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Redefining the concept of sustainable renovation of buildings: state of the art and an LCT-based design framework

Abstract: The sustainable renovation of existing buildings is commonly intended as the upgrade of the constructions by implementing green technologies and eco-friendly materials. More recently, the concept has been broadened to include all the pillars of sustainability (environmental, economic, and social aspects); however, it rarely encompasses structural safety, with the result that buildings renovated to be 'more sustainable' may remain structurally unsafe and even collapse in the case of earthquakes. Recent studies proposed new frameworks to include all these sustainability aspects in the building retrofit; however, these may still fail in the aim of minimizing impacts along the building life cycle and overcoming the barriers to the renovation. In this paper, a critical review of these existing methods for sustainable retrofit is firstly carried out, and the major research needs are highlighted. Trying to overcome these issues, the comprehensive concept of Sustainable Building Renovation (SBR) is introduced, addressing Life Cycle Thinking and holistic perspectives in each phase of the design. Then, an innovative SBR design framework, adopting Multi-Criteria Decision Making (MCDM) methods, a multi-disciplinary Performance-Based Design (PBD) approach, and expanded Life Cycle analyses, is proposed and applied to a typical European building to design and select the most sustainable retrofit option.

Keywords: Sustainable Building Renovation (SBR) design framework; Life Cycle Thinking (LCT); Multi-Criteria Decision Making (MCDM) method; multi-disciplinary Performance-Based Design (PBD); holistic renovation; Life Cycle analyses.

1. Introduction and research motivation

In the last 30 years, **sustainability** has become a priority for the socio-economic development of the global society. The rapid growth following WWII put the basis for a development that was unsustainable under a social and environmental point of view. In 1987, the Bruntland Commission (General Assembly of the United Nations) thus introduced for the first time the concept of "sustainable development", which "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). Such a development may be obtained from concurrently addressing economic, environmental, and social issues, i.e. the so-called "three pillars" of sustainability (United Nations, 1997), or sustainability triple bottom line.

The **construction sector** is one of the most impacting sectors of the global economy; possibly the one requiring a more systematic and thorough transformation. It is liable for the largest environmental impacts in terms of energy consumption (40%), waste production (33%), and raw material depletion (50%) in Europe (Marini et al., 2014). The need to foster sustainability in the building sector may thus be considered as a priority. In addition, about 35-40% of the European constructions was built before the 1960s (BPIE, 2011) and have already exhausted their nominal structural service life (50 years). These buildings are structurally obsolete and are inherently vulnerable to hazardous actions. The risk of damage or collapse induced by natural disasters is a major cause of additional impacts associated with waste, disposal and repair/reconstruction actions (Pan et al., 2014), besides causing the possible loss of assets and, more importantly, of human lives. When considering sustainability in the building sector, the protection of human lives through natural hazard risk mitigation (including anti-seismic interventions) should thus be considered among the social priorities. The need to 'make cities and human settlements inclusive, safe, resilient and sustainable' was indeed listed among the 17 goals of the United Nations' *2030 Agenda for Sustainable Development* (United Nations, 2015).

So far, the major attempts to foster sustainability in the construction sector has been the promulgation of national and European incentives and the definition of protocols for the construction of new eco-efficient buildings (LEED and GBC protocols, among others). Accordingly, sustainability may be pursued by constructing new buildings in unspoiled areas or by demolishing existing buildings and reconstructing new ones. In the former case, the occupation of unspoiled lands increases the burden on the environment; in the latter, demolition generates additional waste to be disposed, increasing the already unbearable pressure on existing landfills (Preservation Green Lab 2012, UCL Urban Lab 2014). In both cases, the alternatives do not solve the impacts of unsafe and energy-consuming existing buildings on the environment; hence, considering the current low construction rate (1.5% - Baek and Park, 2012), the construction of new eco-efficient buildings is insufficient to substantially decrease the greenhouse gas (GHG) emissions connected to the building sector. Therefore, renovation should be preferred when demolition is not strictly mandatory, i.e. when damage is so impairing and extended that the structures cannot be retrofitted.

Recently, the EU commission and the Member States have allocated funds and incentives for the retrofit of existing constructions, targeting either energy efficiency or seismic resilience (e.g. Italian 'Ecobonus' and 'Sismabonus'). However, also this strategy demonstrated serious limitations under two main points of view. First, to date, in the renovation practice, critical needs associated with structural safety, energy efficiency, comfort and architecture are still addressed separately with an **uncoupled approach**. Such a practice is the result of a quite sectorial technical culture established and corroborated by sectorial standards, codes and scientific literature, which has led, so far, to a renovation that mostly disregards the complex multiple needs of a single building as well as the possible interferences among different types of interventions (e.g. energy and structural, architectural and structural, etc.). As a result, safe buildings, i.e. retrofitted following Eurocode 8 recommendations (EC8), may remain severely unsustainable or may even worsen their environmental impacts after the structural retrofit; whereas an upgraded nearly-Zero Energy Building (or LEED Platinum), renewed according to most updated design criteria, may collapse for a medium-intensity earthquake, demonstrating that important public investments on energy improvements vanish when structurally deficient constructions are hit by an earthquake. The same could be said for the design of acoustical upgrading interventions, architectural renovations, etc. The uncoupled approach is therefore ineffective in fostering a sustainable transformation of the existing buildings (Figure 1).

In addition, considering the current low renovation rate (1% - Baek and Park, 2012), it appears that even the retrofit actions and policies nowadays adopted will barely lead to a consistent reduction of the CO_2 emissions unless they address the main barriers to the renovation. BPIE (2011) and La Greca and Margani (2018) analyzed the **main technical, economic, and cultural/social barriers** to the renovation, showing that the major issues to be solved are connected to: the need for inhabitants' relocation and the building downtime during the intervention; high initial construction costs; long duration of the renovation works and impairing construction sites.

In such a scenario, two different approaches have been embraced by the scientific community to contribute to the sustainable building renovation. A first type of approach was aimed at the conceptual design of new sustainable solutions sets and techniques for the improvement of the performances of the existing buildings; the second one consisted in developing optimization tools for the selection of the most sustainable solutions implementing economic, environmental, and/or social criteria. Considering the three pillars of sustainability and the sole safety of the inhabitants against seismic risk as social aspect, both the approaches may be further divided into four main categories, namely: a- methods combining environmental and economic sustainability; b- methods combining safety and economic sustainability; c- methods combining safety and environmental sustainability; and, only recently, d- methods combining safety, environmental and economic sustainability.

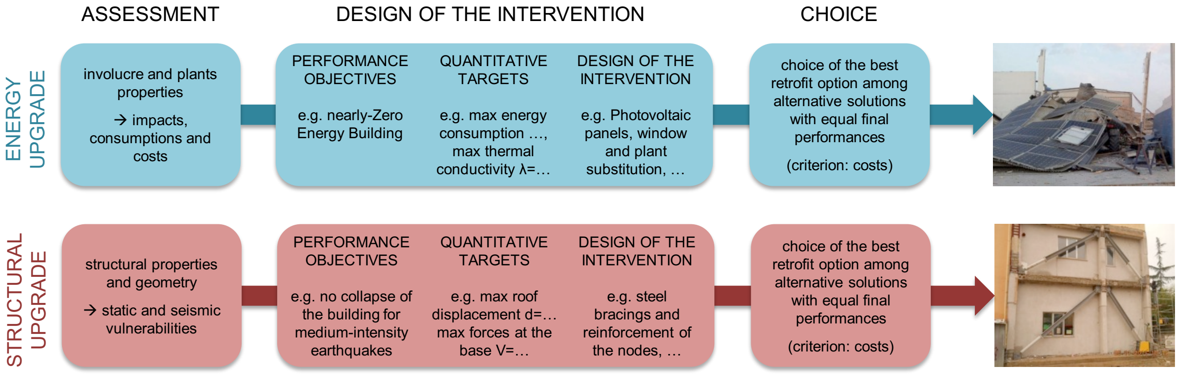


Figure 1. Example of current approach to the design of renovation based on sectorial PBD and decision-making practice (adapted from (Marini et al. 2017).

Based on these categories, in this paper, an in-depth analysis of the state of the art on sustainable renovation is first presented, distinguishing between studies proposing sustainable techniques and solution sets from those studies developing tools and frameworks for sustainable design. The main research needs are highlighted, and, trying to overcome such gaps, a new concept of Sustainable Building Renovation (SBR) is introduced and an innovative LCT-based framework for the holistic design of sustainable retrofit interventions is proposed. The framework represents a major synthesis and further effort of the leading-edge research on sustainable design, where innovative studies find a coherent collocation, allowing all the stakeholders to share a common language and foster sustainability in the built environment. As a major innovation, the framework introduces a qualitative prescreening of possible retrofit solutions before the design procedure to select the best options under the new enlarged vision of sustainability of the SBR approach. The proposed framework is finally applied to a reference building typical of the European post-WWII reinforced concrete (RC) building stock.

2. Sustainable renovation of existing buildings: a critical review of the state of the art

2.1. Sustainable techniques and solution sets

In order to improve the overall sustainability of the existing building stock and to overcome the major barriers to the renovation, new techniques and solution sets have recently been developed and proposed. These aim to improve not only the energy and structural performances of the existing buildings, but also other aspects related to innovative sustainability principles:

- Embrace a comprehensive **life cycle (LC) perspective**, which extends the reference design time frame to the entire life cycle of the building and allows the reduction of the economic, environmental, and social impacts in each LC phase by adopting the principles of **Life Cycle Thinking (LCT)** (Marini et al. 2017, 2018). In the *construction phase*, sustainability could be pursuit by reducing raw material consumption, the emissions due to transportation, and the construction energy and by adopting eco-efficient materials. Focusing on the *operational phase*, operational costs, energy consumptions and CO_2 emissions could be minimized, while safety and resilience maximized. Indeed, the risk of natural hazards could be addressed in this stage, limiting the possible hazard-induced damages so as to reduce waste due to debris disposal, demolition and reconstruction costs, and possible casualties. Accordingly, easily reparable/replaceable, dry-assembled and demountable solutions should thus be preferred. Adoption of micro-prefabricated systems and standardized connections would enable easy adaptability of the structure to possible future needs and usages or easy replacement with new components. Finally, when analyzing the *end-of-life*, the renovation could be conceived as to reduce, if not avoid, the demolition waste, down-cycling, and landfill disposal. Again, this may be obtained from ensuring total demountability and selective dismantling of the retrofitting system – e.g. with prefabricated dry techniques – and fostering reuse and recyclability of each retrofit component.
- Conceive **holistic** interventions able to solve contextually more than one building deficiency, i.e. energy consumption and seismic vulnerability, so as to maximize the intervention effectiveness whilst exploiting the synergy of the integrated retrofit to reduce the costs and duration of the construction works. In this way, it is possible to take advantage of the synergy of the shared construction site and couple the benefits of structural and energy renovations, e.g. by reinvesting the savings on the energy bills to finance the structural interventions (Takeuchi et al., 2009; Marini et al., 2017; Di Lorenzo et al., 2020).
- Adopt techniques installed/implemented/assembled exclusively **from outside** of the building in order to avoid the relocation of the inhabitants and the interruption of building functions, which is one of the major barriers to the renovation (Takeuchi et al., 2009; Marini et al., 2017; Passoni et al., 2020; Zanni et al., 2020; Margani et al., 2020).
- Conceive retrofit techniques inspired by the **incremental rehabilitation** approach (FEMA P-420, 2009; FEMA 395, 2003). This approach consists in meeting seismic and energy performance objectives by

implementing an ordered series of discrete rehabilitation actions over an extended period of time, often carried out together with already scheduled facility maintenance operations. Each retrofit action should provide a positive contribution to structural and energy behavior without leaving the building condition worse than before. The approach is “based on the postulate that incremental improvement is better than delayed improvement or no improvement at all, and that seismic rehabilitation in existing buildings would occur more frequently if initial costs and functional disruption could be reduced” (FEMA P-420). Addressing this approach, Zanni et al. (2019) also introduced the concept of “minimum intervention” for buildings in seismic prone areas, intended as the necessary first step of the incremental renovation process, tackling the major seismic vulnerabilities and guaranteeing a minimum level of safety.

A framing and cataloguing of the solution sets and interventions including one or more of the aforementioned principles is reported in Table 1, which is divided considering the research fields a, b, c, and d previously introduced.

Table 1. Critical Review of recent research fostering sustainable renovation of the building stock.

	Study	**technique**	**LCT**	**Holistic**	**From the outside**	**Incremental rehab.**
a	EU projects (smarTES, EnergieSprong, Winterface)	prefabricated panels for the energy and architectural upgrading applied from the outside	✓	✓	✓	
b	Masi et al. (2017)	Seismic renovation implemented with incremental rehabilitation				✓
c	Misawa et al. (2015), Susteric and Dujic (2014), Della Mora et al. (2015)	Steel/wood sandwich panels with structural and energy functions		✓	✓	
	Triantafillou et al. (2017)	textile reinforced mortars combined with thermal insulation		✓	✓	
	Manfredi and Masi (2018)	Additional infilled RC frame connected to the existing one		✓	✓	
d	Takeuchi et al. (2009), Di Lorenzo et al. (2020)	Structural and energy façade applied from the outside		✓	✓	
	Marini et al. (2017), Passoni et al. (2020), Labò et al. (2020).	Structural and energy exoskeleton applied from the outside with prefabricated standardized elements	✓	✓	✓	
	EU projects (AdESA, Zanni et al. 2020; e-SAFE, Margani et al. 2020)	Wood sandwich panels with structural and energy functions and prefabricated standardized elements	✓	✓	✓	
	Zanni et al. (2019)	Structural and energy exoskeleton applied from the outside with prefabricated standardized elements implemented with incr. rehab.	✓	✓	✓	✓

2.2. Tools for the design of sustainable interventions

In the past, some methodological tools were developed in each field of the sustainability triple bottom line (environmental, economic, and social-safety, Figure 2) with the aim of assessing the most sustainable solution to be applied in different situations occurring in the construction sector.

