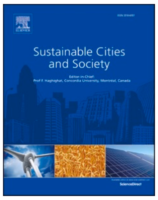
Sustainable Cities and Society 77 (2022) 103556

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs



Review of methods for the combined assessment of seismic resilience and energy efficiency towards sustainable retrofitting of existing European buildings

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ARTICLE INFO

Keywords:
Seismic retrofit
Energy retrofit measures
Integrated renovation
Sustainability
Resilience

ABSTRACT

Sustainable retrofitting of existing buildings is a prerequisite for achieving climatic and energy objectives in the EU. Thus, practical tools supporting the evaluation and decision-making process when planning retrofit interventions are required. In specific areas, in addition to energy efficiency, the improvement in building resilience to natural hazards is requested; in several European regions, seismicity poses a significant hazard. This study aims to analyse the state-of-the-art of the integrated methods for the implementation of structural and energy retrofitting.

The work consists of reviewing available tools, international sustainability protocols, and methods specifically developed for combined energy and seismic assessment. In the first group of methods, assessment is independently referred to specific criteria for energy performance and seismic safety, quantified according to available codes. Besides, in a second group, integrated evaluation is achieved considering 'equivalent' initial or life-cycle costs associated with energy consumption and seismic vulnerability. The collected methods were evaluated for qualitative requirements for optimal integration, such as multidisciplinary, life-cycle approaches, and other indicators.

Finally, a critical evaluation is provided, highlighting what can be used for future developments toward a sustainable and resilient retrofitting of existing European buildings.

1. Introduction

The occurrence of climate-related and other natural hazard events has increased over the last few decades. Simultaneously, the worldwide population is increasing, thus creating relevant implications for human activities.

Knowledge regarding the occurrence of seismic events and the vulnerability of the built environment and its level of exposure to seismic damage are crucial factors for the assessment of seismic hazards at the urban level (Zanini, Hofer & Pellegrino, 2019). The geophysical risk might be reduced if there is an improvement in seismic vulnerability in the built environment; this is a critical solution for mitigating the consequences of earthquakes. The spatial patterns of the most considerable seismic hazards mostly follow tectonic fault lines. Consequently, Europe has often faced geophysical problems because it is on the Eurasian tectonic plate adjacent to the African one. Accordingly, the seismicity level is very high along the Mediterranean coast, principally in Italy and Greece, whereas Northern Europe is mostly free of strong earthquakes. However, Northern Europe can still be affected by low-intensity earthquakes, and no seismic provisions are typically considered for the design of old buildings. This might correspond to a level of risk comparable to high-seismicity zones for which old seismic codes were considered at the time of construction. In Northern Europe, human-induced earthquakes (also known as HiQuakes) (The Human-Induced Earthquake Database (HiQuake) 2019) are more frequent. These are similar to natural earthquakes caused by geothermal operations and hydraulic fracturing (Valagussa, Marc, Frattini & Crosta, 2019;

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https://doi.org/10.1016/j.scs.2021.103556
Received 19 February 2021; Received in revised form 26 October 2021; Accepted 17 November 2021

Nomenclature

AAC	Autoclaved Aerated Concrete
IDA	Incremental Dynamic Analyses
BREEAM	Building Research Establishment Environmental Assessment Method
CDD	Cooling degree-days
CO_2eq	Carbon dioxide equivalent
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DLLS	Damage Limitation
EALs	expected mean annual losses
EEA	European Environment Agency
EIOLCA	Economic Input-Output Life Cycle Assessment
EU	European Union
FEMA	Federal Emergency Management Analysis
FRP	Fibre Reinforced Plastics
FRCM	Fabric-Reinforced Cementitious Matrix
HDD	Heating degree-days
HVAC	Heating, Ventilation and Air Conditioning
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LEED	Leadership in Energy and Environmental Design
LSLS	Life Safety
PBBD	Performance-Based Seismic Design of Buildings
PBEE	Performance-Based Earthquake Engineering
PEER	Pacific Earthquake Engineering Research Centre
PGA	Peak Ground Acceleration
RC	Reinforced Concrete
REDi	Resilience-based Earthquake Design Initiative
SDGs	Sustainable Development Goals
SSD	Sustainable structural design method, also known as SAFESUST approach
SLV	Life Safety limit state
TRM	Textile-Reinforced Mortar

Wang, Zhao, Du & Cheng, 2019) but are usually characterised by a low magnitude of 3 or less. Obviously, they have been considered hazards for buildings, infrastructure, and human life (Reed, 2019). Fig. 1 shows a European map with the recorded geophysical events since 1970 related to a widely used parameter that describes the regions prone to seismic hazards, the peak ground acceleration (PGA). For each seismic zone in the figure, the PGA corresponds to the reference probability of exceedance in 50 years of seismic action for the no-collapse requirement.

In addition to the above considerations, a considerable number of European buildings built before 1970 were designed without considering either seismic vulnerability or energy efficiency (Lamperti Tornaghi, Loli & Negro, 2018). The plan for deep energy renovation of an existing building usually starts with collecting data on local climatic conditions, actual energy consumption and costs, use profiles, and technical properties of the building envelope and heating, ventilation, and air conditioning (HVAC) systems. To facilitate the estimation of building energy demand, the heating degree-days (HDDs) and cooling degree-days (CDDs) can be considered. Fig. 2 shows the Europe maps for HDD and CDD for the span 1981–2017. The observed trends in HDD and CDD are projected to continue throughout the 21st century. The largest absolute decrease in HDD is expected in northern and south-eastern Europe, whereas, for CDD, an increased largest absolute is expected in southern Europe (European Environmental Agency, 2019).

