards, obtained through adoption of sustainable low-impact techniques.

With such premises, a sustainable building renovation design (SBR-D) framework has been recently proposed by the authors, which is aimed at identifying the most sustainable retrofit option under an environmental, social, and economic point of view. The framework is inspired by sustainability principles complying with the Life Cycle Thinking approach, such as: recyclability of the materials, reusability of the components, demountability of the solution, reparability/replaceability of the construction components, cost reduction over the life cycle and so on. This comprehensive approach allows minimizing the impacts during the whole life cycle of the retrofitted building, whilst boosting the actual implementation of the retrofit interventions. The framework also encourages the adoption of holistic retrofit strategies and techniques, tackling multiple building deficiencies in a single step (energy, structural, etc.).

The framework consists of 4 steps: 1- evaluation of the as-is condition of the building under a multidisciplinary point of view; 2- qualitative pre-screening of the possible retrofit solutions adopting multiple-criteria decision-making (MCDM) methods addressing environmental, social, and economic criteria; 3- design of the selected solutions with performance-based methods; 4- choice of the best retrofit option.

This paper presents the framework and its application for the renovation of a reference RC building typical of the European post-WWII building stock. In Step 2, the solutions are compared adopting a Multi Criteria Decision Making method. Different scenarios are considered depending on the building constraints and on the requirements of the stakeholders, thus defining different weights for the selected criteria. The best retrofit option under an environmental, social, and economic point of view is finally determined for each scenario.

*Keywords: building retrofit, sustainability, SBR design framework, Life Cycle Thinking (LCT), multiple-criteria decision-making (MCDM)*



## 1. Introduction

The need to renovate the obsolete existing building stock to tackle the current dramatic environmental situation has led to the definition of new principles for a sustainable renovation of buildings. Initially, sustainable renovation was intended as environmentally-sustainable renovation, mainly targeting the reduction of energy consumption of existing buildings, possibly adopting eco-friendly materials. More recently, the concept of sustainable renovation has been expanded to embrace all the pillars of sustainability: environmental, economic, and social sustainability – where social sustainability is also intended as protection of human life against collapse due to natural disasters. In such a new vision, the Sustainable Building Renovation (SBR) may be defined as the sum of retrofit interventions that should be applied to an existing building in order to reduce costs, CO<sub>2</sub> emissions, waste, losses and even casualties along the whole renovated-building life cycle, i.e. from the application of the retrofit intervention until the end-of-life of the renovated construction.

In this scenario, new Life Cycle Thinking (LCT) principles, such as recyclability of the materials, demountability, standardization and prefabrication for the reusability of the components, reparability/replaceability of the construction components after earthquakes, adaptability to building future needs, possibility of selective dismantling at the end-of-life, and adoption of holistic structural/energy/architectural techniques for the optimization of the resources, have been introduced to maximize the sustainability of the retrofit interventions [1-2]. In addition, deep renovation is always recommended with respect to demolition-and-reconstruction, unless it is strictly recommended for structural or social reasons.

Inspired by this urgent need to renovate the built environment in a sustainable way, new tools have been recently proposed, enabling the selection of the best retrofit option targeting eco-efficiency, cost-effectiveness, and safety. The most remarkable methods were proposed by [3-5], which developed evaluation tools combining Life Cycle Analysis (LCA), loss estimation, Life Cycle Cost (LCC) analysis and/or cost/benefit (C/B) analyses. Calvi et al. [3] proposed a Green and Resilient Indicator (GRI) enabling comparative assessment of different retrofit options by calculating the expected Structural and Energy Expected Annual Loss (EAL) before and after each retrofit intervention and combining the resulting B/C ratios into a comprehensive indicator. Lamperti Tornaghi et al. [4] proposed the Sustainable Structural Design (SSD) method based on 4 steps: energy performance assessment, life cycle assessment, structural performance assessment with a simplified loss assessment procedure, and final transformation and combination of the results into economic terms by introducing the Global Assessment Parameter (GAP), which is the total sum of the estimated environmental and structural impacts over the life cycle. Finally, Wei et al. [5] proposed an LCA framework to evaluate the long-term costs and benefit of seismic retrofit interventions. The procedure converts expected seismic damage, obtained using a HAZUS seismic-loss estimation, into 3 quantifiable social, economic, and environmental losses (corresponding to number of casualties, repair/replacement costs, and CO<sub>2</sub> emissions respectively), which in turn serve as metrics for the objectives of a cost-benefit performance-based design.

These methods embrace the principles of holistic energy/structural renovation of existing buildings and introduce new procedures to compare different solutions by estimating costs and GHG emissions at the construction stage and during the operative phase, also considering the seismic risk. However, although very innovative, those studies have some limitations. First, the impacts at end-of-life are usually not considered. In addition, the best retrofit option is evaluated by expressing losses and environmental impacts just in terms of costs and by identifying the best solution as the most cost-effective. However, Gluch and Baumann (2004) [6], among others, already observed that the oversimplification of the approach to a monetary unit, the lack of reliable data inventory about CO<sub>2</sub> emissions, and the complexity of the building process may often limit the usefulness of cost-based methods for the choice of the most sustainable retrofit alternative. Finally, and most importantly, all these methods are comparative assessment frameworks applied at the end of the design process (ex-post evaluation methods). This implies that: 1- they enable the selection of the most sustainable solution among a set of alternatives that, disregarding the LCT principles in their conceptual design, may be neither eco-efficient nor low-impact by themselves; 2- they enable the comparison of solutions that may lead also to very different performances of the retrofitted building. A multidisciplinary design framework to be



used both as an ex-ante and ex-post tool is still required. Such framework should guide the designer toward the proposal and the selection of the most sustainable and cost-effective solutions, addressing safety and eco-efficiency from the early design phase. In addition, it should enable involvement of all the stakeholders into the pre-design analysis phase and should adopt a Life Cycle perspective, as envisioned by the SAFESUST roadmap [7].