As for **environmental sustainability**, the main tools developed are: Life Cycle Assessment (LCA) (ISO 14040, 2006), evaluating and quantifying the environmental impacts of a system along all the stages of its life cycle; rating certification systems, such as LEED or GBC among others (Shan and Hwang, 2018), which assign a certain amount of points for virtuous and green achievements in the design, construction, operation, and maintenance of buildings; and certification systems, aimed at certifying retrofit solutions or buildings having a certain performance level (e.g. nearly Zero Energy Building – nZEB). As for **economic sustainability**, the main tools that may be applied to evaluate the most cost-efficient solutions are: Cost-Benefit Analyses (CBA); Life Cycle Cost (LCC) analyses, which are aimed at minimizing costs along the life cycle; and Multi-Criteria Decision Making (MCDM) analyses, which compare and score alternative solutions with reference to multiple weighted criteria. As for the **social sustainability**, Social-LCA (UNEP/SETAC, 2009) may be carried out to evaluate social and socio-economic impacts along the Life Cycle. In addition, the previously mentioned rating certification systems are also aimed at guaranteeing a high rate of indoor environmental quality, which may be associated with the social well-being of the inhabitants. However, when social sustainability is interpreted as **safety** of the inhabitants, different tools may be adopted to evaluate the effectiveness of a retrofit intervention. The optimal solution may be obtained from adopting the Performance Based Design (PBD), a framework for the design of solutions respectful of minimum performances, or by carrying out loss analyses, aimed at evaluating the interventions that generates the minimum losses in a considered seismic zone, e.g. by adopting PEER-PBEE or HAZUS frameworks and/or estimating the Expected Annual Loss (EAL) indicator. In the PEER-PBEE framework (Günay and Mosalam, 2013; FEMA P 58-1, 2018), four subsequent analyses – hazard, structural, damage, and loss analyses – are carried out in order to estimate the losses, usually expressed in terms of costs, casualties, or downtime. HAZUS framework (Kircher et al. 2006; FEMA 2013) follows a similar approach, but is usually carried out at a regional scale, thus including additional losses connected to damage to lifelines, and considering further risks, such as inundations, fire, etc. Finally, EAL is a common loss metric (or decision variable) representing the average value of loss that a building will sustain annually over its life span due to seismic or other hazards (Welch et al. 2014). These tools and metrics may express losses in economic terms, casualties and downtime.

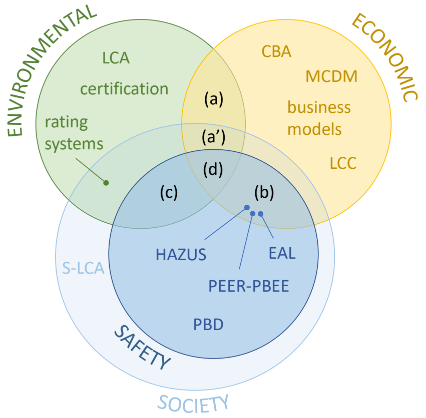


Figure 2. The three pillars of sustainability: environmental, economic and social (here interpreted as safety – or protection of human life). For each field, the tools adopted for the design and for the selection of the best option are represented.

The inefficiency of the current "sectorial" or "separated" approach to the design has been only recently reported, highlighting the need for new methods able to define the most sustainable retrofit solution under a multidisciplinary point of view. Thus, new researches have been developed, proposing new combined design methods and tools. In the following, each of the research field a, b, c and d of Figure 2 is briefly reviewed and critically commented. A synthesis of this critical comparison is reported in Table 2.

Table 2. Cataloguing of available frameworks and tools fostering sustainable renovation of the building stock.

	Study	comparative assessment tools (ex-post)
a	Jagarajan et al. (2017)	(review)
	Hajare and Elwakil (2020)	LCC
	Gangolells et al. (2020)	Energy simulations + LCC + LCA
	Moschetti and Brattebø (2016)	Sustainable-based building models (SBMs)
a'	Si et al. (2016)	MCDM (review)
	Pons et al. (2016)	MCDM
	Bragança et al. (2010)	MCDM = Sustainable Score (SS)
b	Calvi (2013)	EAL + CBA
	Nuzzo et al. (2018)	loss perf. Matrix (based on simplified EAL)
	Vitiello et al. (2017)	LCC + loss
	Caterino et al. (2009)	MCDM
c	Vitiello et al. (2016)	LCA of seismic retrofit interventions
	Comber at al. (2012)	EIO LCA + loss (HAZUS)
	Menna et al. (2013)	LCA + loss
	Arroyo et al. (2012)	econ. & env. Losses
	Wei et al. (2016a)	LCA + loss (HAZUS) + CBA
	Belleri and Marini (2016)	LCA + loss (PEER-PBEE)
	Hasik et al. (2018)	LCA + loss (review)
d	Mauro et al. (2017)	Cost optimal energy solution + LCA + loss
	Giresini et al. (2020)	Economic and ecological iso-cost curves
	Park et al. (2018)	Multi-objective optimization algorithm with econ. & env. & struct. Objectives
	Calvi et al. (2016)	EAL + CBA = green & resilient indicator (GRI)
	Lamperti Tornaghi et al. (2018)	LCC (energy) + LCA + LCC (structure) + loss = global assessment parameter (GAP)
	Wei et al. (2016b)	econ. & env. & social losses + CBA
	Gencturk et al. (2016)	econ. & env. & social losses

2.2.1. Methods combining environmental and economic sustainability

In the construction sector, sustainability is frequently intended as eco-efficiency of buildings. Within this perspective, the first studies about sustainable renovation led to the definition of “green retrofitting”, consisting in actions aimed at reducing the energy consumption, CO_2 emissions, and waste production of existing constructions. Nevertheless, the increasing number of techniques for the green renovation of buildings hasn’t led to an increasing renovation rate of the existing stock (Jagarajan et al. 2017), which is still quite low (BPIE, 2011). In order to favor the implementation of green retrofitting to existing buildings, various researches have thus focused on the study of eco-efficient and cost-effective retrofit actions included in decision-making models (*case a*, Figure 2).

Most of these studies relies on the application of MCDM tools for the selection of the most eco-efficient energy retrofitting option (Jagarajan et al. 2017). When based on both environmental and economic criteria, these tools allow indeed overcoming the current decision-making process, usually based on a single criterion such as either energy efficiency or cost (Si et al. 2016). Among others, Pons et al. (2016) and Bragança et al. (2010) presented standardized Multi-Criteria Decision Making (MCDM) methods for the renovation of buildings following the sustainability triple bottom line. Pons et al. (2016) introduced the MIVES method, a MCDM method adopting variable functions to convert quantitative and qualitative variables of the requirement tree into a set of variables with the same units and scales (from 0 to 1) and aggregating them into a global Sustainability Index (SI) with a Weighted Sum Method (WSM). Bragança et al. (2010) developed a multi-criteria building rating tool (MARS-H Tool) based on the definition of indicators and parameters, which are weighted and aggregated with a WSM to define a global Sustainable Score (SS) for each alternative. In both the studies, however, the social issues were not intended in terms of safety (*case a’*, Figure 2).

As an alternative, the Life Cycle Costing approach (LCC) may be adopted as a tool for the definition of the best energy retrofit strategy (Hajare and Elwakil 2020, among others). Gluch and Baumann (2004) observed that the oversimplification of the approach to a monetary unit, the lack of reliable data inventory, and the complexity of the building process may highly limit the usefulness of LCC method for the choice of the most sustainable retrofit alternative. As an improvement of such method, Gangolells et al. (2020) have recently proposed a model for identifying environmental, cost-effective energy retrofitting measures by combining energy simulations, LCC and LCA analyses and by including the results into a unique user-friendly bubble chart.

Finally, in order to include sustainability principles in the renovation process, Moschetti and Brattebø (2016) highlighted the need to pass from traditional business models for deep energy retrofitting, which are mainly driven by economic issues, to sustainable-based business models (SBMs). In their framework, they proposed to analyze some relevant case studies, define packages of renovation measures and, for each alternative, define quantitative weighted sustainable indicators (such as the ones deriving from LCA) to build a strategic multi-criteria decision support. In this process, each stakeholder – even if non-energy and non-economy related – should be involved from the primary phases of the SMB definition. Aimed at overcoming the major barriers to building renovation, this approach may be easily extended to also include safety and resilience indicators.

2.2.2. Methods combining safety and economic sustainability

Similar observations may be drawn for those researches combining the safety and economic fields, aimed at increasing the rate of structural and seismic renovation of existing buildings (*case b*, Figure 2). Some procedures and decision-making tools have thus been studied to improve the cost-effectiveness of the retrofit interventions carried out in seismic prone areas and to select the optimal retrofit options. It should be noted that all these procedures are ex-post assessment tools, i.e. analyses carried out at the end of the design process to find the most cost-effective seismic retrofit solution.

In order to choose the optimal retrofit option, Calvi (2013), Nuzzo et al. (2018), and Vitiello et al. (2017) proposed methods that define the total cost of the solutions also including the potential losses connected to seismic risk. Calvi (2013) proposed a new cost-benefit parameter to compare alternative seismic retrofit options based on the ratio between the difference of the building's Expected Annual Loss (EAL) before and after the retrofit and the cost of the intervention itself. Similarly, Nuzzo et al. (2018) proposed a new loss ratio performance matrix to be integrated into the PBEE seismic design framework as to allow the implementation of a cost-based design approach. The matrix employs the Probability Maximum Loss (PML) as performance measure, which is a simplification of the EAL and represents the result of a loss analysis for a single given intensity level. Vitiello et al. (2017) proposed an LCC optimization method, where the cost of the retrofit is computed at each performance level for each intervention and is summed to the expected direct and indirect seismic losses over the building lifetime. This sum is represented by the curve of the Total Expected Costs, which is expressed as a function of the Safety Level. All these approaches base the optimization process on the reduction of costs and losses over the building life – also expressed in terms of costs and calculated with a semi-probabilistic approach (simplification of the PEER-PBEE method).

With a completely different approach, Caterino at al. (2009) proposed a Multi-Criteria Decision Making (MCDM) method for the selection of the best seismic retrofitting intervention of RC structures combining the AHP (Saaty, 1980) and the TOPSIS (Hwang and Yoon, 1981) methods. Some criteria are first defined and weighted through an arbitrary procedure based on a pairwise comparison of criteria and eigenvalue theory, and the optimal alternative is then selected as the closest to a determined fictitious best solution. Differently from the previous methods, this approach allows the decision maker to compare alternative options based on criteria of very different nature, both quantitative and qualitative, without transforming all the evaluations in terms of costs, which are often determined through complicated process with respect to oversimplified scenarios.

2.2.3. Methods combining safety and environmental sustainability

The first studies considering simultaneously safety and environmental sustainability aspects (*case c*, Figure 2) consisted in calculating the impacts of different seismic retrofit alternatives by applying Life Cycle Assessment (LCA) procedures either to the materials or to the construction process (Vitiello et al., 2016 among others). Although these analyses, especially the unit process-based assessments, are the most accurate to define the environmental impacts of a building, they still have some drawbacks. They often require a great level of pre-design effort or multidisciplinary skills; indeed, it appears very difficult to find proper environmental databases including local or innovative technologies, especially for those impacts associated with the management of the end of life scenario. This results very often in analyses conducted from-cradle-to-gate rather than from-cradle-to-grave and thus disregarding the major impacts associated with both the operational and end-of-life phases. Also, the current procedures do not address uncertainties related to the estimation of the residual building service life to be used as a reference for the calculation of the costs (Casprini et al. 2019, FEMA P 58-4, 2018). When these analyses are adopted to compare alternative retrofit solutions, selection of the functional unit and system boundary are also quite challenging since only solutions leading to the same performance objectives of the retrofitted building should be compared. Finally, current LCA procedures adopted in such studies do not account for natural hazard risk, i.e. for possible impacts associated with the repairs required after possible extreme event that a building may experience throughout its life cycle. Shortcomings of the current 'static' procedures and a new methodology to consider seismic hazard into probabilistic approaches for life-cycle analyses are presented in Di Bari et al. (2020).

In order to overcome some of those limitations of the traditional LCA procedure, many studies recently introduced the assessment of the environmental impacts due to seismic damage possibly experienced by buildings during their life cycle. Comber et al. (2012) proposed a simplified Performance-Based Earthquake Engineering methodology estimating environmental impacts based on construction costs – this Economic Input Output EIO LCA procedure was then included in FEMA P-58-4 (2018). Menna et al. (2013) proposed a methodology for the probabilistic life cycle assessment of the structures considering the seismic risk-based time-dependent expected losses. Arroyo et al. (2012) proposed a probabilistic framework to include environmental losses in the design of earthquake resistant structures, concluding that this approach may lead to a significant increment of the design load in order to reduce CO_2 emissions associated with the repair of future damages. The need to increment seismic design loads, use eco-efficient materials, and use innovative structural systems with lower seismic vulnerability are envisioned as possible solutions to reduce the environmental impact of buildings. Wei et al. (2016a) proposed an LCA framework based on HAZUS methodology to convert the seismic risk into CO_2 emissions and showing the convenience of risk mitigation in terms of reduction of environmental impacts with a cost-benefit analysis (CBA). The proposed approach considers all the main sources of environmental impacts arising from both retrofitting and post-event rehabilitation and includes impacts due to demolition and debris disposal. Belleri and Marini (2016) adopted a probabilistic "PBEE-Green" approach based on PEER-PBEE method. Unlike other methods, besides focusing on the potential impacts of existing vulnerable buildings, this study also quantified the inefficiency of the sole energy refurbishment of vulnerable buildings. Indeed, when structural deficiencies are not tackled in the retrofit of vulnerable buildings located in high-seismicity regions, an additional expected annual embodied equivalent CO_2 that almost equals the annual operational CO_2 after thermal refurbishment should be considered.

A complete overview of all these methods is included in Hasik et al. (2018). It should be noted that all these studies proposed again ex-post comparative evaluation tools, carried out at the end of the design of alternative seismic retrofitting solutions.

2.2.4. Methods combining safety, economic and environmental sustainability

Only recently, the need to find sustainable retrofit solutions targeting eco-efficiency, cost-effectiveness, and safety (*case d*, Figure 2) has finally been emphasized and new design frameworks have been proposed.

Mauro et al. (2017) proposed a sustainability assessment framework in which the cost-optimal energy retrofit solution, obtained from a genetic algorithm procedure, is identified, and the impact of the expected economic losses due to seismic damage is assessed throughout the building lifecycle. The solution, however, does not identify a comprehensive sustainable structural retrofit solution.

Giresini et al. (2020) proposed economic and ecological iso-cost curves to evaluate the benefit offered by different energy and seismic interventions for the retrofit of masonry façades.

Focused on the seismic design of buildings, Park et al. (2018) developed a performance-based optimal seismic design with sustainability (PBODS) approach that optimizes the structural solution by employing a multi-objective genetic algorithm, which adopts as objective functions CO_2 emissions, production costs, and the coefficient of variation of the interstorey drift ratio. However, the approach still has some limitations since emissions and costs are evaluated without considering the whole building life cycle.