After 50–60 years of service life, existing buildings present energy and structural/seismic inadequacies, mostly in cases that are referred to current national/European legislation. Approximately 35% of the EU buildings are over 50 years old, almost 75% of the existing built environment is energy inefficient, and 75%−80% of them will still be in use by the year 2050 (Fabbri, Groote & Rapf, 2016; Li, Kubicki, Guerriero & Rezgui, 2019). Often, their maintenance and retrofitting are economically unsustainable. Sometimes, it is preferable to demolish and build a new building that is compliant with the structural code and standards regarding energy efficiency and seismic vulnerability. When a building has a historical or still a high technical value, it is not possible or efficient to act in this way, and it is necessary to find a specific solution to reduce its seismic vulnerability and improve its energy performance.

A representative situation is the Italian case. The government introduced the *Sismabonus* initiative, according to the methodology of DM n°65/2017 (DM 65/2017, 2017), to induce a faster seismic retrofit process for existing buildings. This initiative recognises substantial tax incentives (earning up to 85% of the total expenses (Caterino & Cosenza, 2017)) for projects aimed at improving the seismic safety of buildings, from a general perspective of risk prevention (Cosenza et al., 2018). A seismic class is assigned to each building according to the expected mean annual losses (EALs) and the ratio between the capacity and demand of the building based on PGA for the life safety limit state (SLV) (Aggiornamento Delle «Norme Tecniche per Le Costruzioni», 2018). Furthermore, seismic strengthening can be combined with energy efficiency interventions (*Eco-Bonus*), increasing the limit of maximum tax deductions.

When dealing with the definition of seismic mitigation, economic resources should be allocated considering risk-targeted indicators, and thus, a seismic risk map based on reliable risk-targeted indicators is required. In risk identification and risk analysis, three categories of impacts should be considered when assessing the impact of hazard events, including risk scenarios and multi-risk assessments (European Commission, 2010):

1 Human impacts (estimated in terms of the number of affected people): number of expected deaths and permanently displaced people.
2 Economic and environmental impacts (estimated in Euro): the sum of the costs for building retrofitting, public transport systems and infrastructure, and other direct and indirect costs.
3 Political and social impacts (referred to as a semi-quantitative scale comprising five classes), which include issues such as impact on public safety, public outrage and anxiety, political implications, and damage to cultural assets.

These impacts should be considered in the short term and medium term as well. When they are computed, impacts can be expressed as the net present value.

In the last decades, the retrofitting practices adopted in numerous EU countries revealed that energy efficiency and seismic vulnerability aspects have been addressed independently following the corresponding standards/guidelines and are usually not integrated into a common methodological process. Indeed, despite the increasing awareness about sustainability issues associated with the existing building stock, it is a matter of fact that major retrofit plans were undertaken only in the aftermath of devastating earthquakes (Di Ludovico et al., 2017). Generally, national retrofit plans entail fulfilling pre-defined energy and/or structural targets; however, they are implemented without a clear strategy for selecting/assessing available techniques to maximise the benefits of integrated energy/structural interventions. This situation can be summarised as the issue of how to select and combine the techniques, and how to assess the results of their implementation.

When dealing with a building renovation process, the selection of target performances, retrofit materials, and technologies depends primarily on social and political situations. For instance, decisions on demolition and reconstruction choices are frequently affected by political directives. Similarly, with reference to strategic buildings (e.g. schools,