In this paper, a framework for the sustainable renovation of existing buildings, recently proposed by the authors, is presented. The need to introduce a pre-screening phase for a preliminary evaluation of suitability and eligibility of possible retrofit alternatives under a Life Cycle perspective is highlighted. A Multi Criteria Decision Making (MCDM) method based on the TOPSIS method [8-9] is presented and then adopted for the pre-screening of a set of retrofit solutions conceived for the seismic upgrade of a reference RC building typical of the post-WWII building stock. Criteria inspired by the principles of LCT and addressing all the three pillars of sustainability are first defined. Three different scenarios are considered depending on the building constraints and on the requirements of the stakeholders, thus defining different weights for the selected criteria. The best retrofit option under an environmental, social, and economic point of view is finally determined for each scenario.

## 2. A framework for the sustainable renovation of existing buildings and the need for a pre-screening phase including Life Cycle Thinking principles

A framework for the sustainable renovation of existing buildings has recently been proposed by the authors [10-11], aimed at identifying the most sustainable retrofit option under an environmental, social, and economic point of view, according to LCT principles.

The framework consists of a four step procedure (Fig.1), including: 1) assessment of the existing building under a holistic perspective to identify possible deficiencies (energy audit, structural/seismic assessment, etc.); 2) prescreening of the possible retrofit strategies on the basis of the new economic, social, and environmental LCT principles adopting MCDM approaches; 3) design of the selected retrofit solutions adopting a multi-criteria performance based design, i.e. considering from the beginning the possible interferences among the structural/energy/functional/etc. “layers” of the intervention; 4) selection of the best retrofit option under a sustainable point of view, adopting for the assessment of the impacts the most updated Life Cycle procedures, which also include seismic risk [3-5, 12-14], and MCDM approaches for the evaluation of the best retrofit option.

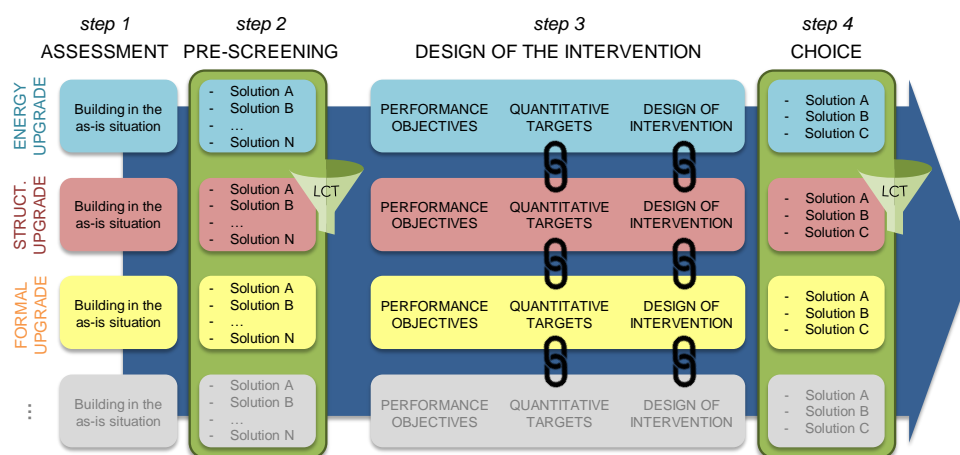


Fig. 1 – Sustainable Building Renovation Design (SBR-D) framework (from [11])

It should be considered that, with respect to the frameworks previously introduced, a major innovation lays in the introduction of the second step of the method, which entails a shift from a pure “ex-post” to an “ex-ante and ex-post” assessment method. In this phase, stakeholders, decision makers, and design professional are invited to collaborate to jointly define pre-requisites and criteria to be addressed in the conceptual design of the renovation project. Those criteria may be both quantitative and qualitative and may be inspired by the



LCT principles (e.g. restriction to operate from outside the building, use of dry solutions/prefabrication, etc.). When such a “filter” is applied before the design phase (Step 3), unsuitable and unsustainable solutions may be discarded from the beginning of the process, while innovative holistic and sustainable solution may be encouraged.

By adopting LCT criteria and principles to critically and comparatively evaluate alternative retrofit interventions, it appears that different techniques may enable attaining the same energy/structural performances, but such alternatives may have quite different impacts and costs over the LC. Considering for example the seismic retrofit techniques, strengthening of the frame nodes can be effective from a structural point of view but may pose some issues in all stages of the building use (Fig.2, left). This solution, in fact, requires the demolition of the finishing, which are worth 70% of the construction value, it requires the relocation of the inhabitants, and it does not enable reparability nor adaptability or demountability at the end of life. On the contrary, when a LC perspective is embraced, the conceptual design of new renovation models and solution sets are encouraged. Holistic retrofit solutions that contextually address more than one deficiency and are compliant with the LCT principles (standardization, demountability, reparability, reusability, etc.), such as the integrated intervention introducing exoskeletons, were conceived within this new and expanded vision of sustainable renovation [1] [15] (Fig.2, right).