More complete frameworks focusing on the whole design procedure were proposed by Calvi et al. (2016), Lamperti Tornaghi et al. (2018), Wei et al. (2016b), and Gencturk et al. (2016), which developed methods combining the evaluation of energy and structural performances, LCA, loss estimation, and LCC or cost/benefit (C/B) analyses. Calvi et al. (2016) extended the procedure adopted in Calvi (2013) by calculating also the Energy Expected Annual Loss (EAL_E) and combining the resulting B/C ratios into a comprehensive Green and Resilient Indicator (GRI). Lamperti Tornaghi et al. (2018) proposed a new 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 costs over the life cycle. Wei et al. (2016b) proposed an LCA framework to evaluate the long-term costs and benefits 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 (number of fatalities, repair/replacement costs, and CO_2 emissions respectively), which in turn serve as metrics for the objectives of a cost-benefit performance-based design. Finally, Gencturk et al. (2016) developed a life-cycle sustainability assessment (LCSA) framework for sustainability quantification of reinforced concrete (RC) buildings subjected to earthquakes. The PBEE framework was applied in combination of LCA analyses in order to evaluate the sustainability through various stages of the lifetime of a RC building in terms of cost and downtime (economy component), environmental emissions and waste generation (environmental component), and deaths (society component).

In the first three studies, the best retrofit option was evaluated by expressing losses and environmental impacts as “equivalent” costs and by identifying the best solution as the most cost effective one, over the building life cycle. However, comparing performances of such different nature (energy, losses, casualties, …) just in terms of costs may result in an oversimplification of the problem. On the other hand, in Gencturk et al. (2016), the quantified metrics were not combined, thus making it difficult to determine a ranking of possible alternative solutions. Most importantly, all these methods are comparative assessment frameworks applied at the end of the design process (ex-post assessment), neglecting many of the LCT principles that may guide the choice of eco-efficient, low-impact solutions, and comparing solutions that may lead to different performance objectives of the retrofitted building.

2.3. Research needs in the current state of the art and research objectives

Recently, the SAFESUST commission has established the basis for a ‘Roadmap for the improvement of earthquake resistance and eco-efficiency of existing buildings and cities’ (Caverzan et al. 2016). Recognizing that sustainability can’t be achieved without safety – from this, the neologism SAFESUST (safety + sustainability) – an integrated approach to the renovation was envisioned. Such a new approach would require:

- The adoption of a **multidisciplinary perspective**: experts on structures, architecture, energy and finance should collaborate and “seek synergies and possible agreed priorities”. In addition, all the stakeholders (including owners, investors, local authorities and communities) should be involved since the first stages of the design.
- The need to **address safety and eco-efficiency together**, at the same time, **in the design phase**; on the contrary, in the traditional approaches, safety is addressed in the design process, while eco-efficiency is checked afterwards along with ex-post assessments.
- The need to carry out “rational and collaborative **pre-design analyses** so as to prevent jeopardizing the integrity of the project at later stages”. All the actors should agree from the beginning on the major objectives

of the renovation, which will then be translated during the design phase into clear performance objectives and correlated design targets.

- The adoption of a **Life Cycle (LC) perspective**, an extended and comprehensive perspective enabling minimizing costs and environmental impacts while maximizing performances over the building life cycle (Marini et al., 2018). Seismic risk and associated losses should be included in Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) procedures, and the principles of Life Cycle Thinking (LCT), i.e. recyclability, demountability, reparability, etc. (Marini et al., 2017), should be integrated in the design process for the selection of the best retrofit option.

Considering the current state of the art, it may be observed that a few virtuous retrofit techniques have been proposed (§2.1); however, a holistic design framework enabling the diffusion of such techniques and the development of new systems and guiding the designer toward the selection of the most sustainable and cost-effective solutions is still missing. To best of the authors' knowledge, none of the existing frameworks entirely complies with the new SAFESUST vision, and presents drawbacks with respect to such an approach:

- Many of them do not contextually pursue the three pillars of sustainability, or they do not consider safety issues in the social sustainability. Nonetheless, they propose some interesting tools that could be included into more comprehensive frameworks.
- The existing frameworks are quantitative "ex-post" assessment tools, thereby enabling the selection of the less impacting technique among a series of already designed solutions, which could be little sustainable by themselves.
- The existing frameworks only partially address the LCT criteria, without maximizing the co-benefits of integrated solutions.
- They are not conceived to overcome the major barriers to the renovation, and their application may result in the selection of disruptive retrofit solutions, which are rarely applied for the renovation of the existing buildings (as proven by the current low renovation rate).

3. Sustainable Building Renovation Design (SBR-D) Framework

Aimed at overcoming the gaps of the current state of the art and at proactively contributing to the SAFESUST roadmap (Caverzan et al. 2016) follow up, a new Sustainable Building Renovation (SBR) approach is herein defined. Such an approach is aimed at managing the transformation of the existing building stock into a safer, more sustainable and resilient renovated heritage. In the SBR approach, LCT principles are addressed since the very first step of the design process in order to select and design retrofit solutions that minimize impacts along the whole building life cycle; in addition, such solutions are conceived to overcome the major barriers to the renovation. To this aim, sustainable strategies such as holistic renovation, retrofit from outside, and criteria such as demountability, recyclability, reparability, prefabrication etc. need to be encouraged (Figure 3).

In order to adopt this new approach for the design and the choice of more sustainable retrofit solutions, a new SBR Design (SBR-D) Framework is proposed, including all these new sustainable principles and strategies. The proposed framework is intended as both a **pre-design** and a **post-design** assessment tool to support the decision-making process associated with the building renovation. The framework is based on current Performance-Based Design (PBD) methods (Figure 1), but it has been adapted to be strongly multi-disciplinary and to overcome the weaknesses and drawbacks of traditional, uncoupled approaches (Figure 4).

The SBR-D framework envisions a 4-step procedure. A detailed description of each step of the framework is addressed in the following and in Figure 5.

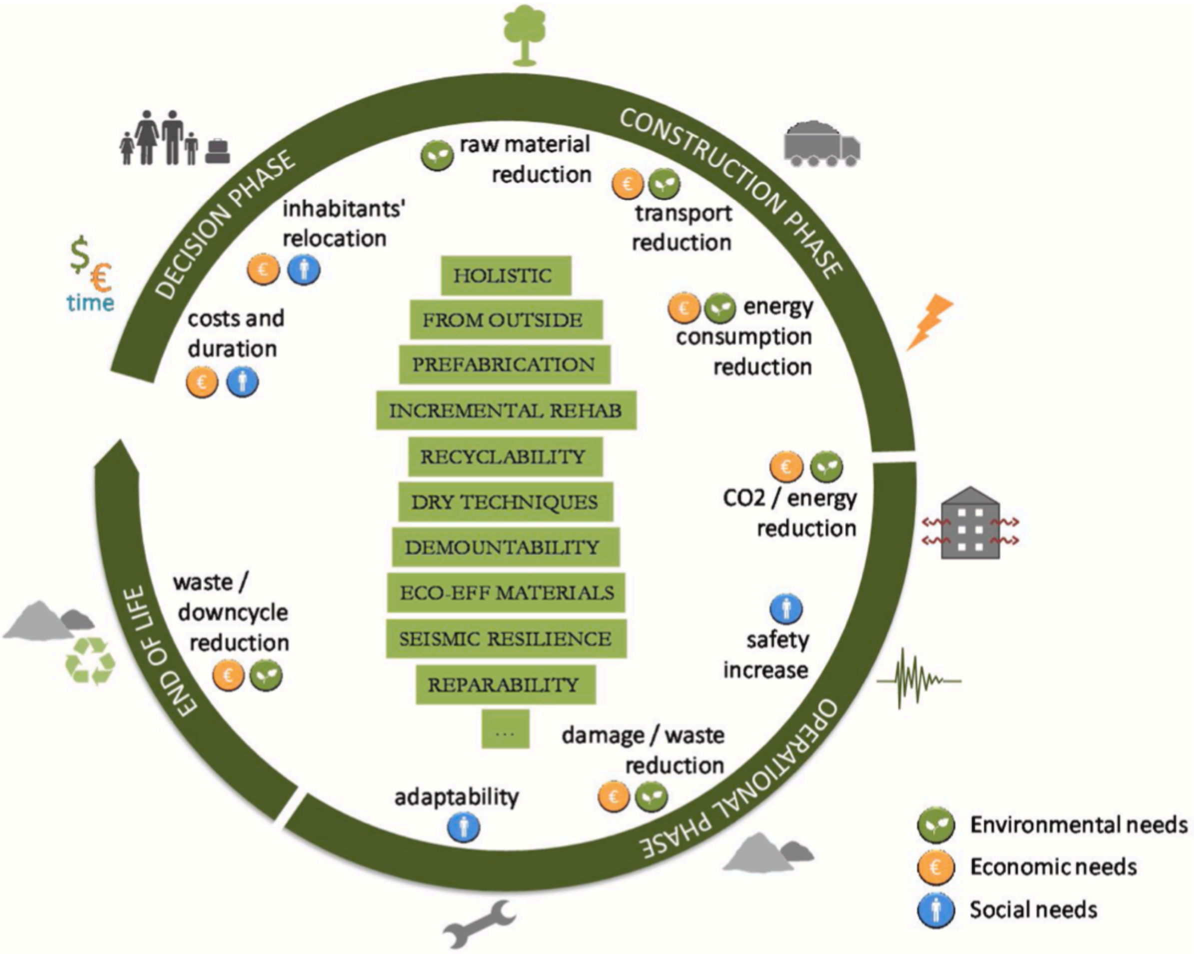


Figure 3. The new Sustainable Building Renovation (SBR) approach: environmental, economic, and social needs along the building life cycle and sustainable strategies to be included in the design of retrofit interventions

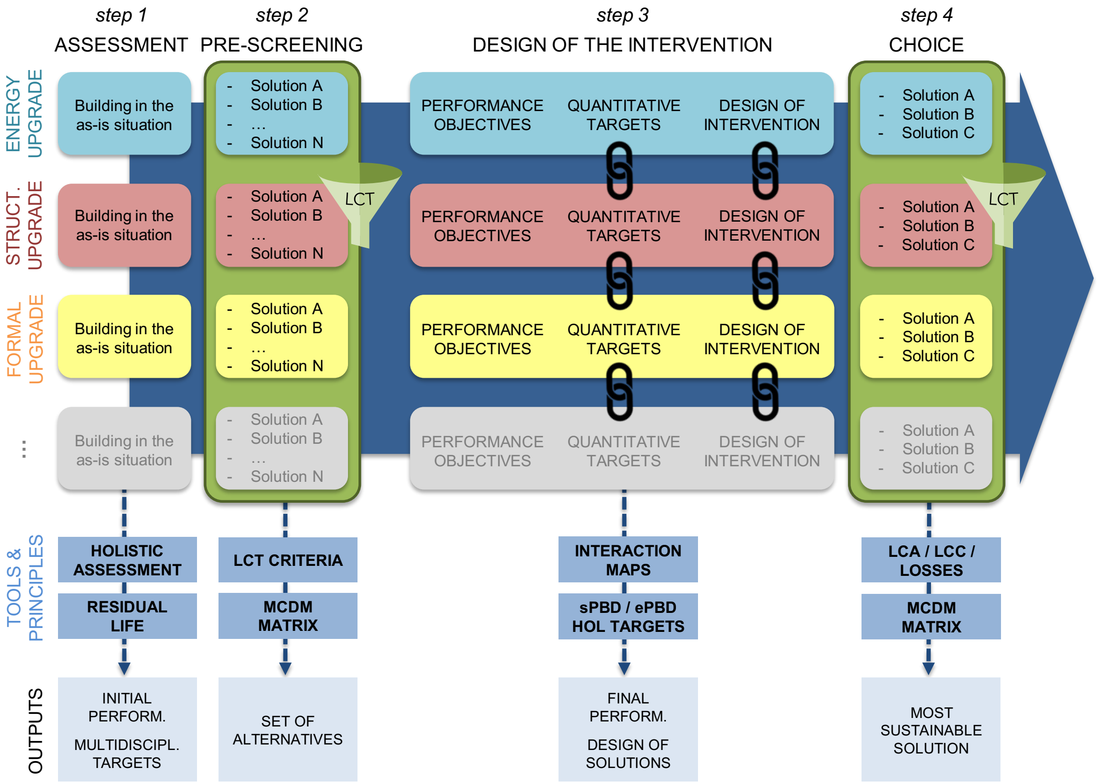
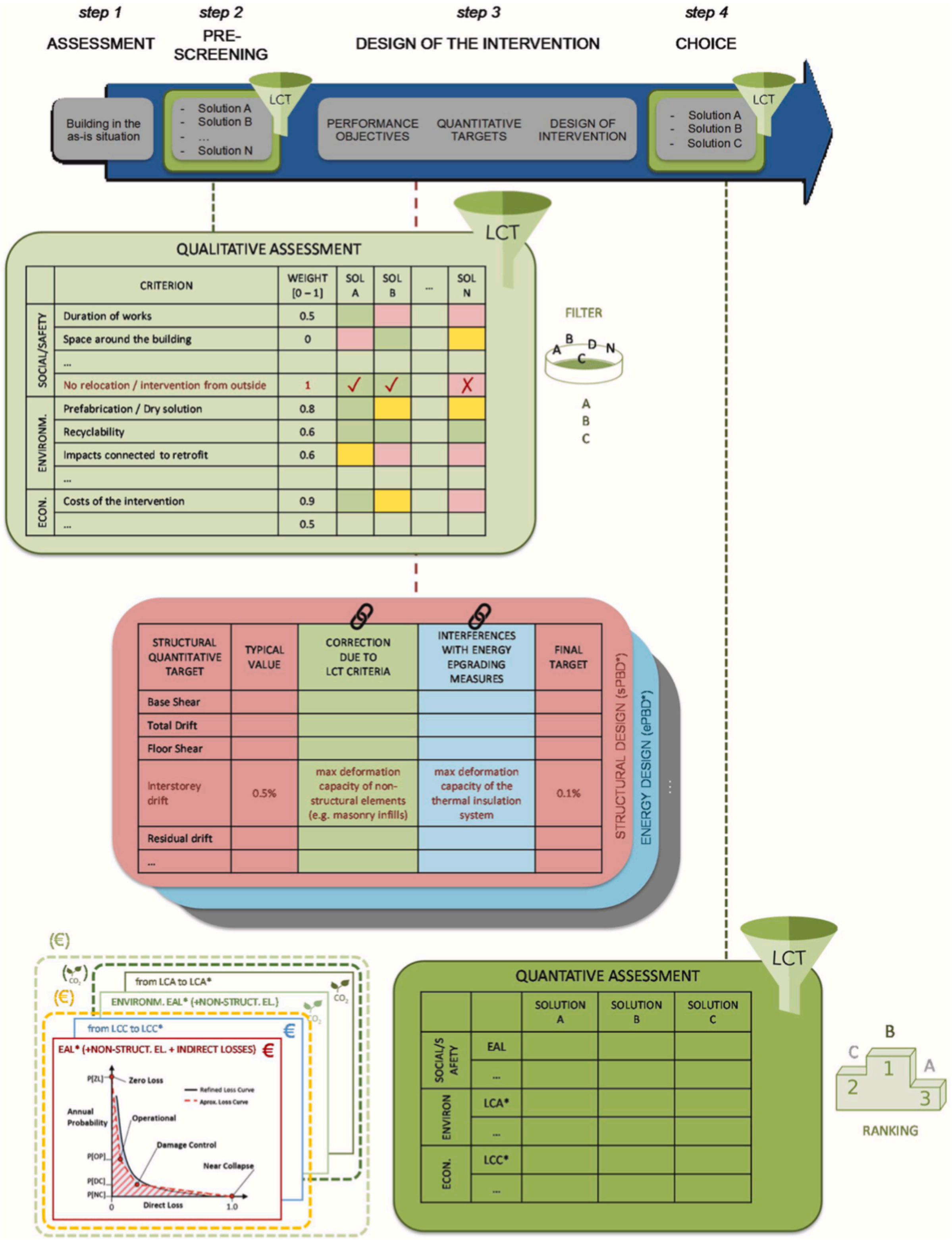


Figure 4. Sustainable Building Renovation Design (SBR-D) Framework.