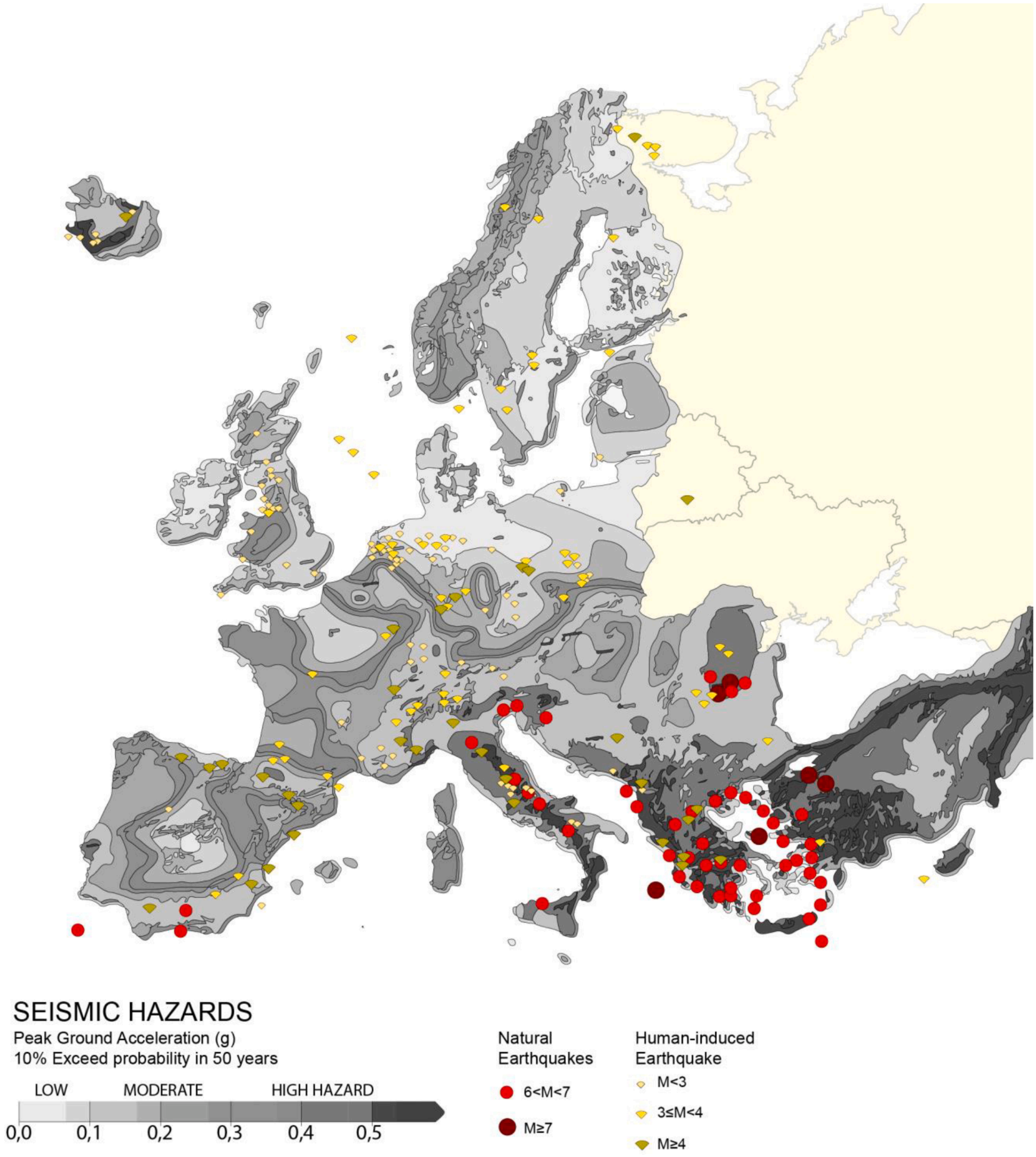

Fig. 1. European Map of the recorded seismic events since 1970 related to a seismic hazard map for the PGA with a 10% probability of exceedance in 50 years for stiff soil conditions. The visualisation is plotted by the authors based on data from European Environment Agency (EEA) and the Human-Induced Earthquake Database.

hospitals, etc.), light strengthening interventions with a low level of disruption and low cost might be preferred in a seismic risk mitigation strategy at a national scale to maximise the number of strengthened buildings with a minimum safety level. Local availability and common practice typically make some retrofit techniques more convenient than others, depending on their cost on the market. For instance, the use of composite materials for seismic strengthening interventions is widespread in the construction industry, and their cost has significantly decreased over the last decade. Additional aspects involved in the decision-making process are also represented by the low invasiveness and compatibility of materials, especially in the retrofit process of buildings with a historical value.

In contrast to the common practice of separated energy/structural interventions, a great potential can be envisioned as the result of combined actions from the perspective of solving several sustainability issues in a single intervention. First, a clear route for the design and assessment of integrated retrofit solutions can reduce the social risks associated with seismic hazards, such as loss of human lives and injuries during earthquakes and disruption of occupancy in a building during the intervention. Second, by extending the lifetime of existing buildings, the

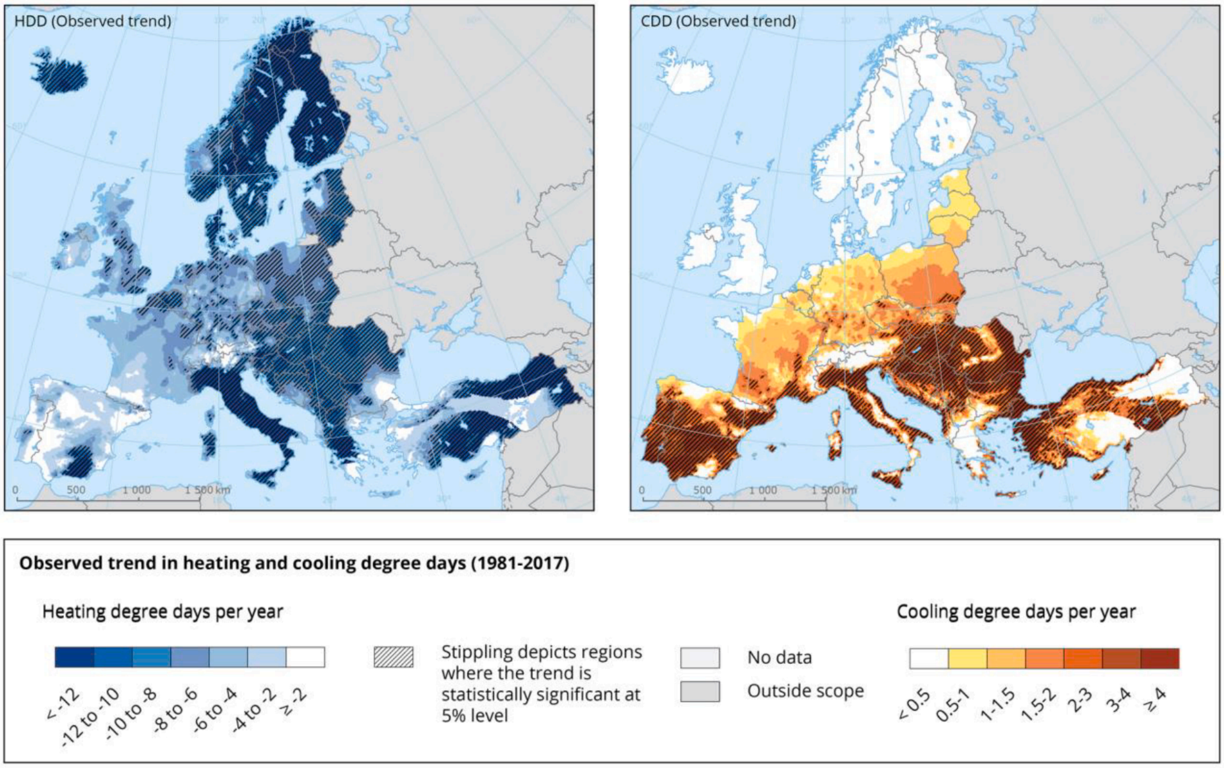

Fig. 2. Observed trends in HDDs and CDDs In Europe (1981–2017). Visualisation source: European Environment Agency (EEA), 2019.

combined seismic and energy retrofitting of the existing EU building stock would support EU sustainable growth policies by reducing both energy supply and new resources required for the construction of new buildings (also preventing demolition waste). Finally, implementing the energy and structural renovation works in a single process reduces additional costs and disturbance to the occupant, as typically occurs in the case of distinct renovation approaches. Such a single renovation process can also be optimised to reduce the amount of building material used, the required energy, and the transport load.