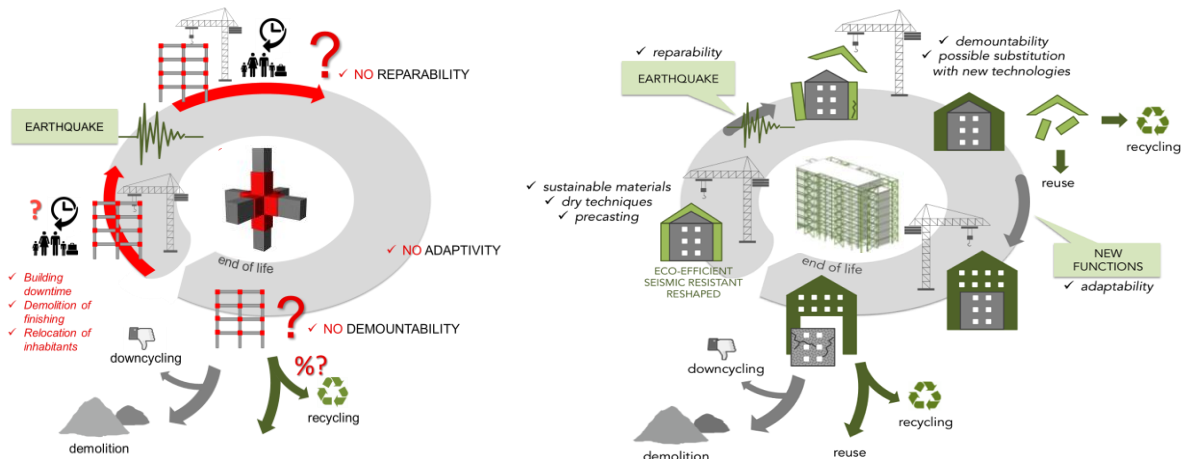


Fig. 2 – LCT principles for the preliminary evaluation of two retrofit alternatives: strengthening of the frame joints (left) and holistic structural and energy exoskeleton (right) (from [2]).

### 3. Application of the TOPSIS method for the qualitative evaluation of possible seismic retrofit solutions under an LCT perspective

Focusing on this second step of the framework, MCDM procedures may be adopted to define the most sustainable retrofit solutions to be designed in the following Step 3. In this paper, a MCDM approach based on the TOPSIS method – first proposed by Saaty [8] and then adapted by Caterino et al. [9] to the building renovation sector – is applied for a pre-screening of possible seismic retrofit solutions of a RC building typical of the post-WWII building stock, located in Brescia, a city of medium seismicity in northern Italy. The method, briefly described in Appendix, is here adapted to be applied as an ex-ante evaluation method adopting new qualitative criteria. Such criteria should be inspired by the principles of Life Cycle Thinking, connected to all the three pillars of sustainability, and defined since the first stage by all the stakeholders involved in the design process. This way, only the most sustainable and suitable solutions may be designed. According to the proposed framework, the multiple retrofit needs of the building were first identified in Step 1. Nonlinear static analyses were carried out to evaluate the capacity of the structure in the as-is condition. According to the analyses, the building experiences extensive damage for an earthquake corresponding to the Damage Limit State and collapses for an earthquake less intense than that corresponding to the Life Safety Limit State, as defined in [16] (Fig. 3) (more details may be found in [10]).

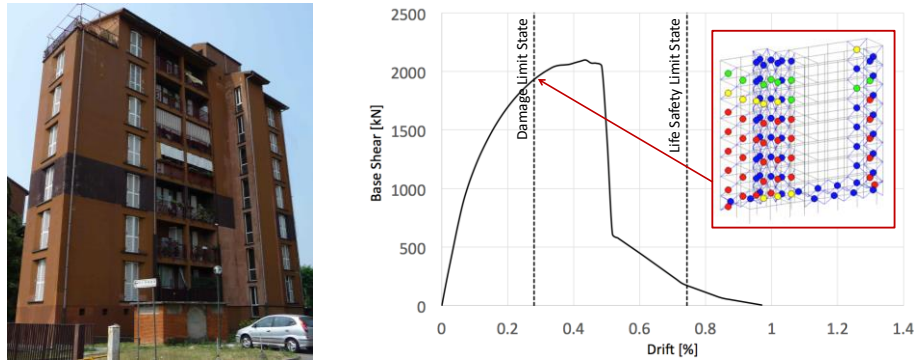


Fig. 3 – Reference RC building typical of the post-WWII building stock: external view (left) and capacity curve of the building in the as-is situation (right) (from [10])

In order to reduce the seismic vulnerability of the existing structure, a pre-screening of possible retrofit interventions is carried out in Step 2 of the design to select the most sustainable solutions to be designed in Step 3 of the framework. The MCDM procedure based on TOPSIS method is here adopted [9]. 6 different alternatives are considered (Fig.4a): frame joint and column strengthening (A1), strengthening of selected bays of the frame (A2), base isolation (A3), and strengthening from outside with either RC (A4) or steel (A5) shear walls [1], or with steel diagrid exoskeletons [15] (A6). Each solution is designed to target the same performance objectives, but substantial differences can be observed in terms of environmental impacts and costs. 14 different criteria, also including those inspired by LCT, are then defined in order to qualitatively evaluate potential environmental, economic, and social impacts of each solution in each stage of the building life cycle (Fig.4b).