QUALITATIVE ASSESSMENT

	CRITERION	WEIGHT [0 – 1]	SOL A	SOL B	...	SOL N
SOCIAL/SAFETY	Duration of works	0.5	🟩	🟥		🟥
	Space around the building	0	🟥	🟩		🟨
	...					
	No relocation / intervention from outside	1	✓	✓		X
ENVIRONM.	Prefabrication / Dry solution	0.8	🟩	🟨		🟨
	Recyclability	0.6	🟩	🟩		🟩
	Impacts connected to retrofit	0.6	🟨	🟥		🟥
	...					
ECON.	Costs of the intervention	0.9	🟩	🟨		🟥
	...	0.5				

STRUCTURAL QUANTITATIVE TARGET	TYPICAL VALUE	CORRECTION DUE TO LCT CRITERIA	INTERFERENCES WITH ENERGY EPGRADING MEASURES	FINAL TARGET
Base Shear				
Total Drift				
Floor Shear				
Interstorey drift	0.5%	max deformation capacity of non-structural elements (e.g. masonry infills)	max deformation capacity of the thermal insulation system	0.1%
Residual drift				
...				

QUANTATIVE ASSESSMENT

		SOLUTION A	SOLUTION B	SOLUTION C
SOCIAL/SAFETY	EAL			
	...			
ENVIRON	LCA*			
	...			
ECON.	LCC*			
	...			

Figure 5. Sustainable Building Renovation Design (SBR-D) Framework: actions of each step.

Step 1 – **Assessment of the building major needs in the as-is situation** evaluating possible deficiencies in all relevant areas (safety, energy, operational, comfort, etc.). This allows clearly identifying the building major needs under a holistic and multi-disciplinary point of view, which in turn results in the selection of the minimum performance objectives to be targeted in the renovation process. To this end, traditional energy/acoustic audit and structural/vulnerability assessment may be adopted.

Feasibility of the renovation as opposed to mandatory demolition and reconstruction is also assessed with the analysis on the state of preservation, structural decay, residual service life and cost benefit evaluations. Most of the buildings requiring renovation have exhausted, or nearly exhausted, their design nominal service life (typically 50 years) and, if the structural residual life is short due to the significant degradation of the structural components and/or materials (carbonation, corrosion, etc.), it might be neither economically convenient nor safe to carry out important and expensive renovation actions. In such cases, demolition and reconstruction might be the only viable solution. A protocol for the estimation of the feasibility of the renovation is being developed in a companion research to be integrated at this stage of the framework. First results are presented in Casprini et al. (2019).

In this first step of the framework, the main actors involved in the process are the design professionals and the building stakeholders, who must collaborate to define shared objectives of the renovation.

Step 2 – **“Pre-screening” for selecting possible alternative solutions**. According to the SBR approach, the suitability of possible retrofit solutions (either structural or energy) is evaluated by analyzing their specific features with respect to a series of requirements and constraints defined on the basis of the multiple building needs, Life Cycle Thinking principles, and possible barriers to the renovation (e.g. inability to relocate the inhabitants during the construction works, low budget, etc.). To this end, a qualitative Multi-Criteria Decision Making (MCDM) approach is adopted, in which the relevance and relative weight of each criterion is established based on priorities addressed by owners and stakeholders, by minimum performance objectives (also according with the reference literature), and by national or international policies/regulations.

This step represents one of the major innovations of this framework. By comparing different solutions based on qualitative estimations rather than on quantitative analyses, the designers and the decision makers are enabled to select the best set of alternatives (and to discard those not complying with the envisioned criteria) in the initial step of the design, without carrying out unnecessary calculations, thereby optimizing the design process in terms of time, resources and results. In fact, by applying this “SBR filter” (step 2) before the design phase (step 3), non-compatible or unsuitable and unsustainable solutions may be discarded from the beginning of the process, while innovative holistic and sustainable solutions may be encouraged. When adopting LCT criteria and principles as a sort of “new lens” under which one could critically evaluate existing techniques, it becomes clear that the same performances could be attained with very different techniques, having quite different impacts and costs over the LC. When considering seismic retrofit under a LC perspective, for example, it may be observed that some techniques, such as strengthening of the frame nodes, may introduce some issues in all stages of the building use. This solution requires demolition of the finishing, which are worth 70% of the construction value. It requires relocation of the inhabitants (it is mainly carried out in post-earthquake scenarios, when the building is empty, rather than as a prevention strategy), and it does not entail reparability nor adaptability or demountability (Figure 6, left). On the contrary, adopting a LC perspective in the renovation process will foster the proposal of new renovation models and the conceptual design of new solution sets. An example of possible holistic retrofit solution, which contextually addresses more than one deficiency, and solutions conceived to be compliant with the LCT principles (standardization, demountability, reparability, reusability, etc.), can be represented by "holistic" exoskeletons (Marini et al. 2017, Labò et al. 2020, Zanni et al. 2020), (Figure 6, right).

The main actors of this step are the design professionals and all the stakeholders (owners, investors, users), who provide the requirements and constraints that would lead the design of the retrofit intervention.

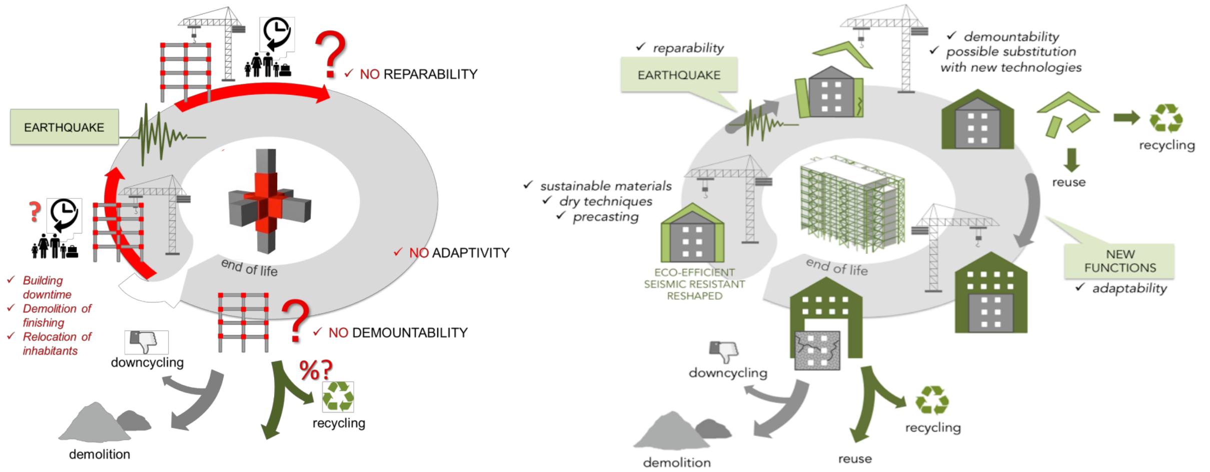


Figure 6. Application of the LCT principles for the preliminary evaluation of two retrofit alternatives: strengthening of the frame joints (left) and holistic structural and energy exoskeleton (right). Adapted from: (Marini et al. 2017 and Marini et al. 2018).

Step 3 – **Conceptual design of possible alternative retrofit solutions characterized by the same energy, structural, etc. performances.** Structural and energy PBD procedures are adopted for the design of the interventions selected during step 2 but considering a holistic and multi-disciplinary perspective. However, differently from the traditional procedures, the adoption of the new SBR approach from the beginning of the design process requires that the designers modify typical design target values on the base of LCT principles and on possible conflicting interferences and interactions among different retrofit actions. As an example, if the insulating panels are to be installed on the building envelope to improve energy efficiency, their connection to the structural system needs to sustain low intensity frequent earthquakes without damage, therefore specific and quite demanding design targets on the maximum lateral deformation capacity of both the insulating envelope and the structural system must be enforced. As another example, considering that the work from the inside of the building may not be allowed, specific design targets may be required to limit the in-plane load demand on the existing floors in order to avoid floor strengthening (Marini et al., 2017). Similarly, the details of the structural system should be studied to avoid possible thermal bridges, which may reduce the efficiency of the designed energy-saving measures.

As for the **structural PBD**, several aspects should be considered for the application of the procedure under the envisioned global design approach. In current design practice, the retrofit interventions are designed for the sole Life Safety Limit State, without defining a limit to the collapse probability of the retrofitted building, nor the environmental footprint and economic losses associated with the repair works required after hazardous events. Furthermore, focus should be made on specific aspects of the building structural behavior and on the definition of specific performance levels. Infills (rigid masonry could detrimentally affect the structural response and become a hazard for the people inside and outside the building), stairwells (typically very stiff elements poorly detailed which have a fundamental role during the building evacuation), floors (needed to distribute the seismic action to the seismic resisting elements), and foundations (whose failure may jeopardize the stability of the whole building) are elements that require careful assessment and may be protected by introducing further stricter design targets such as the maximum floor action, maximum interstorey drift, shear action in the stairwell walls, and maximum shear flow at the base. In addition, non-structural elements (NSE) should be included in the loss evaluation analyses since the percentage of the total direct losses during earthquakes that can be reasonably attributed to NSEs can be up to 90% (O'Reilly at al., 2018). Therefore, the protection of those elements is critical in order to effectively reduce the expected impacts due to earthquakes and other natural disasters.

In this step, the actors involved are the design professionals of different disciplines, who design the pre-selected retrofit interventions (obtained in step 2) to be respectful of the performance objectives defined in the previous steps of the design framework. It should be noted that each selected retrofit solution must entail the retrofitted building to achieve the same performance levels; this is fundamental to allow a fair comparison among different alternatives in the final step.

Step 4 – **Selection of the best retrofit option based on comparative assessment of the solutions along the building life cycle considering the sustainability triple bottom line**. In this step, the tools developed for the comparative assessment of different solutions presented in the review of the state of the art may be applied. Probabilistic (not static) 'expanded' LCA and LCC procedures also accounting for the losses generated by natural hazards, such as earthquakes, (LCA* and LCC* in Figure 5) should be considered to evaluate the environmental, economic, and social impacts associated with each solution in each phase of the building life cycle. 'Expanded' EAL analyses (EAL* in Figure 5), also accounting for the damage to nonstructural elements and indirect losses, should be also carried out. Existing frameworks for the choice of the retrofit interventions according to the sustainable triple bottom line may be here integrated. Among them, Multi-Criteria Decision Making (MCDM) approaches are particularly efficient in the definition of the best option. The impacts and the performances of each solution are converted into different indicators, a weight is assigned to each indicator, and the best solution is detected by ranking the selected suitable alternatives. The indicators associated with each criterion may be both quantitative (i.e. eCO_2, €, etc.) and qualitative (easy assemblage, reusability, recyclability, etc.) and, differently from the other assessment methods, do not necessarily need to be transformed into economic values for the comparison. **Minimum thresholds** may be considered to guarantee a minimum fixed level of performance in the three main areas of sustainability, thus fostering excellence and encouraging highly sustainable retrofitting actions.

It should be pointed out that the proposed framework may be easily adopted today by including at each step the **tools** already available from the state of the art. MCDM tools may be adopted in step 2 and 4, just considering criteria compliant with the sustainability triple bottom line and integrating new sustainable LCT principles; structural and energy PBD methods may be applied for the design of the selected solutions (step 3), being careful in the choice of the targets to account for the possible interferences and interactions; LCA, LCC, and loss analyses may be integrated in step 4 for the evaluation of the most sustainable options. However, the framework is also open to future development of such tools, which could be further updated to consider the higher level of integration of the interventions, the impacts due to hazard risks along the building life cycle (LCA*, LCC*), and the integration of criteria connected to LCT and to the overcoming of the barriers to the renovation.

4. Preliminary application of the proposed SBR-D Framework to a reference RC building

A proof-of-concept application of the proposed SBR Design Framework is presented in the following.

The reference building is a masonry infilled RC frame built in 1973, without any energy and seismic provisions. It is an 8-floor building (24.75m) and has a plan with maximum dimensions 27.5m x 13.5m (Figure 7). The structure consists of three longitudinal one-way frames on shallow foundations. The outer frames are infilled with masonry panels made of a double layer of hollow clay bricks (8cm inner leaf and 12cm outer leaf) with a 15cm inner cavity and 1.5cm plasters on both sides. A stiff RC staircase core is located along the Northern alignment. On the same alignment, masonry infills are missing at the ground floor of the garages, thus introducing a vertical geometric irregularity (soft-story irregularity). Floors are one-way composite RC beam and clay block floor systems. Windows are single glazed with PVC frames. More details may be found in Ioannes (2015) and Passoni et al. (2018).