So far, integrated approaches have been introduced mainly having a more comprehensive perspective of the entire system to be retrofitted. The attitude of an integrated approach for concurrent energetic and structural improvement is closely associated with the knowledge of the typological, morphological, and technological aspects and the construction process. Consequently, it is vital to develop an integrated methodology that can reduce the effects of seismic events and energy consumption (Moschella et al., 2018).

1.1. Motivation and objectives

In this context, the present study contributes to the exploration of available methods for facilitating the implementation of large-scale combined energy-seismic retrofits. Hence, the main objectives are, from one side, to collect information regarding the different integrated techniques recently developed for the implementation of energy and seismic retrofit measures, and from the other, to collect and discuss the assessment methods adopted to quantify the effects of seismic vulnerability and energy efficiency resulting from a renovation process in a combined manner. The originality of this review is related to the fact that the scientific literature or sustainability protocols address very differently the topic of improving seismic resilience and energy efficiency in existing buildings. Thus, the results of combined retrofits are typically complex interpretations owing to the various methodological approaches available.

The work specifically focusses on existing buildings and consists of a broad literature review on available tools, international sustainability protocols, and ad hoc methods explicitly developed for combined energy and seismic assessment. The main findings were grouped into the following categories:

1 Evaluation methods are found in sustainability protocols, in which the assessment is referred independently to specific criteria/credits for energy performance and seismic safety. These are quantified according to the available codes/standards.
2 Evaluation methods for combined energy and seismic performance, in which integrated evaluation is achieved considering ‘equivalent’ initial or life-cycle performance indicators, such as costs (monetary, environmental, etc.) associated with energy consumption and seismic vulnerability.

This review reflects the complex nature of retrofitting when energy/structural measures are considered in a combined manner. Indeed, technical compatibility and homogeneity criteria must be carefully evaluated before the renovation process (Menna et al., 2021) and related, for instance, to (i) the level or extent of disruption, (ii) compliance with national legislation, (iii) increasing performance, and (iv) increasing costs and benefits. Therefore, reliable assessment methods are currently required to support such a decision and selection process. The development of adequately integrated technologies, as well as the definition of integrated performance indicators, could represent key factors for taking advantage of energy efficiency and seismic safety improvements (e.g. measuring savings associated with reduced labour costs, avoiding seismic damage during the building life cycle, and reduced energy consumption).

2. Materials and methods

The work started with gathering available studies through a broad literature review of the types of tools and evaluation methods developed specifically for the combined energy and seismic assessment of existing buildings. The collected information was organised into two groups, and consequently, into different short sections to describe the specific features of each tool or method.

In the first group of methods, the assessment of energy performance and seismic safety refers to specific criteria/credits, which are quantified according to available codes/standards within sustainable protocols. Research on the most commonly used sustainable certification schemes for existing buildings has been conducted. Three rating systems were selected for the purposes of this study: in-use versions of BREEAM (BREEAM, 2016a), DGNB (DGNB, 2020a), and LEED (USGBC, 2018a). The next step was the research and acquisition of the manuals of tools, and consequently, their examination aimed at collecting data on energy and seismic safety criteria included in each scheme. The tools were then compared to assess the weights of these two impacts (energy performance and seismic safety). As an initial point, a research hypothesis was developed, assuming that these tools play an essential role in recognising new opportunities and setting directions for further energy and structural retrofitting strategies. The analysis revealed that, even though they are focused on energy performance, the tools are not adequately ready to guarantee the seismic safety for existing buildings.

In the second group, integration is achieved by considering the combination of seismic and energy aspects by means of 'equivalent' initial or life-cycle performance indicators, such as costs (monetary or others) associated with energy consumption and seismic vulnerability. The second group of methods reflects the recent increase in available integrated energy and seismic retrofit techniques applied to both existing reinforced concrete (RC) and masonry buildings, which have encouraged the research community to establish reliable methods to evaluate the effectiveness of the novel renovation strategies. An additional motivation behind such novel evaluation methods is that the integrated intervention might often be invasive and/or costly with undetermined long-term benefits compared to the initial economic investment. Indeed, implementing integrated retrofitting techniques has the potential to reduce, first of all, labour costs, scaffolding etc., making the combined intervention up to 25% cheaper than when energy interventions and seismic retrofit applied separately (Gkournelos, Bournas & Triantafillou, 2019). Therefore, multi-objective evaluations are desired to demonstrate both the short- and long-term sustainability of the intervention itself, which also accounts for a set of existing building-related constraints such as minimum performance target compliance, historical value, non-invasiveness, reversibility and compatibility with traditional materials, reparability and maintenance, and total demountability-recyclability/reuse at end-of-life. For the sake of clarity in presenting the combined evaluation methods, a preliminary section is introduced on the technological aspects of a combined energy-seismic retrofit. Indeed, several assessment methods have been developed for specifically combined techniques. The collection/discussion of the different integrated assessment methods available in the literature is divided into two parts: component- and global-level assessment. This is due to the fact that the reference target of the assessment can be either a building component or the whole structure undergoing the combined retrofit.