<b>A1</b>	Node strengthening
<b>A2</b>	Strength of selected bays
<b>A3</b>	Seismic isolation
<b>A4</b>	RC shear walls
<b>A5</b>	Steel shear walls
<b>A6</b>	Steel diagrid

(a)

<b>C1</b>	duration of works	SOC
<b>C2</b>	renovation costs	ECO
<b>C3</b>	need for additional space	TEC
<b>C4</b>	need for inhabitant relocation	SOC
<b>C5</b>	fast assembling*	ENV
<b>C6</b>	waste generation*	ENV
<b>C7</b>	possibility to increase living space	ECO/SOC
<b>C8</b>	adaptability (IR)*	ECO
<b>C9</b>	need for maintenance	ECO
<b>C10</b>	repair cost	ECO
<b>C11</b>	impacts connected to repair	ENV
<b>C12</b>	building downtime	SOC
<b>C13</b>	fast disassembling*	ENV
<b>C14</b>	recyclability/reusability*	ENV

(b)

Fig. 4 – Seismic retrofit alternatives (a) and criteria connected to the pillars of sustainability (SOC: social, ECO: economic, ENV: environmental) (TEC: technical) (b) (\*new criteria inspired by LCT)

In the first stage of Step 2, the retrofit alternatives are assessed adopting a pairwise comparison. For each criterion  $C_k$ , a matrix is assembled, where each line  $i$  represents how better/worse is alternative  $A_i$  than alternative  $A_j$  in column  $j$  (Fig.5). The eigenvectors corresponding to the maximum eigenvalue of each matrix, normalized first with Eq. (1) and then with Eq. (2) reported in Appendix, lead to the matrix  $D$  and  $R$ , reported in Table 1 and 2, respectively. The normalized decision matrix  $R$  is also represented in Fig.6. It should be noted that such matrices are based on qualitative considerations exclusively referred to the reference building and based on the experience of the evaluators. They may thus change when a different building with different construction technology and geometry, erected in a different period or in a different site, were considered.



C1 - duration of works							C2 - renovation costs						C3 - need for additional space							
	A1	A2	A3	A4	A5	A6		A1	A2	A3	A4	A5	A6		A1	A2	A3	A4	A5	A6
A1	1	1/2	1/2	1/2	1/7	1/7	A1	1	1/2	1/5	1/2	1/2	1/5	A1	1	1	1	7	7	7
A2	2	1	1	1	1/3	1/3	A2	2	1	1/3	1	1/2	1/3	A2	1	1	1	7	7	7
A3	2	1	1	1	1/3	1/3	A3	5	3	1	3	2	1	A3	1	1	1	7	7	7
A4	2	1	1	1	1/3	1/3	A4	2	1	1/3	1	1/2	1/3	A4	1/7	1/7	1/7	1	1	1
A5	7	3	3	3	1	1	A5	2	2	1/2	2	1	1/2	A5	1/7	1/7	1/7	1	1	1
A6	7	3	3	3	1	1	A6	5	3	1	3	2	1	A6	1/7	1/7	1/7	1	1	1

C4 - need for inhabitant relocation							C5 - fast assembling						C6 - waste generation							
	A1	A2	A3	A4	A5	A6		A1	A2	A3	A4	A5	A6		A1	A2	A3	A4	A5	A6
A1	1	1	1/9	1/9	1/9	1/9	A1	1	1	1/3	1/3	1/9	1/9	A1	1	1	1/5	1/5	1/9	1/9
A2	1	1	1/9	1/9	1/9	1/9	A2	1	1	1/3	1/3	1/9	1/9	A2	1	1	1/5	1/5	1/9	1/9
A3	9	9	1	1	1	1	A3	3	3	1	1	1/3	1/3	A3	5	5	1	1	1/2	1/2
A4	9	9	1	1	1	1	A4	3	3	1	1	1/3	1/3	A4	5	5	1	1	1/2	1/2
A5	9	9	1	1	1	1	A5	9	9	3	3	1	1	A5	9	9	2	2	1	1
A6	9	9	1	1	1	1	A6	9	9	3	3	1	1	A6	9	9	2	2	1	1

C7 - poss. to increase living space							C8 - adaptability (IR)						C9 - need for maintenance							
	A1	A2	A3	A4	A5	A6		A1	A2	A3	A4	A5	A6		A1	A2	A3	A4	A5	A6
A1	1	1	1	1/9	1/9	1/9	A1	1	1/5	1	1/5	1/9	1/9	A1	1	1	9	1	9	9
A2	1	1	1	1/9	1/9	1/9	A2	5	1	5	1	1/2	1/2	A2	1	1	9	1	9	9
A3	1	1	1	1/9	1/9	1/9	A3	1	1/5	1	1/5	1/9	1/9	A3	1/9	1/9	1	1/9	1	1
A4	9	9	9	1	1	1	A4	5	1	5	1	1/2	1/2	A4	1	1	9	1	9	9
A5	9	9	9	1	1	1	A5	9	2	9	2	1	1	A5	1/9	1/9	1	1/9	1	1
A6	9	9	9	1	1	1	A6	9	2	9	2	1	1	A6	1/9	1/9	1	1/9	1	1

C10 - repair cost							C11 - impacts connected to repair						C12 - building downtime							
	A1	A2	A3	A4	A5	A6		A1	A2	A3	A4	A5	A6		A1	A2	A3	A4	A5	A6
A1	1	1	1/9	1/5	1/9	1/9	A1	1	1	1/9	1/5	1/9	1/9	A1	1	1/5	1/9	1/5	1/9	1/9
A2	1	1	1/9	1/5	1/9	1/9	A2	1	1	1/9	1/5	1/9	1/9	A2	5	1	1/2	1	1/2	1/2
A3	9	9	1	2	1	1	A3	9	9	1	2	1	1	A3	9	2	1	2	1	1
A4	5	5	1/2	1	1/2	1/2	A4	5	5	1/2	1	1/2	1/2	A4	5	1	1/2	1	1/2	1/2
A5	9	9	1	2	1	1	A5	9	9	1	2	1	1	A5	9	2	1	2	1	1
A6	9	9	1	2	1	1	A6	9	9	1	2	1	1	A6	9	2	1	2	1	1