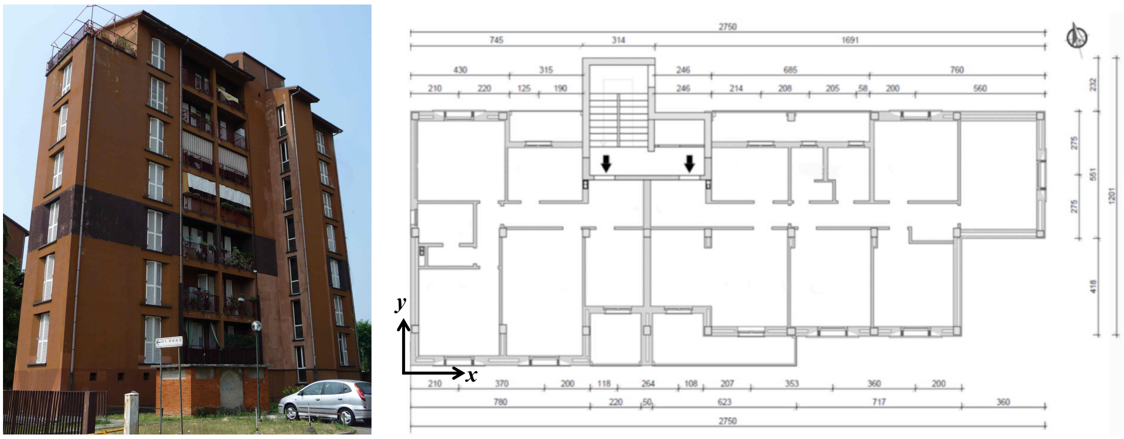


Figure 7. Reference building: view (left) and plan (right).

4.1. Step 1 – Assessment of the building performances in the as-is situatiom

In the first step of the framework, the performances of the building in the as-is condition are assessed. Preliminary checks of the state of preservation, seismic vulnerability and energy audit are performed to evaluate the building initial conditions and to define the main retrofit needs. In the analyses, the building is supposed to be located in L'Aquila, a city in the Italian Apennines, characterized by high seismicity (PGA=0.261g, Zone 2, NTC 2018) and a quite cold climate (HDD=2.514, Region E, DPR 412/93).

The building is inhabited, and the state of preservation of the structure appears to be fairly good, without evidences of material deterioration and decay. A retrofit intervention is thus preferred to demolition and reconstruction.

As far as the **structural performances** are concerned, a non-linear static analysis is performed with the commercial FEM software MidasGen (2018). The frame elements are modeled as beam elements with lumped plasticity, and the flexural and shear plastic hinges are calculated according to the Italian building code (NTC2018). For the sake of simplicity, beam and column sections are standardized (columns: 30x60cm with 6 ϕ16 at the ground floor and 30x50cm with 6ϕ14 at the other floors; beams: 30x42cm with 2ϕ14 at the top and 4ϕ14 at the bottom; material: concrete C25/30 and steel FeB44k). Infills are modeled as compression-only struts converging in the frame nodes, implementing the model by Decanini et al. (1993). The staircase core is modelled as an infilled frame. The frame is considered as fixed at the base. Non-linear static pushover analyses confirmed the transversal direction (y direction in Figure 7) as the most critical. The pushover curve in Figure 8 (a) shows that the building experiences severe damage at the Damage Limit State (DLS – according to the Italian building code, corresponding to an earthquake with 63% probability of exceedance and a return period of 50 years for a reference building service life of 50 years), and collapses before reaching the Life Safety Limit State (LSLS – 10% on a return period of 475 years). The main structural vulnerabilities are connected to the uneven distribution of stiff nonstructural infill walls along the height of the building that, associated with a poor detailing of the nodes, causes the collapse for the early onset of a soft-story mechanism. Further simulations showed that, even if this vulnerability was corrected by means of local interventions, the poor structural details would not guarantee the interstory drift demand. Global structural interventions are thus required.

The **energy audit** is performed adopting the software DOCET v.3 released by the Italian National Agency for the Energy Efficiency ENEA (http://www.docet.itc.cnr.it) enabling the simplified assessment of the energy performances of existing buildings (adapted from Ioannes 2015). According to the international energy efficiency classification (EPBD – European Union Directive 2002/91/EC), all the apartments resulted either in class F or G, with the worse value of primary energy consumption equal to 475.3kWh/m^{2}year (Figure 8, b). Such bad performances are due to the poor properties of the windows, to the absence of thermal layers along the vertical and horizontal closures, to the presence of thermal bridges, and to the obsolescence of the heating system.

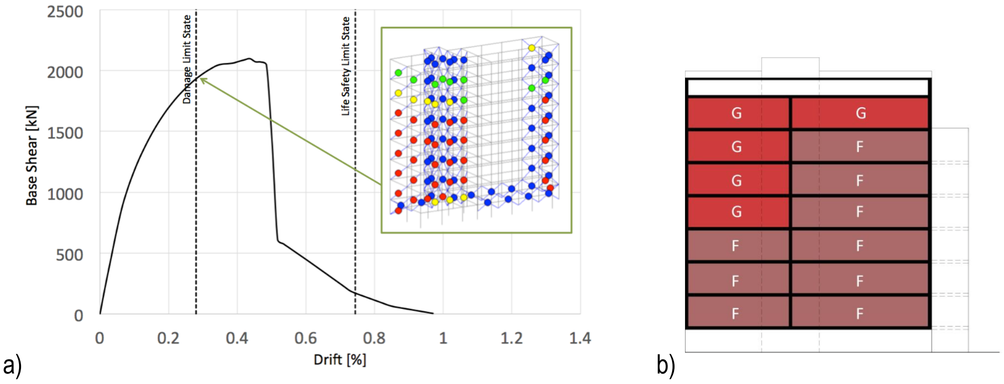


Figure 8. Seismic (a) and energy (b) assessment of the existing reference building. Adapted from: Passoni et al. 2018 (a) and Ioannes 2015 (b).

Based on these simplified analyses, structural and energy deficiencies are identified, and the critical retrofit needs outlined. Ordinary maintenance interventions (e.g. due to environmental degradation) to improve the aesthetic of the façades are also required. Such multiple needs are considered when selecting the most suitable retrofit strategy.

4.2. Step 2 – Pre-screening of possible seismic retrofit solutions from a sustainable perspective

Once the multiple retrofit needs of the building are identified, a pre-screening of possible retrofit solutions is carried out by adopting sustainable principles as envisioned by the new SBR design framework. This step allows all the actors of the renovation process to clearly define the major priorities and constraints of the retrofit project, thus avoiding the design of unsuitable solutions. Criteria and relevance of each criterion are defined for each main area of sustainability, and several possible retrofit measures are qualitatively compared so as to determine the most sustainable solutions according to LCT principles and decision maker needs.

In this step, the comparison of the possible alternatives is limited to qualitative evaluations in order to reduce the design effort, by discarding those solutions which may not be compliant with the principles of LCT, which do not overcome the barriers to the renovation, and, in general, which do not meet the needs and requirements of the decision makers. Only after the optimal set of alternatives has been selected, the solutions are designed (step 3) and compared by means of quantitatively analyses (step 4).

As for the structural retrofit of the case study building, 6 possible alternatives are here considered: 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, or with steel diagrid exoskeletons (*A6*) (Table A1). Each solution can be designed to achieve the same performance objectives, but substantial differences can be observed in terms of environmental impacts and costs along the retrofitted building life cycle.

Potential environmental, economic, and social impacts of each solution in each stage of the building life cycle are qualitatively evaluated in Table 3 considering 14 different criteria (Table A2). It should be noted that such estimations are based on qualitative considerations exclusively referred to the reference building and based on the experience of the evaluators. Table 3 may thus change when a different building with different construction technology and geometry, built in a different period or in a different site, was considered.

The MCDM approach proposed by Caterino et al. (2008), combining the AHP (Saaty 1980) and TOPSIS (Hwang and Yoon 1981) MCDM methods, is here applied to select the retrofit solutions that are potentially more suitable. This method, which is conceived to be adopted also for qualitative comparisons, consists in two main phases. In a first phase, the retrofit alternatives are assessed adopting a pairwise comparison (AHP method), which compares the performances of each solution with respect to each criterion by assigning a 'quantitative score' (more details are reported in the Appendix). For each criterion C_k, a matrix is assembled, where each line i represents how better/worse is the alternative A_i with respect to alternative A_j in column j (Table A3). The eigenvector of the matrix, first normalized by the sum of the values and then by its norm, is considered as a quantitative description of the performances of each alternative with respect to each criterion. The normalized vectors are then assembled into a matrix referred to as 'normalized decision matrix' (Table A5). With reference to the case study, the pairwise comparison was carried out on the basis of the qualitative analysis of Table 3. The normalized vectors obtained by the analysis are reported in Figure 9.

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 are considered more important than the others. The eigenvector of this matrix, normalized by the sum of its values, represents the weight vector that is adopted to scale the decision matrix. A 'weighted normalized decision matrix' may thus be determined, and a ranking of the solutions may be carried out by calculating a 'global score' C_i^*, which represents the relative closeness of each retrofit solution to the ideal one (TOPSIS method). For the reference building, three different scenarios are discussed. Only the main results are presented in the following, while the complete application of the method, the matrices and the data, are reported in the Appendix (Table A6-A9 for Scenario 1, Table A10-A13 for Scenario 2, and Table A14-A17 for Scenario 3).

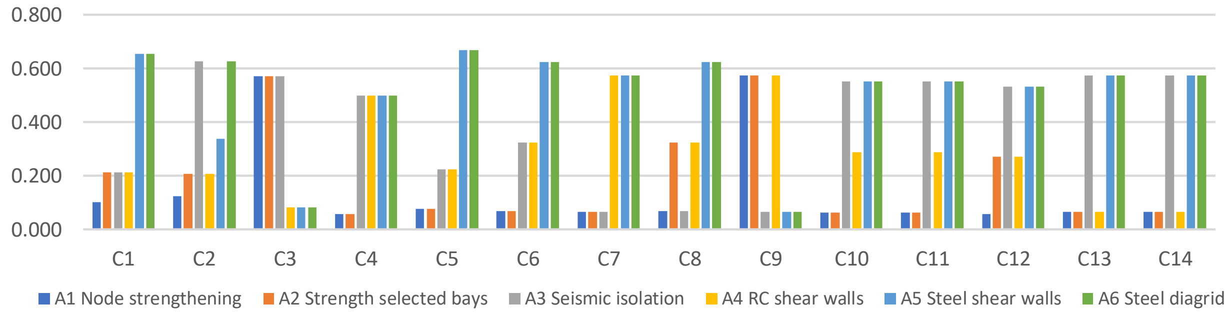


Figure 9. Normalized performances of the different alternatives with respect to each criterion (representation of the 'normalized decision matrix' in Table A5).

Table 3. Qualitative comparison of possible structural retrofit solutions considering LCT principles.

	A1 – NODE/ COLUMN STRENGTH.	**A2 – STRENGTH. OF SELECTED BAYS**	**A3 – BASE ISOLATION**	**A4 – EXT. RC SHEAR WALLS**	**A5 – EXT. STEEL SHEAR WALLS**	**A6 – STEEL DIAGRID**
DECISION MAKING AND CONSTRUCTION PHASE						
C1 – Duration of works *	**HIGH**	**MEDIUM**	**MEDIUM**	**MEDIUM**	**LOW** (prefabricated)	**LOW** (prefabricated)
C2 – Renovation cost *	**HIGH** (need for localized/ finishing demolitions)	**MEDIUM/HIGH** (high costs for foundations)	**MEDIUM/LOW** (if no need of important ancillary works)	**MEDIUM/HIGH** (high costs for foundations)	**MEDIUM** (high costs for foundations)	**MEDIUM/LOW**
C3 – Need for additional space around the building	**NO**	**NO**	**NO**	**YES/MEDIUM** (it may be in close proximity)	**YES/MEDIUM** (it may be in close proximity)	**YES/MEDIUM** (it may be in close proximity)
C4 – Need for inhabitants' relocation	**YES** (need for localized/ finishing demolitions)	**YES**	**NO**	**NO** (from outside)	**NO** (from outside)	**NO** (from outside)
C5 – Fast assembling	**NO** (need for localized/ finishing demolitions)	**NO** (need for localized/ finishing demolitions)	**MEDIUM**	**MEDIUM**	**YES** (prefabricated)	**YES** (prefabricated)
C6 – Waste generation	**YES** (need for localized/ finishing demolitions)	**YES** (need for localized/ finishing demolitions)	**LOW** (need for localized demolitions)	**LOW** (not prefab., from outside)	**NO** (prefabricated, from outside)	**NO** (prefabricated, from outside)
C7 – Possibility to increase living space	**NO**	**NO**	**NO**	**YES**	**YES**	**YES**
OPERATIONAL PHASE						
C8 – Adaptability (incremental renovation plans)	**NO**	**MEDIUM** (immediately active)	**NO**	**MEDIUM** (may be activated at the end of the intervention)	**YES**	**YES**
C9 – Need for extraordinary maintenance	**NO**	**NO**	**YES**	**NO**	**YES**	**YES**
OPERATIONAL PHASE – POST-EARTHQUAKE						
C10 – Repair cost *	**HIGH** (demolitions may be required)	**HIGH** (demolitions may be required)	**LOW** (lumped damage)	**MEDIUM** (repair of walls may be required)	**LOW** (lumped damage)	**LOW** (lumped damage)
C11 – Impacts connected to the repair operations	**HIGH** (demolitions may be required)	**HIGH** (demolitions may be required)	**LOW** (lumped damage)	**MEDIUM** (repair of walls may be required)	**LOW** (lumped damage)	**LOW** (lumped damage)
C12 – Building downtime *	**HIGH** (demolitions may be required)	**MEDIUM** (demolitions may be required)	**LOW** (lumped damage)	**MEDIUM** (repair of walls may be required)	**LOW** (from outside)	**LOW** (from outside)
END-OF-LIFE PHASE						
C13 – Fast disassembling	**NO**	**NO**	**YES**	**NO**	**YES**	**YES**
C14 – Reusability or recyclability	**NO**	**NO**	**YES**	**NO**	**YES**	**YES**

* A very rough estimation of both duration and costs of the interventions may be based on the plane and elevation geometric dimensions of the structure and on the number of elements. The location of the building should also be considered to evaluate the costs of material supply, manufacturing, and man labor.

- *Scenario 1 – the building has a residential use and the inhabitants are not willing to leave their apartments during the retrofit works; they also have a limited budget*. When such requirements significantly influence 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 making is governed by the criteria *C1*, *C2*, *C7*, and *C9*, corresponding to ‘duration of works’, ‘renovation costs’, ‘possibility to increase living space’, and ‘need for maintenance’, respectively, which have the highest weight. The graph of the resulting weight vectors is shown in Figure 10 (left). Multiplying each line of the decision matrix by this vector, the performances of each alternative are thus scaled to consider the weight of each criterion. A representation of the decision matrix before and after the weighting process is shown in Figure 11a and 11b respectively by means of radar graphs. 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 is the line from the center, the better is the alternative with respect of each criterion. The alternative associated with the outer polyline (thus the larger inscribed area) represents the best among the considered solutions. Finally, the representation of the global score C_i^* adopted for the ranking of the alternatives is reported in Figure 12 (left). In this case, the best alternative is the steel diagrid exoskeleton, followed by the ones adopting exterior steel and RC walls.