A list of principal requirements on an 'ideal' evaluation tool is also formulated, and every collected method is evaluated for this list of qualitative requirements for optimal integration. The discussion highlights the optimum requirements for the assessment of existing building interventions, that is, providing a combined qualitative/quantitative evaluation of structural and energy improvements in terms of the following issues:

1 Multidisciplinarity: Since different performance aspects are involved in the renovation of existing buildings, a multidisciplinary approach is necessary to find the interaction between structural and energy issues, as well as the environmental impacts associated with the renovation process.
2 Resilience: improvement of the building's resilience to hazardous events minimising the downtime, financial loss, and guaranteeing the occupants' safety.
3 Site-specific context: Recognising the problems and hazards by methods and/or tools allows solutions and strategies to be adequately addressed for the location.
4 Energy efficiency: improvement of the energy efficiency while considering the broader technical, architectural, and socio-cultural site-specific context of a particular building.
5 Life cycle approach: considering the initial investments and demolition and/or construction impacts, which covers the overall impact along with the entire designed service life of the intervention.
6 Ease of use: features easy to apply methods, which will ensure its potential to be widely adopted, followed by the guidelines.
7 Economics: capability of monetary estimation of the interventions and their consequences.

To conclude, an analysis of the evaluations created the basis for conclusions and hypotheses for the discussion of future research directions. A schematic representation of the state-of-the-art review approach adopted in this study is shown in Fig. 3.

3. Results

3.1. Details of energy/seismic assessment methods in sustainability protocols

The current European building stock is ageing and needs notable improvements to optimise energy performance and guarantee structural safety with respect to environmental changes and the occurrence of natural hazards, particularly seismic events. According to the European Green Deal (European Commission, 2019), it is necessary to increase the number of building renovations twice to meet the EU energy-saving and decarbonisation goals by 2030 and 2050 (Pohoryles, Maduta, Bournas & Kouris, 2020). In this way, sustainable protocols can be helpful tools for guiding projects to meet the proper sustainable and seismic safety levels, mainly during the decision process by different stakeholders, such as architects, because they provide particular guidelines to address an optimum sustainable design.

Generally, sustainable protocols assign diverse weight factors or points to each considered sustainability criterion. They use different methods or calculation tools to assess energy savings and seismic safety, and their performance results in a 'weighted' score. Numerous methodologies and tools for energy and environmental assessments are based on well-established standards for LCA and energy efficiency. In contrast, seismic safety is not always considered, or it covers only a modest part of the sustainability protocol, but the main objective of the current national regulations is to protect building occupants. However, when a seismic event strikes, the losses due to damaged buildings and infrastructure are extensive, including the financial costs of post-earthquake demolition, repair, and restoration of utilities. Nevertheless, the most significant vulnerability can be represented by indirect losses due to downtime, i.e., the people's quality of life can be impacted due to the inability to return to homes or workplaces for years after a major shock. For example, in a high hazard seismic country like Italy, the national non-mandatory rating system *Protocollo Itaca* (iiSBE Italia, 2019) does not consider any criterion for seismic safety and improvement measures for tackling earthquakes or other natural events.

The selected tools BREEAM (BREEAM, 2016a), DGNB (DGNB, 2020a), and LEED (USGBC, 2018a), and their relative energy performance and seismic safety criteria are described.

3.1.1. BREEAM

The English Building Research Establishment Environmental Assessment Method (BREEAM, 2016a) is one of the most used tools for designing new and existing buildings, covering energy efficiency and

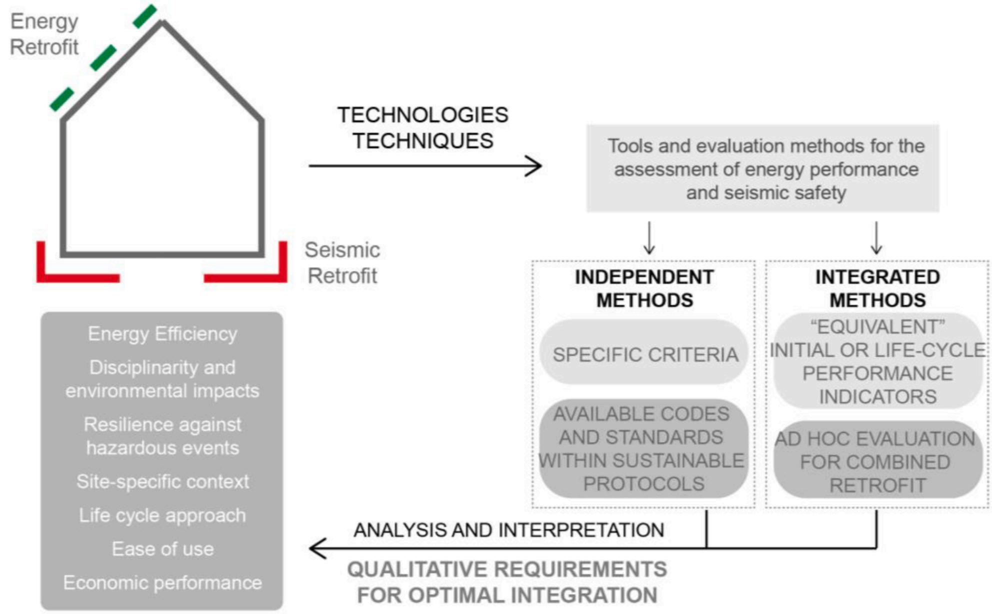

Fig. 3. Schematic representation of the approach for reviewing and interpreting the results.

environmental impacts.

Because it is followed worldwide (over 86 countries (BREEAM, 2019)), it requires adaptations for specific site conditions in the country in which it is being used, according to provisions for facing threats related to the considered region (BREEAM, 2018). In the In-Use version, the energy savings credits are 108, covering 42% of the tool. To assess the energy performance, the primary energy source (renewable and non-renewable) is used within an energy model in a calculator. The information required for the calculation of the energy score is about the building type, the age of the building, and the servicing strategy; further information to describe the performance of various systems has to be added.