C13 - fast disassembling							C14 - recyclability/reusability						
	A1	A2	A3	A4	A5	A6		A1	A2	A3	A4	A5	A6
A1	1	1	1/9	1	1/9	1/9	A1	1	1	1/9	1	1/9	1/9
A2	1	1	1/9	1	1/9	1/9	A2	1	1	1/9	1	1/9	1/9
A3	9	9	1	9	1	1	A3	9	9	1	9	1	1
A4	1	1	1/9	1	1/9	1/9	A4	1	1	1/9	1	1/9	1/9
A5	9	9	1	9	1	1	A5	9	9	1	9	1	1
A6	9	9	1	9	1	1	A6	9	9	1	9	1	1

Fig. 5 – Pairwise comparison of the possible alternatives with respect to each criterion

Table 1 – Decision matrix D

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
A1	0.049	0.058	0.292	0.026	0.038	0.033	0.033	0.033	0.300	0.029	0.029	0.026	0.033	0.033
A2	0.104	0.097	0.292	0.026	0.038	0.033	0.033	0.159	0.300	0.029	0.029	0.123	0.033	0.033
A3	0.104	0.295	0.292	0.237	0.115	0.159	0.033	0.033	0.033	0.268	0.268	0.242	0.300	0.300
A4	0.104	0.097	0.042	0.237	0.115	0.159	0.300	0.159	0.300	0.139	0.139	0.123	0.033	0.033
A5	0.320	0.159	0.042	0.237	0.346	0.308	0.300	0.308	0.033	0.268	0.268	0.242	0.300	0.300
A6	0.320	0.295	0.042	0.237	0.346	0.308	0.300	0.308	0.033	0.268	0.268	0.242	0.300	0.300

Table 2 – Normalized decision matrix R

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
A1	0.101	0.124	0.572	0.055	0.074	0.067	0.064	0.067	0.574	0.060	0.060	0.057	0.064	0.064
A2	0.212	0.207	0.572	0.055	0.074	0.067	0.064	0.324	0.574	0.060	0.060	0.271	0.064	0.064
A3	0.212	0.627	0.572	0.498	0.222	0.324	0.064	0.067	0.064	0.551	0.551	0.532	0.574	0.574
A4	0.212	0.207	0.082	0.498	0.222	0.324	0.574	0.324	0.574	0.286	0.286	0.271	0.064	0.064
A5	0.654	0.337	0.082	0.498	0.667	0.625	0.574	0.625	0.064	0.551	0.551	0.532	0.574	0.574
A6	0.654	0.627	0.082	0.498	0.667	0.625	0.574	0.625	0.064	0.551	0.551	0.532	0.574	0.574

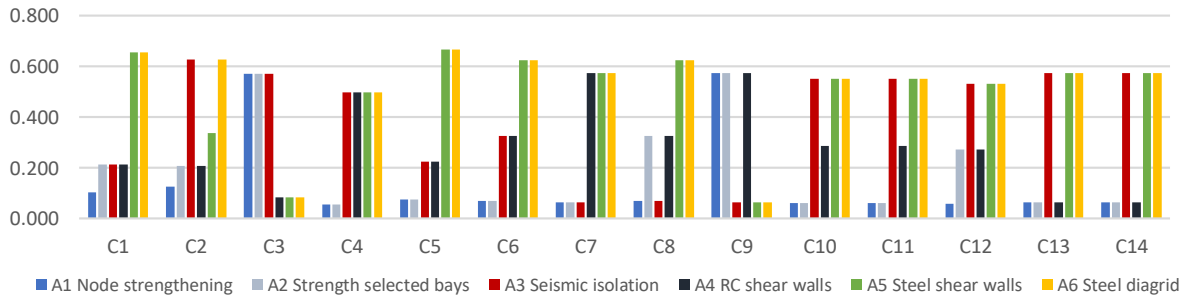


Fig. 6 – Representation of the normalized decision matrix R: comparison of the normalized performances of each alternative with respect to each criterion (the higher corresponds to the better performance)

In the second phase of the method, possible operative constraints, owners' and stakeholders' requirements are considered in order to assign different weights to the selected criteria. Adopting the same approach considered to compare retrofit alternatives, a pairwise comparison of the criteria is carried out, and a matrix is assembled to define which criteria is considered more important than the other. The eigenvector  $\lambda_{max}$  corresponding to the maximum eigenvalue of this matrix, normalized by Eq. (1) reported in Appendix, represents the weight vector  $w$  that is adopted to scale the normalized decision matrix. For the reference building, three different scenarios are discussed.

### 3.1 Scenario 1

In a first scenario, the building has a residential use. In this case, the inhabitants are not willing to leave their apartments during the retrofit works and have a limited budget. When such requirements lead the choice of the retrofit measures, the weight associated with the criterion C4 'need for inhabitants' relocation' is so high that the structural solutions requiring the relocation of the inhabitants are strongly penalized, and the decision is governed by the criteria C1, C2, C7, and C9, which are the 'duration of works', 'renovation costs', 'possibility to increase living space', and 'need for maintenance', respectively, which have the highest weight (Table 3).

Table 3 – Pairwise comparison of criteria for Scenario 1

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
C1	1	1	5	1/2	2	3	1	5	1	2	3	2	3	3
C2	1	1	5	1/2	2	3	1	5	1	2	3	2	3	3
C3	1/5	1/5	1	1/9	1/2	1/2	1/5	1	1/5	1/2	1/2	1/2	1/2	1/2
C4	<b>2</b>	<b>2</b>	<b>9</b>	<b>1</b>	<b>5</b>	<b>7</b>	<b>2</b>	<b>9</b>	<b>2</b>	<b>5</b>	<b>7</b>	<b>5</b>	<b>7</b>	<b>7</b>
C5	1/2	1/2	2	1/5	1	2	1/2	2	1/2	1	2	1	2	2
C6	1/3	1/3	2	1/7	1/2	1	1/3	2	1/3	1/2	1	1/2	1	1
C7	1	1	5	1/2	2	3	1	5	1	2	3	2	3	3
C8	1/5	1/5	1	1/9	1/2	1/2	1/5	1	1/5	1/2	1/2	1/2	1/2	1/2
C9	1	1	5	1/2	2	3	1	5	1	2	3	2	3	3
C10	1/2	1/2	2	1/5	1	2	1/2	2	1/2	1	2	1	2	2
C11	1/3	1/3	2	1/7	1/2	1	1/3	2	1/3	1/2	1	1/2	1	1
C12	1/2	1/2	2	1/5	1	2	1/2	2	1/2	1	2	1	2	2
C13	1/3	1/3	2	1/7	1/2	1	1/3	2	1/3	1/2	1	1/2	1	1
C14	1/3	1/3	2	1/7	1/2	1	1/3	2	1/3	1/2	1	1/2	1	1