  If the requirement of no relocating the inhabitants was mandatory, the same analysis should have been carried out by directly reducing the possible choice to the sole interventions from outside (thus excluding alternatives *A1* and *A2*) and erasing the criterion *C4*.
- *Scenario 2 – the building 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, and they want 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, the graph of the resulting weight vector is shown in Figure 10 (center) and leads to the graph of Figure 11c and 12 (center). In this case, alternatives *A1* and *A2* are the least suitable, followed by alternative *A4*, *A3*, *A5*, and *A6,* respectively. Even in this case, the best solution is represented by alternative *A6*, steel diagrids. It is worth noting that alternative *A3*, base isolation, is considered more sustainable than the *A4*, exterior RC walls.
- *Scenario 3 – the main constraints for the renovation are the low budget and the impossibility to increase the building space (i.e. according to the Italian urban planning restriction the building can only be supplemented with a 200mm thick 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. The graph of the resulting weight vector is shown in Figure 10 (right) and leads to the graph of Figure 11d and 12 (right). 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).

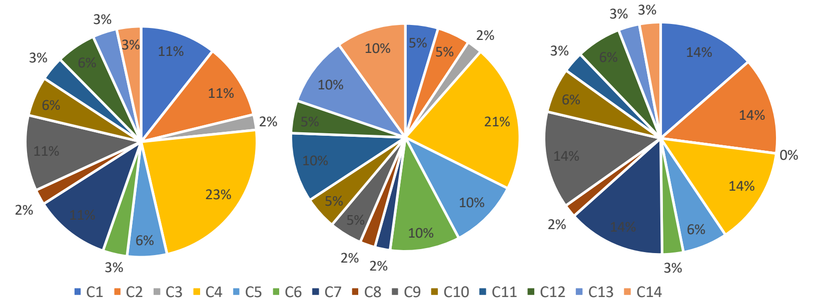
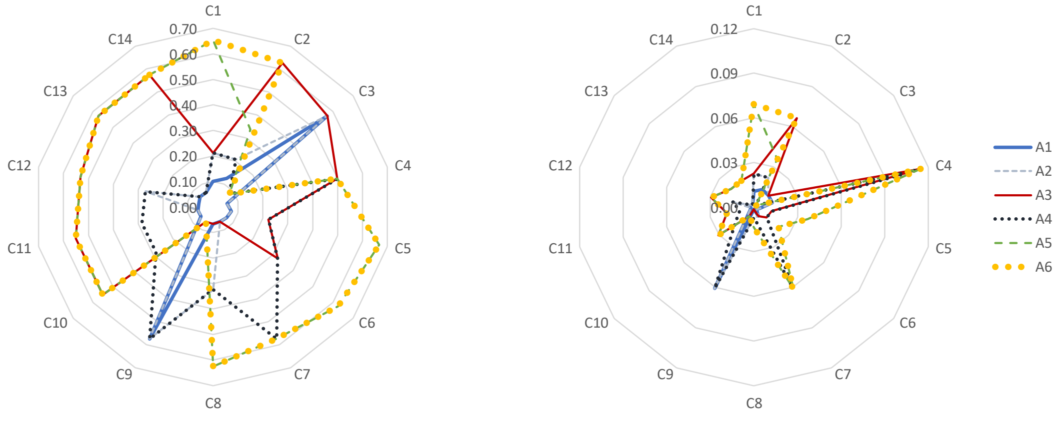
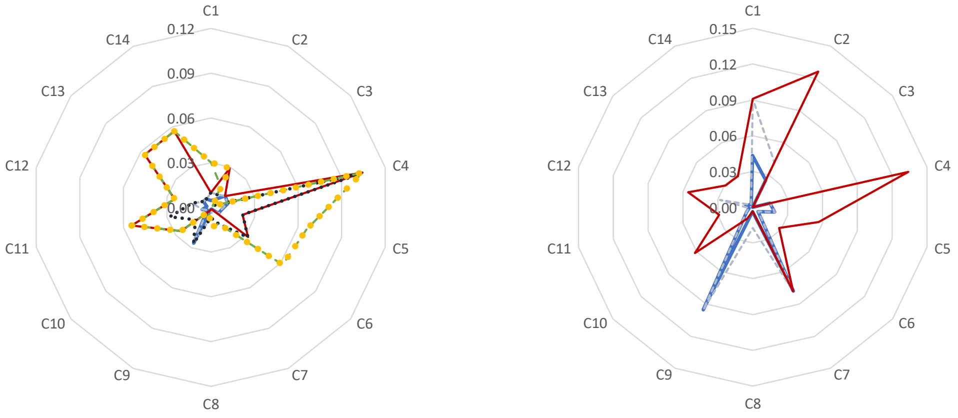


Figure 10. Representation of the weight vectors for the scenario 1 (left), 2 (center) and 3 (right).



SC-1,2,3 normalized performances

SC-1 weighted normalized performances



SC-2 weighted normalized performances

SC-3 weighted normalized performances

Figure 11. Normalized performances (a) and weighted normalized performances of the different alternatives with respect of each criterion for the scenario 1 (b), 2 (c) and 3 (d).

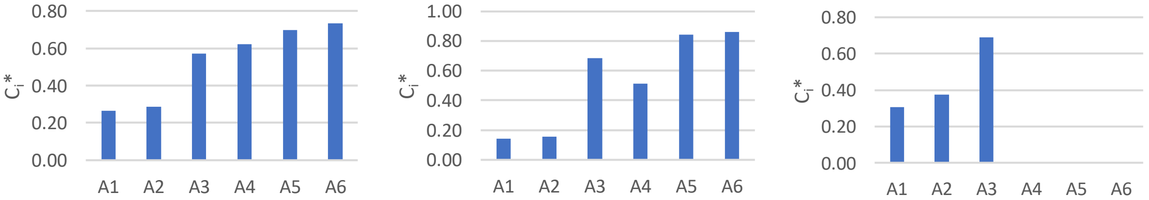


Figure 12. Ranking of the alternatives on the basis of their relative closeness C_i* from the ideal solution for Scenario 1 (left), 2 (center) and 3 (right).

Similar evaluations can be carried out for the choice of the best energy retrofit alternative according to the SBR approach. Even though energy retrofit measures include building systems' upgrading and/or thermal improvement of the envelope, in this example only the envelope thermal issue was addressed due to its better compatibility with seismic retrofit construction works, especially from the outside. In this case, the adoption of an additional thermal insulating layer made of either traditional glued panels or panels mounted on rails screwed on the façade (dry technique), or a ventilated façade is considered. Alternatives are compared in Table 4. Even for energy upgrading solutions, the presented MCDM method may be applied to define the best energy retrofit option, but this lays beyond the scope of the paper.

Table 4. Qualitative comparison of possible energy solutions adopting a SBR approach.

	THERMAL LAYER TRADITIONAL	**THERMAL LAYER DRY TECHNIQUE**	**VENTILATED FAÇADE**
DECISION MAKING AND CONSTRUCTION PHASE			
Duration of works	**LOW**	**LOW**	**HIGH**
Renovation cost	**LOW**	**MEDIUM**	**HIGH**
Need for additional space around the building	**NO**	**NO**	**YES**
Fast assembling	**NO**	**YES**	**YES**
OPERATIONAL PHASE			
Need for maintenance	**NO**	**NO**	**YES**
OPERATIONAL PHASE – POST-EARTHQUAKE			
Repair costs and impacts	**LOW** (if coupled to seismic retrofit interventions adopting LCT principles)		
END-OF-LIFE PHASE			
Fast disassembling	**NO**	**YES**	**YES**
Reusability or recyclability	**NO**	**YES**	**YES**

4.3. Step 3 – Design of the holistic retrofit intervention

Supposing to be in the scenario 1, in which the building has a residential function, inhabitants may not be relocated, the budget is low, and there is no urban planning restriction, the optimal seismic retrofit solution under a global environmental, social, and economic perspective and according to decision maker needs is the addition of an exoskeleton either implementing shear walls or conceived as a diagrid structure. As for the energy upgrading, a dry thermal insulating layer is selected. This system also implies the renovation of the façade under an aesthetic point of view as in a regular maintenance intervention – i.e. façade repainting or re-cladding. By combining these interventions together, some co-benefits may be derived in terms of reduction of total construction time and costs (shared construction site, shared scaffolding and man labor) and, in addition, the savings due to the improvement of the energy efficiency may partly pay for the structural interventions. Finally, if an extra budget was available and urban restrictions would allow, additional living spaces could be added in the space between the exoskeleton and the existing building, that may be transformed into rooms, balconies, or solar greenhouses, thus also increasing the commercial value of the apartments (Marini et al. 2017).

For the design of both the structural and energy interventions, a modified Performance Based Design (PBD) is here addressed, which also accounts for the additional constraints deriving from the combined approach and from the Life Cycle Thinking principles. First, new performance objectives and related design targets should thus be defined. In this case, to reduce the impacts connected to a possible earthquake, the structural retrofit is designed not only to control the structural damage, but also the damage in some nonstructural elements such as the infills and the additional thermal layer. In addition, the staircase well, which is the sole egress path in the case of an emergency, is protected and its damage completely avoided. All these additional performance objectives require the definition of more strict targets for the demand parameters, especially for the target drift, which is here fixed at 0.5% for the design earthquake at the Life Safety Limit State (LSLS) (with return period equal to 475 years according to the Italian building code - NTC 2018). It should be noted that a reduction of the inter-story drift, obtained through the increase of the exoskeleton stiffness, may cause an increase of the maximum base and floor shear, and the strengthening of the foundations and of the floor in-plane capacity may be required, which should thus be verified at the end of the design process. More about the sustainable design of this kind of elastic high-strength exoskeletons may be found in Passoni et al. (2020) and Labò et al. (2020). In this example, the sole transversal direction (direction y in Figure 7) is here discussed, which is the most critical.

Two different approaches are adopted to improve the seismic performances of the building. In the first case, an additional seismic resistant system with stiffness ($K_{retrofit}$) equal to 2.5 the stiffness of the existing frame (K_{frame}) is designed, resulting in a building with higher capacity and ductility that does not collapse for the design earthquake at the LSLS (Figure 13) and thus being compliant with a traditional PBD design (e.g. NTC 2018). However, the target drift of 0.5% is overcome, and ultimate capacity is reached in the infill walls and in the staircase walls, requiring some repair actions after the earthquake, especially to protect the egress path. Protection of the thermal layer is also not guaranteed. A second solution with stiffness equal to 3.5 K_{frame} is thus designed. Two different technologies are envisioned: the addition of steel walls or of a steel diagrid exoskeleton (Figure 13, right and Figure 14). In both these cases, the maximum drift for the design earthquake at the LSLS is lower than the target drift (Figure 13), so the infills and the stairwell do not experience any damage (and, consequently, the thermal insulating layer is protected). Protection of both human life and the investment are guaranteed.

The steel bracing solution consists in concentric diagonal bracing made of S355 steel and variable sections (Figure 14, left). On the transversal façades two bracings of 5.13m length (walls 1 and 5 in Figure 13) are considered, with beams and columns consisting of circular profiles with 244.5mm diameter and 16mm thickness and diagonals with 139.7mm diameter and 12.5mm thickness; while along the two longitudinal sides six bracings (walls 2 to 4 and 6 to 8) are inserted, with a plan dimension of 2.55m, beams and columns equal to the ones in the transversal direction, and diagonal elements with 101.6mm diameter and 10mm thickness.

Finally, the diagrid exoskeleton (Figure 14, right) consists in 3 modules in the longitudinal x-direction and 2 in the transversal y-direction, with an inclination angle Ψ=39° and steel profiles with 193.7mm diameter and 12.5mm thickness. A reduced stiffness of the system due to the non-rigid behavior of the connections between diagrid and building is considered in the model by adopting rigid links and an equivalent reduced section of the elements of 101.6mm diameter and 10mm thickness (Labò et al., 2020).

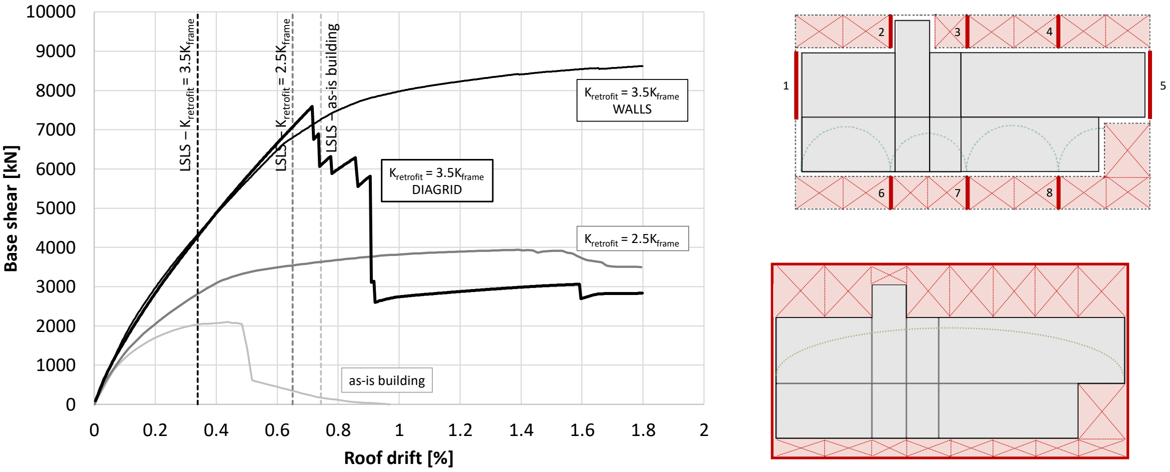


Figure 13. Evaluation of the building capacity in the transversal y-direction after the two possible seismic retrofit interventions ($K_{retrofit}$=2.5 and 3.5 K_{frame}) compared to the building in the as-is situation (left) and in-plane disposition of the additional resisting elements (right) – only the walls in the transversal direction are here represented. (in light red: new floors for additional living space).

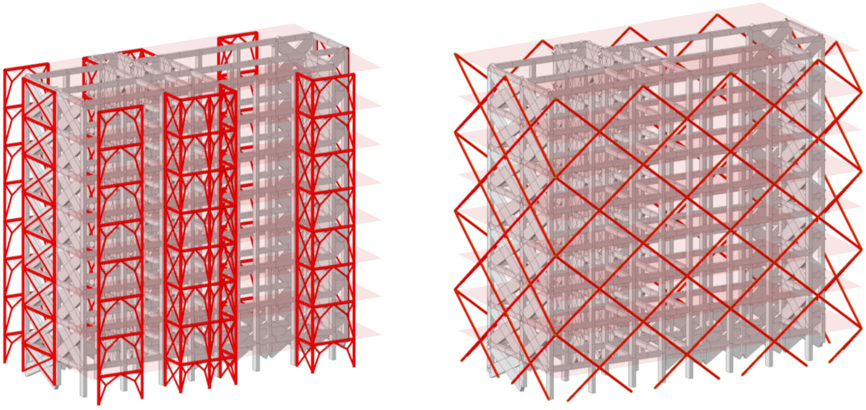


Figure 14. Schematic representation of the building retrofitted with additional steel bracings (left) and with diagrid exoskeleton (right), both having a stiffness equal to 3.5 K_{frame}.