Instead, seismic safety criteria cover only 6.2% of the entire system (16 credits on 257 available). These provisions focus directly on assessing the area to ensure that the building is protected against the potential impacts of natural hazards. The approach to this issue changes according to country and scheme. Moreover, BREEAM determines the capacity of a structure to confront an increased burden of weather, increased pressure (such as temperature variation, wind, heavy rain, and floods), or hazards (such as subsidence or ground movement).

3.1.2. DGNB

The German *Deutsche Gesellschaft für Nachhaltiges Bauen*) sustainable protocol (DGNB, 2020b) has just released the new 2020 version of the tool both for new construction and existing buildings. This version has maximum flexibility in the site-specific context; it may be necessary to adapt criteria or reference values and the weighting of criteria to create tailored solutions for diverse countries (DGNB, 2020b). DGNB is currently used in 30 countries worldwide (DGNB, 2019).

Concerning energy savings for In-use DGNB version (DGNB, 2020a), the proper credit is ENV1-B/Climate Action and Energy (DGNB, 2020a) with a weight of 30% in the complete tool. The supply to climate action and the reduction of energy consumption in building operations are assessed in both management and performance. This indicator estimates how the energy consumption data are recorded and collected. The main goal of this criterion is holistic optimisation of building operation. Evaluating the results of alternative assessments and selecting optimisation measures should be carried out while recognising and balancing environmental, economic, and social impacts.

In contrast, the criterion ECO2-B/Risk management and long-term asset value, with a weight of 15% in the tool, intends to have a resilient building stock by managing risk proactively, guaranteeing structural safety after environmental risks, and promoting cost-optimised change processes and action plans. This criterion is not appropriately specific to seismic events, but generally focuses on natural hazards that can represent a risk to existing buildings (such as earthquakes, volcanic eruptions, avalanches, storms, floods, heavy rain, hail, landslides, climatic extremes, and forest fires). Thus, it recommends evaluating the site regarding significant environmental risks; i.e., for seismic analysis, the EMS scale must always be used (from very low hazards <1 to high hazard level >8). In addition, it is necessary to assess the structural status of a building and its technical systems in energetic terms. This evaluation is used to determine the subsequent maintenance and repair costs and recommendations for repair measures.

3.1.3. LEED

Leadership in Energy and Environmental Design (LEED) (USGBC, 2019c) is a sustainable international protocol used for projects in more than 167 countries (USGBC, 2018c), which allows receiving points when quantitative criteria are satisfied. The relationship between rating tools and calculation tools is usually relevant to quantitative criteria such as carbon footprint, energy performance (following ASHRAE 90.1–2010 (Pacific Northwest National Laboratory, 2016)), and water and resource consumption.

The LEED method presents criteria with an intent (the aim of each criterion) and requirements (what should be done to gain points). There are usually different ways to achieve these requirements; thus, it is necessary to certify that the goal has been reached with documents that prove it. For instance, to assess energy performance (34 points out of 110, the weight of 30.9% in the Operation and Maintenance ($O + M$): Existing Buildings version (USGBC, 2018a)), LEED uses tools that follow ASHRAE requirements (Pacific Northwest National Laboratory, 2016), such as Energy Plus (U.S. Department of Energy. n.d., 2020), DOE-2 (James, 2020), IES-VE (IES, 2020), Tas Engineering (Environmental Design Solutions, n.d.), and EnerSim (Chehrzad, Pooshideh, Hosseini & Sardroud, 2016).

In the version for New Construction and Major Renovation, the new Pilot credit 'Design for Enhanced Resilience' (USGBC, 2019b) (2 points available on maximum 110) and the Pilot credit 'Assessment and Planning for Resilience' (USGBC, 2019a) (1 point) promote the proactive planning of the possible impacts of natural disasters (such as earthquakes, floods, and droughts) and classify the potentially high risks correlated with these stressors. If a seismic risk is identified, it is essential to seek an additional specific analysis of the site and surrounding conditions that will affect seismic hazards, such as soil conditions, adjacent structures, and service to the site, without forgetting the probable secondary danger of fire-following-earthquake.

LEED does not properly consider seismic safety within the protocol; in fact, the LEED $O + M$ version does not present any credits about it and suggests meeting at least the Silver benchmark using the Arup REDi Rating System. The Resilience-based Earthquake Design Initiative (REDi) (Almufti et al., 2014) is an independent method for evaluating building resilience and intensely focused on seismic vulnerability. Fundamentally, for each credit, REDi standard requirements have to be pursued, such as improving the structure or resuming the building operation after the event. The system requires a loss assessment to verify that a sufficient number of non-mandatory recommendations have been adopted, measured in terms of downtime and financial loss. Preparedness for post-earthquake recovery is one of the crucial aspects of resilience-based design, which aims to ensure continuous operation and liveable conditions immediately after an extreme event. In this sense, the severity of damage is proportional to the time required to repair a building.

REDi is a standardised methodology for estimating potential losses from various hazards such as earthquakes, floods, and landslides. For instance, the Federal Emergency Management Analysis (FEMA) developed Hazus (Federal Emergency Management Agency, 2017) and FEMA P-58 methodologies, better known as performance-based seismic design of buildings (PBBD) for new and existing buildings (Fema, 2018). The first independent method is a geographic information system-based hazard analysis tool for assessing the physical impacts of calamities. It is used to estimate economic and social losses, mainly at a regional scale, for both repair cost and replacement of damaged components as well as non-material costs (e.g. income loss, relocation costs, etc.), which may create problems when relating damage costs to environmental impacts via financial cost ratios or economic input-output LCA (EIOLCA).

In contrast, PBBD can design buildings with predictable and reliable performance in seismic events. This independent methodology suggests that the building's energy retrofit should be combined with seismic safety measures to reduce overall economic losses. At the same level, performance-based earthquake engineering (PBEE) (Günay & Mosalam, 2013) is another independent probabilistic method developed by the Pacific Earthquake Engineering Research Centre (PEER). One benefit is the incorporation of the uncertainty resulting from the damage estimation caused by construction and the related repair costs, and the suggestion as output of the forecast, in terms of repair costs, downtime, and human losses, of the influence of possible seismic events on a given building in a specific location (Caverzan, Lamperti Tornaghi & Negro, 2016).