The eigenvector  $\lambda_{max}$  of the matrix in Table 3 and the weight vector  $w_l$  of Scenario 1 are respectively:

$$\lambda_{max} = [-0.32 \quad -0.32 \quad -0.06 \quad -0.69 \quad -0.17 \quad -0.10 \quad -0.32 \quad -0.06 \quad -0.32 \quad -0.17 \quad -0.10 \quad -0.17 \quad -0.10 \quad -0.10]$$

$$w_l = [0.11 \quad 0.11 \quad 0.02 \quad 0.23 \quad 0.06 \quad 0.03 \quad 0.11 \quad 0.02 \quad 0.11 \quad 0.06 \quad 0.03 \quad 0.06 \quad 0.03 \quad 0.03]$$



By multiplying each line of the normalized decision matrix  $R$  by the weight vector  $w_j$ , the performances of each alternative are scaled to consider the weight of each criterion (Table 4). The best and worst ideal solutions  $A^+$  and  $A^-$  are then selected (Table 5), and the ranking of the alternatives for the Scenario 1 are calculated by applying Eq. (3-4) reported in Appendix (Fig.7). In this case, the best alternative is the steel diaphragm exoskeleton, followed by the ones adopting exterior steel and RC walls.

A representation of the decision matrix before and after the weighting process is also shown in Fig.8a and b by means of a radar graph. In the graph, each radius represents a criterion ( $C1$  to  $C14$ ), and each colored line is a different retrofit alternative ( $A1$  to  $A6$ ). The farther the line from the center, the better is the alternative with respect to each criterion.

Table 4 – Weighted normalized decision matrix  $V$  for Scenario 1

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
A1	0.011	0.013	0.012	0.013	0.004	0.002	0.007	0.001	0.061	0.003	0.002	0.003	0.002	0.002
A2	0.023	0.022	0.012	0.013	0.004	0.002	0.007	0.007	0.061	0.003	0.002	0.015	0.002	0.002
A3	0.023	0.066	0.012	0.115	0.012	0.011	0.007	0.001	0.007	0.031	0.019	0.030	0.020	0.020
A4	0.023	0.022	0.002	0.115	0.012	0.011	0.061	0.007	0.061	0.016	0.010	0.015	0.002	0.002
A5	0.069	0.036	0.002	0.115	0.037	0.021	0.061	0.013	0.007	0.031	0.019	0.030	0.020	0.020
A6	0.069	0.066	0.002	0.115	0.037	0.021	0.061	0.013	0.007	0.031	0.019	0.030	0.020	0.020

Table 5 – Ideal solutions  $A^+$  and  $A^-$  for Scenario 1

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
$A^+$	0.069	0.066	0.012	0.115	0.037	0.021	0.061	0.013	0.061	0.031	0.019	0.030	0.020	0.020
$A^-$	0.011	0.013	0.002	0.013	0.004	0.002	0.007	0.001	0.007	0.003	0.002	0.003	0.002	0.002

	$S_i^+$	$S_i^-$	$C_i^*$
A1	0.153	0.055	0.26
A2	0.144	0.058	0.29
A3	0.094	0.126	0.57
A4	0.078	0.130	0.62
A5	0.063	0.146	0.70
A6	0.055	0.153	0.74

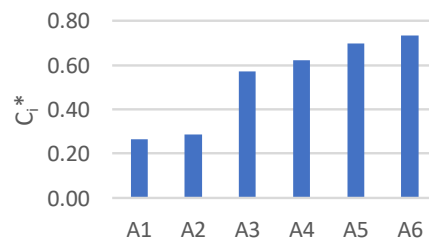


Fig. 7 – Ranking of the alternative solutions for Scenario 1

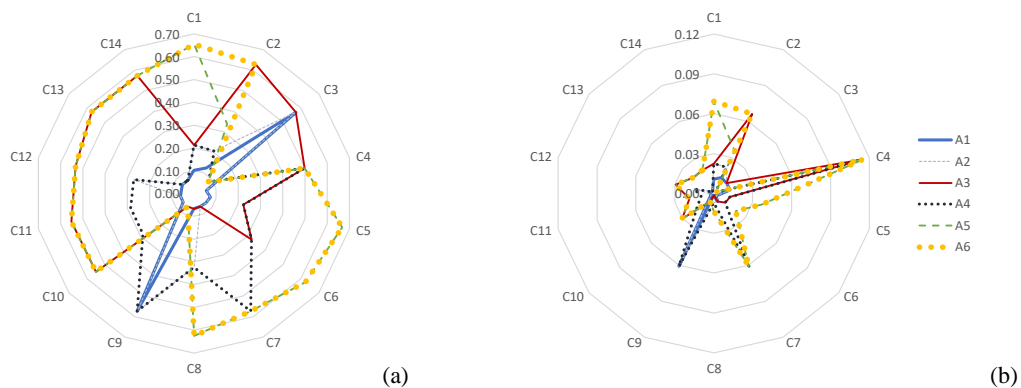


Fig. 8 – Normalized performances (a) and weighted normalized performances of the different alternatives with respect to each criterion for the scenario 1 (b).