Due to the high stiffness of the retrofit interventions, the total base shear highly increases, so foundation piles would be required at the base of the additional seismic resistant structure. This is particularly relevant for the solutions with shear walls, which concentrate the shear action into a few elements, whilst diagrid exoskeletons allow to distribute the shear flow by exploiting all the extension of the façades. The shear wall solution will require 12 to 18 foundation piles for each wall/bracing (each pile having length L=12m and diameter 160mm), while 40 piles are required for the diagrid exoskeleton, 2x10 piles in the longitudinal x-direction and 2x10 in the transversal y-direction. It should be noted that the great number of foundation piles is due to the high stiffness of the intervention required to minimize the damage in the building both at the Life Safety and at the Damage Limit State. This has a great impact in the initial cost of the intervention, whilst it guarantees a safe egress from the building in the case of an earthquake and reduces impacts and costs along the building life cycle.

As for the floors, in the shear wall exoskeleton, the shear-wall spacing can be accurately selected to avoid exceeding the floor in plane capacity. In fact, considering an arch-and-tie resistant system for the diaphragms, the number of arches and their span are determined by the distance between adjacent walls (Feroldi et al. 2019, Marini et al. 2020). On the other hand, when the diagrid exoskeleton is applied, the span of the arch becomes too high, thus reducing the floor capacity, and the strengthening of the two upper floors is thus required. For both solutions, resistant arches are represented in green in the right part of Figure 13. For diagrid solutions, innovative strengthening techniques carried out from the outside of the building should be adopted to be consistent with the design criteria of no inhabitants' relocation. In this case, new steel floors acting as external diaphragms, are added in the space between the building and the diagrid exoskeleton and in correspondence of the additional balconies (Figure 15). The floors are conceived as an in-plane horizontal truss-work. They are connected to the existing building by means of studs fixed to existing RC ring beams and deep anchors/post tensioned bars drilled into the existing floors and connecting the diagrid from side to side (Marini et al. 2017). In the other stories, where diaphragms are not required, a simple steel deck with parallel joist is assembled to carry the static loads of the additional living spaces.

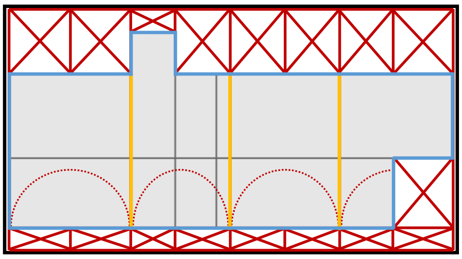


Figure 15. Schematic representation of the additional floor diaphragms (in red: floor diaphragm; in blue: steel chords fixed to the RC ring beams with studs; in yellow: deep anchors drilled into the existing floors) (the resistant arches after the intervention are represented with red dotted lines).

As for the energy efficiency amelioration, an additional thermal layer made of rockwool panels of 12 cm thickness is adopted, thereby reducing the thermal transmittance from U=0.89W/m^{2}K of the existing wall to U=0.23W/m^{2}K. The intervention enables the apartments to reach class B (adapted from Ioannes 2015). At this stage, the interactions between the structural and energy interventions should be considered (Table 4). Possible thermal bridges caused by the connection of the additional shear walls to the existing structure must be solved by designing ad-hoc technological details.

4.4. Step 4 – Choice of the best seismic retrofit option

At the end of the design process, the most suitable retrofit option has to be selected. Considering the sole structural issues, the solutions designed in Step 3 of the SBR are compared adopting metrics related to environmental, social, and economic sustainability. A simplified comparison is herein carried out.

The life cycle stages of the retrofitted building and the activities for each stage are first defined (adapted from UNI EN 15978:2011); then, metrics are selected in order to quantitatively estimate the impacts of each solution (Figure 16). Since the objective of this step is the selection of the best option based on comparative assessment, impacts and costs associated with activities that are common to both alternative solutions are excluded from the calculation. For example, in the use phase, the costs connected to the operation of the building will be the same given that all the retrofit solutions implement the same energy upgrading measures (envelope). Also, when the seismic retrofit interventions are designed to lead to the same structural responses, as required in Step 3, all the impacts connected to the effects of a possible earthquake during the building life cycle will be the same for the alternative solutions. In addition, when the SBR approach is applied for the design of the retrofit interventions, the reduction of the impacts along the building life cycle is a design objective; therefore, the most impacting solutions are directly discarded in Step 2, and the final impacts due to earthquakes and at the end-of-life will be very low for every designed solution. Similarly, at the end-of-life stage, both retrofit interventions will be demounted, and the majority of the waste will derive from the demolition of the initial existing structure, which is the same for the two solutions. When considering such observations, it becomes clear that, in the definition of the best retrofit option, the most relevant metrics are the ones connected to the construction and to the maintenance phases. In any case, a global evaluation of costs and impacts along the building life cycle is recommended in order to define the incidence of these relative costs and impacts on the total amount.

In the case study example, a preliminary simplified quantitative evaluation of the construction and maintenance impacts is carried out (in blue in Figure 16). In particular, costs for the construction material, transportation, use of equipment, and labor are roughly computed into a unique cost, but considering separately the construction of the steel exoskeleton and the foundations. Costs associated with the completion of the additional living space, the construction of the balconies/floor diaphragms, and the assembly of the energy upgrade is not computed since it is assumed to be almost equal for both solutions. It should be noted that the costs consider the retrofit intervention in both the transversal and longitudinal direction (Figure 14).

As for the duration of the works, it was supposed that a team of four men assembles two story-height portions of a brace in a day in the steel braced solution, while a team of three men assembles two diagrid levels in a week. As for the foundations, a team of four men is assumed to lay about five piles per day.

As for the maintenance, an inspection every 5 years (2500€/5 years) and the cost for the possible restoration/repair/repainting of the steel surface (35 € per hour for a team of two people) should be considered. However, given the use of galvanized profiles, the sole cost of the inspections can be computed a priori, and it is the same for the two solutions.

As far as the environmental impacts are concerned, it should be pointed out that both the solutions adopt steel as the dominant material in the corresponding retrofit technique. For the sake of simplicity, the potential impacts' calculation is here referred only to the total kg of steel adopted in each structural solution, being this number related to a pre-selected impact category using available databases (e.g. total CO_2).

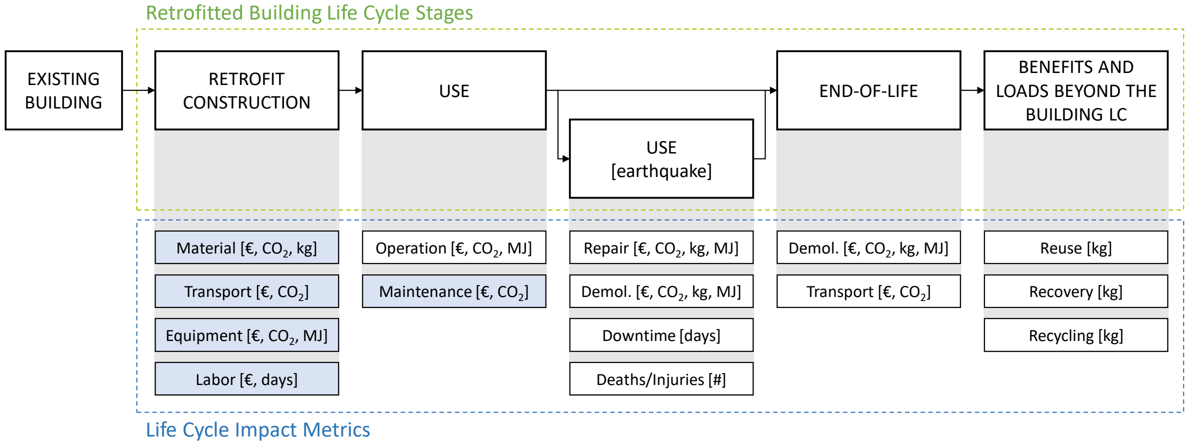


Figure 16. Life Cycle stages (top) and life cycle stage activities and impact metrics (bottom) for the retrofitted building (€: cost, CO_2: equivalent carbon dioxide, MJ: energy consumed, kg: quantity of material, days: quantity of time) - the activities considered in the example are marked in blue.

The results of the analysis are reported in Table 5. In this reference case, the diagrid exoskeleton outperforms the steel shear wall solution, both considering the qualitative criteria of Step 2 and further quantitative performances in Step 4. The application of additional MCDM analyses to aggregate the results into a unique score would thus be superfluous.

Table 5. Quantitative comparison of the designed structural solutions.

LC Phase	Type	Metrics	STEEL SHEAR WALLS	STEEL DIAGRID
Construction	Economic	Cost of walls/diagrid [€]	570000	183000
Construction	Economic	Cost of additional foundations [€]	166000	62000
Construction	Environmental	Environmental impact [kg of steel]	167000	54000
Construction	Economic/ Social	Duration of works - exoskeleton [hours]	1660	480
Construction	Economic/ Social	Duration of works - foundations [hours]	260	130

More accurate estimations of the impacts by means of LCC and LCA analyses may be carried out, but it is beyond the scope of this paper.

5. Novelty of the proposed approach and concluding remarks

The transition toward a more sustainable society, as envisioned by the recent European Roadmaps and UN's Agendas, requires the renovation of the existing building stock under a structural, seismic, energy, technological, and architectural point of view. Although some integrated techniques for the renovation of existing structures have recently been studied (§2.1), much research is still needed to adapt the current design procedures to this new holistic vision.

In order to select the most sustainable retrofit solutions, new innovative frameworks have been developed. Although these represent a fundamental step forward in the transition toward a more sustainable building stock, they often disregard some of the pillars of sustainability, and they never directly address the principles of Life Cycle Thinking (LCT) and the need to overcome the barriers to the renovation. These frameworks are proposed as ex-post evaluation tools, to be adopted for the comparative evaluation of different retrofit techniques after they have already been designed, and to enable the selection of the most cost-effective or eco-efficient solution among a set of alternatives that may also be seriously impacting by themselves.

Adopting a completely different approach and inspired by the SAFESUST Roadmap (Caverzan et al. 2016), in this paper, a new concept of Sustainable Building Renovation (SBR) has been introduced. According to this new approach, a sustainable solution is a solution that is conceived from the beginning to minimize the economic, environmental, and social impacts along the whole building life cycle. To this aim, the principles of LCT, the need to overcome the barriers to the renovation, and the specific needs of the decision makers are addressed even before the design of the possible alternatives. This way, the designer may also realize that the available techniques should be re-engineered and optimized to comply with all these initial requirements. More sustainable strategies could thus be adopted in the renovation projects (Figure 3). For example, dry and prefabricated techniques may be used to reduce the time of construction and optimize the process of deconstruction at the end of life; holistic solutions may be adopted to exploit the synergies of a combined technique, reducing time and costs of construction and limiting the interferences; retrofit solutions from outside may be applied without relocating the inhabitants, thus overcoming one of the major barriers to renovation; and so on.

When this new SBR approach is applied for the design of sustainable solutions, a completely new design framework should be adopted. In this paper, the new SBR-D framework is thus proposed, which considers a Performance-Based Design (PBD) approach but includes some major innovations at each step of the design. In the first step, the needs and constraints of the existing building are addressed under a multi-disciplinary point of view, and new shared performance objectives are defined together with the decision makers. Then, a second step is introduced aimed at selecting a set of solutions which comply with the LCT principles and the needs of the decision makers. This set is defined by applying a Multi Criteria Decision Making approach, where qualitative criteria are considered. In the third step, the pre-selected solutions are designed adopting a multidisciplinary and

LC perspective. Differently from a traditional design, the reduction of environmental, economic and social impacts along the building life cycle should be considered in the definition of the performance objectives and of the related design targets. As an example, the reduction of structural and non-structural damages after an earthquake should lead to the definition of more severe design targets in terms of drift and shear capacity of the structural elements. Finally, in the fourth step, the designed alternatives are quantitatively compared in terms of losses, environmental impacts, and costs along the whole life cycle in order to identify the most sustainable solution.

In synthesis, the main differences with respect to the other frameworks consist in:

- the adoption of a complete holistic framework reinterpreting the three pillars of sustainability so as to contextually foster eco-efficiency, cost-optimization, safety, resilience, and feasibility of the retrofit intervention, as envisioned in the SAFESUST Roadmap (Caverzan et al. 2016);
- the shift from an ex-post assessment method, where the sustainability is assessed at the end of the design, to a framework including sustainability principles inspired by the LCT approach in each phase of the design;
- the possibility to compare different alternatives not only in terms of costs, but also on the basis of weighted criteria that may be both qualitative and quantitative and that may be customized by stakeholders and decision makers;
- the involvement of all the players of the construction sector, fostering the concept of holistic and sustainable renovation and facilitating the cooperation of different professionals. Each player is involved in the renovation process from the beginning and can interact with the holistic retrofit project to redefine performances/targets against the multifaceted building needs. The framework may be adopted by design professionals for the design of sustainable solutions; by owners and investors as a decision-making tool; and by policy makers and urban planning specialists, as a guideline to promote sustainable urban regeneration. This will lead to a paradigm shift in the awareness of the existing building needs, with relevant consequences in terms of operative choices, innovative solution sets, and societal conventions and demands related to building renovation.

Future developments of this research require the collaboration among researchers and professional from each discipline in order to develop updated design and assessment tools under this new holistic and LCT perspective (LCC* and LCA*, including seismic losses, and structural and environmental EAL*, including damage to nonstructural elements and indirect losses), the definition of multi-criteria decision-making methods considering the new sustainable principles, especially for the pre-screening of different retrofit options, and a more detailed validation of the proposed framework with reference to case study buildings with different initial conditions and needs.

Appendix A – Application of a MCDM procedure for the qualitative evaluation of different solutions (Step 2)

The application of the MCDM method proposed by Caterino et al. (2008) for the qualitative evaluation of the best seismic retrofit options to be applied to the considered building is here presented. The method may be divided in few steps:

1) Definition of the alternatives and of the criteria

The alternatives and the criteria selected for the case study building are reported in table A1 and A2.