3.1.4. Comparison amongst energy/seismic assessment methods in sustainability protocols

Fig. 4 summarises the weightings of energy performance (green) and seismic safety (red) in the three sustainability protocols compared to the overall weightings of other criteria (grey) in which, for instance, water efficiency, indoor environmental quality, and the preservation of building site biodiversity are included. It is evident that energy performance is one of the main factors considered in these protocols.

The BREEAM In-USE version has 42% of the tool directly focused on energy assessment, while only 6.2% focusses on hazard resilience (not only aimed at geophysical events). The methodology for metering energy performance (Table 1) uses a specific BREEAM calculator (Table 1). The metered energy consumption is used as the starting point for establishing the applicable energy consumption for an actual building. Then, it is necessary to enter the metered energy consumption for different fuel types (such as grid-supplied electricity, natural gas, district heating, and district cooling). Consequently, the tool calculates the associated equivalent carbon dioxide CO_{2eq} emissions for the actual building by multiplying the consumption data by the relevant carbon emission factors for each fuel type. In contrast, there is no specific methodology for safety assessment, but BREEAM recognises two credits for policies that are in place to reduce the risk of damage from natural hazards (BREEAM, 2016b). DGNB certification, as well as BREEAM, requires, for seismic analysis, the localisation of the specific building on a risk map, and associated assessment of the potential threat with a suggestion to ask the opinion of a qualified expert (DGNB, 2020a). The German certification, with a weight of 30% on the whole system, considers the energy analysis by collecting consumption data of the actual building (quantitative method), which will be compared to the target value that the stakeholders fixed at the beginning, to identify if the target value is met. Otherwise, the qualitative approach is to interpret and check the data for plausibility (e.g., effects of vacancy, occupancy density, and usage profile). Regarding environmental analysis, DGNB

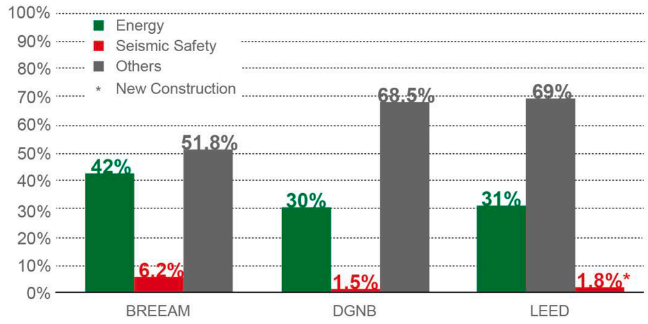

Fig. 4. Weightings comparison of the analysed tools (BREEAM, DGNB, and LEED) for existing buildings in terms of energy and seismic safety. The visualisation has been plotted by the authors based on data from BREEAM International In-Use 2017, DGNB In-Use 2020.

Table 1
Comparison of assessment methods for each In-Use protocol. Source of data: BREEAM International In-Use 2017, DGNB In-Use 2020, and LEED $O + M$: Existing Buildings 2018.

Sustainable protocol for existing buildings	Method for seismic analysis	Method for energy analysis	Method for environmental analysis
BREEAM	Risk assessment and potential impact of the area. Relevant emergency plans are identified by experts	BREEAM calculator to determine the Energy Performance Ratio (EPR_{INC})	BREEAM calculator referred to EN ISO 14,001: 2004
DGNB	Risk assessment and potential impact of the area by allocation in earthquake risk maps (475-year event)	Quantitative analysis by checking the variation between the target value and the actual value of actual building energy consumption Qualitative analysis by interpretation and checking the data for plausibility	CO_2-calculation tool provided by DGNB, including all calculation input data
LEED	N/A for existing buildings	ASHRAE/ASHRAE/ IESNA Standard 90.1–2010. (For the USA, EPA ENERGY STAR's Portfolio Manager tool)	ENERGY STAR Portfolio Manager Greenhouse Gas Emissions Technical Reference

provides a CO_2-calculation tool by including all calculation input data.

In the end, within the LEED protocol, the energy analysis complies with the ASHRAE/ASHRAE/IESNA Standard 90.1–2010 (Pacific Northwest National Laboratory, 2016), and the emission factors are used to calculate greenhouse gas emissions by energy source. In contrast, the American protocol does not adequately consider the resilience of existing buildings, but only for new construction; there are new pilot credits for the weight of 1.8% of the total (USGBC, 2020) (Fig. 4). In addition, the USGBC, the LEED developer, designed a new tool focusing on every kind of resilience, known as RELi 2.0 (USGBC, 2018b).

3.2. *Details of 'ad hoc' assessment methods for the combined energy and seismic retrofit*

3.2.1. *Technological aspects of combined seismic-energy retrofit interventions*

The lack of compliance with current design standards (accounting for seismic safety and energy efficiency requirements) represents a common feature of the existing building stock in European countries due to its relatively old age. Notably, the insufficient energy performance is mainly associated with less performing façade materials, scarce insulation of walls (e.g. lightweight clay bricks) and roof building components, poor performance of heating/cooling systems, and ineffective sun exposure. In addition to the seismic safety of existing RC buildings, in-situ post-earthquake inspections (Di Ludovico et al., 2019; Polese, Di Ludovico & Prota, 2018) have highlighted that the vulnerability to earthquake loadings is mainly due to the lack of proper seismic detailing, such as transverse reinforcement or stirrups in beam-column joints. The mechanical interaction with low energy efficiency and stiff infill masonry walls (commonly as double-leaf configuration made of light clay bricks) can also be a cause of the premature shear failure of RC buildings. As far as masonry constructions are concerned (including those with a historical value), seismic vulnerability is typically attributable to the fact that the structures were not designed to withstand proper seismic forces but generally to only carry their actions primarily in compression. In addition, poor quality of the masonry (units and bed joints), conservation status, and insufficient connections between the walls (with and without interlocking) reduce the global seismic response in terms of 'box behaviour' which is responsible for promoting the structural collaboration between masonry walls.