### 3.2 Scenario 2

In scenario 2, the building still has a residential function, and the inhabitants are not willing to leave their apartments during the renovation works. However, this time, they have no restricted budget, but they want to realize the most environmental-friendly retrofit. In such a scenario, the leading criterion remains the C4, ‘need for inhabitants relocation’, followed by the criteria C5, C6, C11, C13, and C14, corresponding to ‘fast assembling’ and ‘waste generation’ during the construction time, ‘impacts connected to repair’ after an earthquake, and ‘fast disassembling’ and ‘recyclability/reusability’ at the end of life. Accordingly, a matrix similar to the one in Table 3 was compiled (here omitted), leading to a resulting weight vector:

$$w_{II} = [0.05 \quad 0.05 \quad 0.02 \quad 0.21 \quad 0.10 \quad 0.10 \quad 0.02 \quad 0.02 \quad 0.05 \quad 0.05 \quad 0.10 \quad 0.05 \quad 0.10 \quad 0.10]$$

Following the previous procedure, the ranking of the alternative retrofit solutions may be estimated (Fig.9). In this case, alternatives A1 and A2 are the least suitable, followed by alternative A4, A3, A5, and A6, respectively. The best solution is represented by alternative A6, steel diagrids. It is worth noting that alternative A3, base isolation, is considered eco-friendlier than the A4, exterior RC walls (Fig.11a).

	Si+	Si-	Ci*
A1	0.158	0.026	0.14
A2	0.155	0.029	0.16
A3	0.064	0.136	0.68
A4	0.099	0.105	0.51
A5	0.029	0.157	0.84
A6	0.026	0.158	0.86

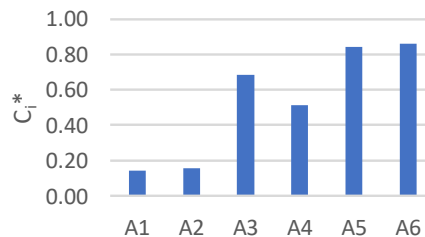


Fig. 9 – Ranking of the alternative solutions for Scenario 2

### 3.3 Scenario 3

In the last scenario, the main constraints for the renovation are the low budget and the impossibility to increase the building space (i.e. according to the urban planning restriction the building can only be supplemented with a thermal layer and no extra spaces/volume are allowed). In this case, this requirement would reduce the choice to the three structural solutions that do not require additional space around the building, corresponding to: the strengthening of either the frame joints (A1) or of selected bays (A2), and the base isolation (A3). Given the mandatory technical constraint, solutions A4 to A6 are directly disregarded, and criteria C3 is excluded. The leading criteria are C1, C2, C4, C7, and C9, as in Scenario 1, but, in this case, they have the same importance. Even in this case, a matrix similar to the one in Table 3 was compiled (here omitted), and the resulting weight vector is:

$$w_{III} = [0.14 \quad 0.14 \quad 0.00 \quad 0.14 \quad 0.06 \quad 0.03 \quad 0.14 \quad 0.02 \quad 0.14 \quad 0.06 \quad 0.03 \quad 0.06 \quad 0.03 \quad 0.03]$$

The ranking of the alternative retrofit solutions may thus be estimated (Fig.10). From the comparative analysis, the best retrofit solution is the base isolation (A3). In fact, this solution outperforms alternatives A1 and A2 with respect to each criterion, except for criteria C8 and C9 (‘adaptability – possibility to apply incremental rehabilitation’ and ‘need for maintenance’, respectively) (Fig.11b).

	Si+	Si-	Ci*
A1	0.190	0.085	0.31
A2	0.170	0.102	0.37
A3	0.086	0.190	0.69



Fig. 10 – Ranking of the alternative solutions for Scenario 3

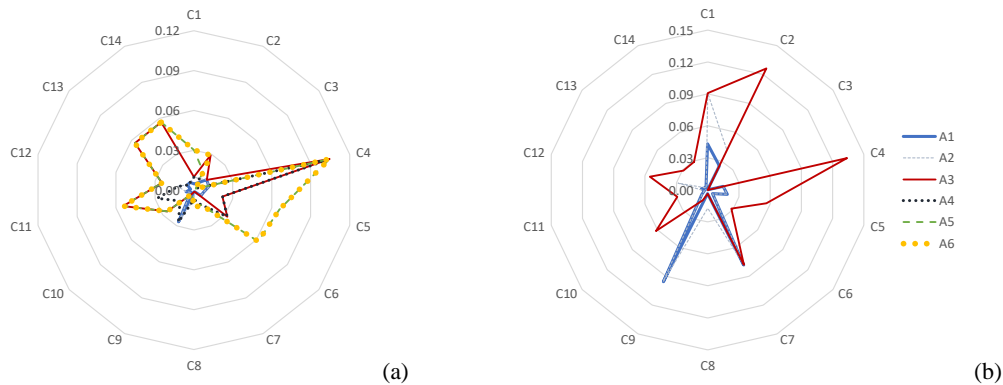


Fig. 11 – Weighted normalized performances of the different alternatives with respect to each criterion for the scenario 2 (a) and 3 (b).

#### 4. Concluding remarks

The need to introduce sustainability in the renovation of existing buildings has led to the development of new frameworks and tools for the selection of the best retrofit options under an environmental and economic point of view, also accounting for the losses due to potential earthquakes during the building life cycle. Nevertheless, such frameworks have two main limitations: 1- they convert all the impacts and losses in costs, which may result in an oversimplification of the problem; 2- they are ex-post assessment tools which are applied at the end of the renovation process, neglecting many of the LCT principles that may guide the choice of eco-efficient, low-impact solutions.