Table A1. Alternatives

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

Table A2. Criteria

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

2) Evaluation of the alternatives

2.1) Evaluation matrices

The AHP method, or eigenvalue approach (Saaty 1980), is first adopted. The method consists into a pairwise comparison of the alternatives with respect of each criterion. 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 thus 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*, and when $a_{ij}=9$ *i* it is 9-times better than *j*; accordingly, when $a_{ij}=1/2$ the performance of alternative *i* is considered 2-times worse than the alternative *j* and when $a_{ij}=1/9$ *i* it is 9-times worse than *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 *nxn* 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:

$$\sum_{i=1}^{n} x_i = 1$$

where x_i represent the normalized value of the eigenvector.

The pairwise comparison of all the solutions with respect to each criterion is reported in Table A3.

Table A3. Pairwise comparison of the possible alternatives with respect to each criterion.

C1 - duration of works

	A1	A2	A3	A4	A5	A6
A1	1	1/2	1/2	1/2	1/7	1/7
A2	2	1	1	1	1/3	1/3
A3	2	1	1	1	1/3	1/3
A4	2	1	1	1	1/3	1/3
A5	**7**	**3**	**3**	**3**	**1**	**1**
A6	**7**	**3**	**3**	**3**	**1**	**1**

C2 - renovation costs

	A1	A2	A3	A4	A5	A6
A1	1	1/2	1/5	1/2	1/2	1/5
A2	2	1	1/3	1	1/2	1/3
A3	5	3	1	3	2	1
A4	2	1	1/3	1	1/2	1/3
A5	2	2	1/2	2	1	1/2
A6	**5**	**3**	**1**	**3**	**2**	**1**

C3 - need for additional space

	A1	A2	A3	A4	A5	A6
A1	**1**	**1**	**1**	**7**	**7**	**7**
A2	**1**	**1**	**1**	**7**	**7**	**7**
A3	**1**	**1**	**1**	**7**	**7**	**7**
A4	1/7	1/7	1/7	1	1	1
A5	1/7	1/7	1/7	1	1	1
A6	1/7	1/7	1/7	1	1	1

C4 - need for inhabitant relocation

	A1	A2	A3	A4	A5	A6
A1	1	1	1/9	1/9	1/9	1/9
A2	1	1	1/9	1/9	1/9	1/9
A3	**9**	**9**	**1**	**1**	**1**	**1**
A4	**9**	**9**	**1**	**1**	**1**	**1**
A5	**9**	**9**	**1**	**1**	**1**	**1**
A6	**9**	**9**	**1**	**1**	**1**	**1**

C5 - fast assembling

	A1	A2	A3	A4	A5	A6
A1	1	1	1/3	1/3	1/9	1/9
A2	1	1	1/3	1/3	1/9	1/9
A3	3	3	1	1	1/3	1/3
A4	3	3	1	1	1/3	1/3
A5	**9**	**9**	**3**	**3**	**1**	**1**
A6	**9**	**9**	**3**	**3**	**1**	**1**

C6 - waste generation

	A1	A2	A3	A4	A5	A6
A1	1	1	1/5	1/5	1/9	1/9
A2	1	1	1/5	1/5	1/9	1/9
A3	5	5	1	1	1/2	1/2
A4	5	5	1	1	1/2	1/2
A5	**9**	**9**	**2**	**2**	**1**	**1**
A6	**9**	**9**	**2**	**2**	**1**	**1**

C7 - poss. to increase living space

	A1	A2	A3	A4	A5	A6
A1	1	1	1	1/9	1/9	1/9
A2	1	1	1	1/9	1/9	1/9
A3	1	1	1	1/9	1/9	1/9
A4	**9**	**9**	**9**	**1**	**1**	**1**
A5	**9**	**9**	**9**	**1**	**1**	**1**
A6	**9**	**9**	**9**	**1**	**1**	**1**

C8 - adaptability (IR)

	A1	A2	A3	A4	A5	A6
A1	1	1/5	1	1/5	1/9	1/9
A2	5	1	5	1	1/2	1/2
A3	1	1/5	1	1/5	1/9	1/9
A4	5	1	5	1	1/2	1/2
A5	**9**	**2**	**9**	**2**	**1**	**1**
A6	**9**	**2**	**9**	**2**	**1**	**1**

C9 - need for maintenance

	A1	A2	A3	A4	A5	A6
A1	**1**	**1**	**9**	**1**	**9**	**9**
A2	**1**	**1**	**9**	**1**	**9**	**9**
A3	1/9	1/9	1	1/9	1	1
A4	**1**	**1**	**9**	**1**	**9**	**9**
A5	1/9	1/9	1	1/9	1	1
A6	1/9	1/9	1	1/9	1	1

C10 - repair cost

	A1	A2	A3	A4	A5	A6
A1	1	1	1/9	1/5	1/9	1/9
A2	1	1	1/9	1/5	1/9	1/9
A3	**9**	**9**	**1**	**2**	**1**	**1**
A4	5	5	1/2	1	1/2	1/2
A5	**9**	**9**	**1**	**2**	**1**	**1**
A6	**9**	**9**	**1**	**2**	**1**	**1**

C11 - impacts connected to repair

	A1	A2	A3	A4	A5	A6
A1	1	1	1/9	1/5	1/9	1/9
A2	1	1	1/9	1/5	1/9	1/9
A3	**9**	**9**	**1**	**2**	**1**	**1**
A4	5	5	1/2	1	1/2	1/2
A5	**9**	**9**	**1**	**2**	**1**	**1**
A6	**9**	**9**	**1**	**2**	**1**	**1**

C12 - building downtime

	A1	A2	A3	A4	A5	A6
A1	1	1/5	1/9	1/5	1/9	1/9
A2	5	1	1/2	1	1/2	1/2
A3	**9**	**2**	**1**	**2**	**1**	**1**
A4	5	1	1/2	1	1/2	1/2
A5	**9**	**2**	**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**	

Given the arbitrary nature of the comparison and of the assignation of the values a_{ij}, conflicts may arise when assembling each evaluation matrix (supposing to have three alternatives, if alternative *i* is better than alternative *j*, and *j* is better than *k*, *i* should be better than *k* and should be $a_{ik}=a_{ij}\ a_{jk}$). According to Caterino et al. (2008), a consistency check is thus carried out, according a consistency ratio CR, which should be less than 5% if n=3, 9% if n=4, and 10% if n>4.

$$CR = \frac{CI}{RCI} = \frac{\lambda_{max} - n}{n - 1} \cdot \frac{1}{RCI}$$

where CI is the ‘consistency index’ with λ_{max} is the maximum eigenvalue of the evaluation matrix and n the number of alternatives; RCI is the ‘Random Consistency Index’ equal to [0 0 0.58 0.9 1.12 1.24 1.32 1.41 1.45 1.49 1.51 1.48 1.56 1.57 1.59] for *n*=1 2 … 15, respectively. In this example the consistency check is always verified.

2.2) Decision matrix D and normalized decision matrix R

The decision matrix is the synthesis of the quantitative evaluation of the alternatives with respect of each criterion. The rows of the matrix represent the alternative retrofit solutions and the columns the various criteria. When a qualitative comparison of the alternatives is carried out, the decision matrix is the collection of all the normalized eigenvectors of the evaluation matrices. Such vectors are then normalized considering the following equation:

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

where x_{ij} is the performance measure of the i-th alternative (i=1 … n) with respect of the j-th criterion and r_{ij} is the normalized value of x_{ij}.

The decision matrix D and the normalized decision matrix R for the considered example are reported in Table A4 and A5, respectively.

Table A4. 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 A5. 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

3) Choice of the best alternatives

3.1) Weighting of the criteria:

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 normalized eigenvector of the matrix associated to the maximum eigenvalue contains the weights associated to each criterion, also called weight vector.

3.2) Weighted normalized decision matrix V:

The decision matrix is scaled in order to consider the weights assigned to each criterion. A weighted normalized decision matrix is thus derived by multiplying each column of the normalized decision matrix by the weight vector ($v_{ij}=w_j\, r_{ij}$).

3.3) Ideal solutions A+ and A-:

From the weighted normalized decision matrix, the ideal solutions A+ and A- may be defined selecting the best and worst performance values for each criterion.

3.4) Ranking of the alternative solutions:

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):

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

And the relative closeness of each retrofit solution to the ideal one C_i^*:

$$C_i^* = \frac{S_{i-}}{S_{i+} + S_{i-}}$$

It should be noted that $0 \leq C_i^* \leq 1$; if $C_i^*=1$ A_i=A+, if $C_i^*=0$ A_i=A-. The best solution is the one with higher C_i^*. Different scenarios may be defined depending on building constraints and on stakeholders' requirements.

- Scenario 1: residential building, avoid the relocation of inhabitants and reduce the initial costs.

The pairwise comparison of the criteria, the normalized eigenvector λ_{max}, the weight vector w, the weighted normalized decision matrix V, and the definition of the ideal solutions A+ and A- and of the ranking of the solutions for Scenario 1 are reported in the following (Table A6 to A9).

Table A6. 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	2	2	9	1	5	7	2	9	2	5	7	5	7	7
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

λ_{max}= [-0.32 -0.32 -0.06 -0.69 -0.17 -0.10 -0.32 -0.06 -0.32 -0.17 -0.10 -0.17 -0.10 -0.10]

w= [0.11 0.11 0.02 0.23 0.06 0.03 0.11 0.02 0.11 0.06 0.03 0.06 0.03 0.03]

Table A7. 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 A8. 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

Table A9. Calculation of the closeness C_i* of each solution to the ideal one for Scenario 1

	Si+	Si-	Ci*
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

- Scenario 2: residential building, avoid the relocation of inhabitants and reduce the environmental impacts along the building life cycle

The pairwise comparison of the criteria, the normalized eigenvector λ_{max}, the weight vector w, the weighted normalized decision matrix V, and the definition of the ideal solutions A+ and A- and of the ranking of the solutions for Scenario 1 are reported in the following (Table A10 to A13).

Table A10. Pairwise comparison of criteria for Scenario 2

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
C1	1	1	2	1/5	1/2	1/2	2	2	1	1	1/2	1	1/2	1/2
C2	1	1	2	1/5	1/2	1/2	2	2	1	1	1/2	1	1/2	1/2
C3	1/2	1/2	1	1/9	1/5	1/5	1	1	1/2	1/2	1/5	1/2	1/5	/5
C4	5	5	9	1	2	2	9	9	5	5	2	5	2	2
C5	2	2	5	1/2	1	1	5	5	2	2	1	2	1	1
C6	2	2	5	1/2	1	1	5	5	2	2	1	2	1	1
C7	1/2	1/2	1	1/9	1/5	1/5	1	1	1/2	1/2	1/5	1/2	1/5	1/5
C8	1/2	1/2	1	1/9	1/5	1/5	1	1	1/2	1/2	1/5	1/2	1/5	1/5
C9	1	1	2	1/5	1/2	1/2	2	2	1	1	1/2	1	1/2	1/2
C10	1	1	2	1/5	1/2	1/2	2	2	1	1	1/2	1	1/2	1/2
C11	2	2	5	1/2	1	1	5	5	2	2	1	2	1	1
C12	1	1	2	1/5	1/2	1/2	2	2	1	1	1/2	1	1/2	1/2
C13	2	2	5	1/2	1	1	5	5	2	2	1	2	1	1
C14	2	2	5	1/2	1	1	5	5	2	2	1	2	1	1

λ_{max}= [0.14 0.14 0.07 0.65 0.31 0.31 0.07 0.07 0.14 0.14 0.31 0.14 0.31 0.31]

w= [0.05 0.05 0.02 0.21 0.10 0.10 0.02 0.02 0.05 0.05 0.10 0.05 0.10 0.10]

Table A11. Weighted normalized decision matrix V for Scenario 2

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
A1	0.005	0.006	0.012	0.012	0.007	0.007	0.001	0.001	0.027	0.003	0.006	0.003	0.006	0.006
A2	0.010	0.010	0.012	0.012	0.007	0.007	0.001	0.007	0.027	0.003	0.006	0.013	0.006	0.006
A3	0.010	0.029	0.012	0.104	0.022	0.032	0.001	0.001	0.003	0.026	0.054	0.025	0.057	0.057
A4	0.010	0.010	0.002	0.104	0.022	0.032	0.012	0.007	0.027	0.013	0.028	0.013	0.006	0.006
A5	0.030	0.016	0.002	0.104	0.066	0.062	0.012	0.013	0.003	0.026	0.054	0.025	0.057	0.057
A6	0.030	0.029	0.002	0.104	0.066	0.062	0.012	0.013	0.003	0.026	0.054	0.025	0.057	0.057

Table A12. Ideal solutions A+ and A- for Scenario 2

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
A+	0.030	0.029	0.012	0.104	0.066	0.062	0.012	0.013	0.027	0.026	0.054	0.025	0.057	0.057
A-	0.005	0.006	0.002	0.012	0.007	0.007	0.001	0.001	0.003	0.003	0.006	0.003	0.006	0.006

Table A13. Calculation of the closeness *C*

	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

- Scenario 3: residential building, avoid relocation of inhabitants; in this case there is not space around the building, so solutions that require to expand the volume of the building should be disregarded

The pairwise comparison of the criteria, the normalized eigenvector λ_{max}, the weight vector w, the weighted normalized decision matrix V, and the definition of the ideal solutions A+ and A- and of the ranking of the solutions for Scenario 1 are reported in the following (Table A14 to A17).

Table A14. Pairwise comparison of criteria for Scenario 3

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

λ_{max}= [0.41 0.41 0.00 0.41 0.19 0.09 0.41 0.06 0.41 0.19 0.09 0.19 0.09 0.09]

w= [0.14 0.14 0.00 0.14 0.06 0.03 0.14 0.02 0.14 0.06 0.03 0.06 0.03 0.03]

Table A15. Weighted normalized decision matrix V for Scenario 3

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
A1	0.043	0.025	0.000	0.015	0.019	0.006	0.078	0.004	0.095	0.007	0.003	0.006	0.003	0.003
A2	0.091	0.042	0.000	0.015	0.019	0.006	0.078	0.017	0.095	0.007	0.003	0.028	0.003	0.003
A3	0.091	0.126	0.000	0.134	0.057	0.028	0.078	0.004	0.011	0.062	0.029	0.055	0.029	0.029

Table A16. Ideal solutions A+ and A- for Scenario 3

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
A+	0.091	0.126	0.000	0.134	0.057	0.028	0.078	0.017	0.095	0.062	0.029	0.055	0.029	0.029
A-	0.043	0.025	0.000	0.015	0.019	0.006	0.078	0.004	0.011	0.007	0.003	0.006	0.003	0.003

Table A17. Calculation of the closeness C_i* of each solution to the ideal one for Scenario 3

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

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