A framework for the sustainable renovation of existing buildings has been recently proposed by the authors, aimed at identifying the most sustainable retrofit option under an environmental, social, and economic point of view. The framework is inspired by sustainability principles of Life Cycle Thinking with the aim of minimizing the impacts during the whole life cycle of the retrofitted building, whilst increasing the actual implementation of the retrofit interventions. The framework consists of 4 steps: 1- evaluation of the as-is condition of the building under a multidisciplinary point of view; 2- qualitative pre-screening of the possible retrofit solutions adopting multiple-criteria decision-making (MCDM) methods addressing environmental, social, and economic criteria; 3- design of the selected solutions with performance-based methods; 4- choice of the best retrofit option.

In the framework, particular importance is assumed by step 2, which entails an extension from an “ex-post” to an “ex-ante and ex-post” assessment of the possible retrofit solutions. In this phase, stakeholders, decision makers and design professional are invited to collaborate to jointly define pre-requisites and criteria to be addressed in the conceptual design of the renovation project and principles of LCT may be addressed for the definition of the criteria. This way, unsuitable and unsustainable solutions may be discarded from the beginning of the process, while innovative holistic and sustainable solution may be encouraged.

This paper presents an application of the Step 2 of the framework for the preliminary assessment of possible techniques for the seismic retrofit of a reference RC building typical of the European post-WWII building stock. The solutions are compared adopting a MCDM method based on the TOPSIS method. Different scenarios are considered depending on the building constraints and on the requirements of the stakeholders, thus defining different weights for the selected criteria. The best retrofit options under an environmental, social, and economic point of view is finally determined for each scenario and are selected to be designed in the following step of the framework. The complete application of the framework to the considered building is under development in a companion research.

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## Appendix: Review of the TOPSIS Method

A brief review of the MCDM evaluation procedure based on the TOPSIS method – first proposed by Saaty [8] and then adapted by Caterino et al. [9] to the building renovation sector – is here presented. The method consists of two phases. In a first phase, the retrofit alternatives are assessed adopting a pairwise comparison. Considering two alternatives at a time, a preliminary qualitative evaluation defines which alternative is better than the other according to the considered criterion and with which ‘intensity of importance’. A value  $a_{ij}=1$  is assigned if the alternatives have the same importance; an  $a_{ij}$  included into the interval [2 3 ... 9] is considered if the alternative  $i$  is better than the alternative  $j$ ; and an  $a_{ij}$  included into the interval [1/9 1/8 ... 1/2] is considered if  $j$  is better than  $i$ . For example, when  $a_{ij}=2$  the performance of alternative  $i$  is considered 2-times better than the alternative  $j$ , when  $a_{ij}=1/2$  the performance of alternative  $i$  is considered 2-times worse than the alternative  $j$ . It should be observed that, for example, the distance between the values 2 and 3 is higher than the distance between the values 7 and 8, being  $a_{23}=3/2$  and  $a_{78}=8/7$ .

Each one of this pairwise comparison is then assembled into a  $n \times n$  matrix where the columns and the rows represent the  $n$  selected alternatives and where  $a_{ii}=1$  and  $a_{ij}=1/a_{ji}$ . The eigenvector of this matrix associated to the maximum eigenvalue will represent a quantitative evaluation of the performance of each alternative with respect to the considered criterion. The eigenvectors are then normalized as to have:

$$\sum_{i=1}^n x_i = 1 \quad (1)$$

where  $x_i$  represent the normalized value of the eigenvector.

A  $n \times m$  decision matrix  $D$  is then assembled where rows represent the alternative retrofit solutions and the columns the various criteria. This matrix contains all the normalized eigenvectors of the evaluation matrices. Such matrix is then normalized considering the following equation:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^n x_{kj}^2}} \quad (2)$$

where  $x_{ij}$  is the performance measure of the  $i$ -th alternative ( $i=1 \dots n$ ) with respect to the  $j$ -th criterion and  $r_{ij}$  is the normalized value of  $x_{ij}$ , leading to the normalized decision matrix  $R$ .

In a second phase of the method, a similar procedure is applied to compare the criteria and define the weight vector. Pairs of criteria are compared and a value  $c_{ij}$  is assigned into a matrix. The eigenvector of the matrix associated to the maximum eigenvalue normalized with Eq. (1) represents the weight vector  $w$  and contains the weights associated to each criterion. A weighted normalized decision matrix  $V$  is thus derived by multiplying each column of the normalized decision matrix  $R$  by the weight vector  $w$  ( $v_{ij}=w_j r_{ij}$ ). From the weighted normalized decision matrix  $V$ , the ideal solutions  $A^+$  and  $A^-$  may be defined selecting the higher and the lower values for each criterion. The choice of the best and worse solutions is made by calculating the distances of each retrofit solution to the ideal positive and negative solutions ( $S_{i^+}$  and  $S_{i^-}$ , respectively) and the relative closeness of each retrofit solution to the ideal one  $C_i^*$ :

$$S_{i^+} = \sqrt{\sum_{j=1}^m (v_{ij} - v_{j^+})^2}; S_{i^-} = \sqrt{\sum_{j=1}^m (v_{ij} - v_{j^-})^2}; i=1 \dots n \quad (3)$$

$$C_i^* = \frac{S_{i^-}}{S_{i^+} + S_{i^-}} \quad (4)$$

where  $0 \leq C_i^* \leq 1$ ;  $A_i=A^+$ , if  $C_i^*=1$ ;  $A_i=A^-$ , if  $C_i^*=0$ . The best solution is the one with higher  $C_i^*$ .