Given this situation, several strategies are commonly implemented to improve the energy efficiency or (independently) seismic safety in existing buildings; their extent depends on the climatic zone or seismic hazard representative of the building location in addition to the requirements of the reference legislation in force. In terms of energy consumption reduction, five major groups of applications can be identified, encompassing measures concerning the whole building, HVAC systems, components of the envelope (roof, wall, ceiling, and floor), windows and shading, appliances, and lighting. In particular, thermal insulation of the roof and/or of the external walls is commonly improved with traditional materials (e.g. polystyrene, rock wool, etc.) or innovative systems (e.g. nano insulation materials or phase change materials), and the replacement of windows—glasses and frames—and/or HVAC systems (including the installation of photovoltaic panels and artificial lighting systems with energy-saving devices) is generally required to achieve the highest levels of energy efficiency. In addition to the energy retrofit matter, available techniques for improving seismic safety aim to increase the structure's strength and/or ductility capacity following a global or local approach (or, in some cases, a combination of both). In the former case, the building is joined with new seismic-resistant elements, e.g. RC shear walls, exoskeleton or steel-braced frames (Passoni et al., 2021), to resist the seismic loads better. Alternatively, the local approach improves the compression, flexural, and/or shear strength/ductility of individual structural elements (beams, columns, joints, walls, etc.) to withstand seismic actions. In the case of RC structures, local structural enhancement can be achieved using steel/RC jacketing, fibre reinforced plastics/textile-reinforced mortar/fabric-reinforced cementitious matrix (FRP/TRM/FRCM) jacketing or wrapping (Akbari Hadad, Erickson & Nanni, 2020; Mugahed Amran, Alyousef, Rashid, Alabduljabbar & Hung, 2018). The load-bearing capacity of masonry wall structures or masonry infills in RC buildings can be improved by partial replacement of masonry wall portions, deep repointing, grout injections, jacketing and transversal tying of the external walls, and advanced composite materials using FRP meshes/grids. An alternative retrofitting strategy applicable to either RC or masonry structures is to reduce the seismic demand of the structure by base isolation. However, this solution is often not viable owing to practical constraints.

From the discussion above, it is clear that the overall benefits in terms of cost-effectiveness, optimisation of resources, time saving, and logistics management are achievable only if the retrofit intervention is conceived as 'integrated' at the design stage and, at the same time, if properly combined technologies are implemented. For instance, it is desirable to improve the energy efficiency of the building by enhancing the thermal insulation of the strengthening materials (Fenoglio, Fantucci, Serra, Carbonaro & Pollo, 2018), thus generating an economic advantage that can partly return the investment for the integrated energy-structural renovation; similarly, it is important that energy and seismic retrofit measures are applied at a consistent dimensional scale (e.g. structural walls, envelope, etc.) to take advantage of common labour operations (Bournas, 2018). To this end, combined solutions have been recently developed for the renovation of existing structures. Some examples of possible combined approaches are shown in Fig. 5. At the building level of external wall/masonry/infill, that is, affecting the thermal envelope behaviour, integrated strengthening systems make use of low-density and efficient thermal mortars in combination with polymer/glass/carbon reinforcements or, in some cases, insulation panels with plaster and transverse connectors (Mistretta, Stochino & Sassu, 2019b). amongst this group, lightweight strain-hardening cementitious composites (Zhu et al., 2018), such as hybrid steel and polyethene fibre combined with hollow micro glass bubbles (with a dry density of approximately 1350 kg/m^3), can improve the load capacity and ductility of masonry while guaranteeing a thermal conductivity of approximately 25% less than that of normal structural concrete. Alkali-activated slags have also been proposed to serve both as structural plaster (applied in GFRP-reinforced jacketing interventions) and as a thermo-insulating layer to improve the structural performance and energy efficiency of poor-quality masonry typologies; the overall energy efficiency gain was attributed to the thermal conductivity of the innovative plaster (0.35 W/mK) with a mass density close to 700 kg/m^3 (Coppola et al., 2019). Following an analogous approach, several authors (Bournas, 2018; Gkournelos et al., 2019) proposed an innovative hybrid structural and energy retrofitting system using TRM combined with thermal insulation systems (i.e. the mortar system itself and/or additional insulation panels) for RC and masonry building envelopes. The same authors estimated that combining the two interventions could reduce the overall cost by approximately 30% by significantly reducing labour costs. The structural efficiency was demonstrated through in-plane/out-of-plane experimental tests carried out on walls with a TRM/insulation retrofitting system which outperformed their non-retrofitted counterparts.

A different combined retrofit strategy applied to the envelope of RC framed buildings is based on the replacement of the external layer of double-leaf infill walls (generally made of hollow clay bricks) with thermally efficient blocks, such as autoclaved aerated concrete (AAC) blocks (Artino, Evola, Margani & Marino, 2019). These are typically characterised by a dry density between 350 and 600 kg/m^3, and corresponding thermal transmittance U-values up to less than 0.20 W/m^{2}K. This feature allows for a significant reduction in the energy demand for heating (e.g. $\approx -38\%$), which is associated with the improved thermal efficiency of the envelope. In contrast, from a structural viewpoint, this approach can provide enough structural improvement, mainly at the damage limitation limit state (DLLS) rather than at the life safety limit state and near-collapse limit state. This is because AACs are stiffer blocks

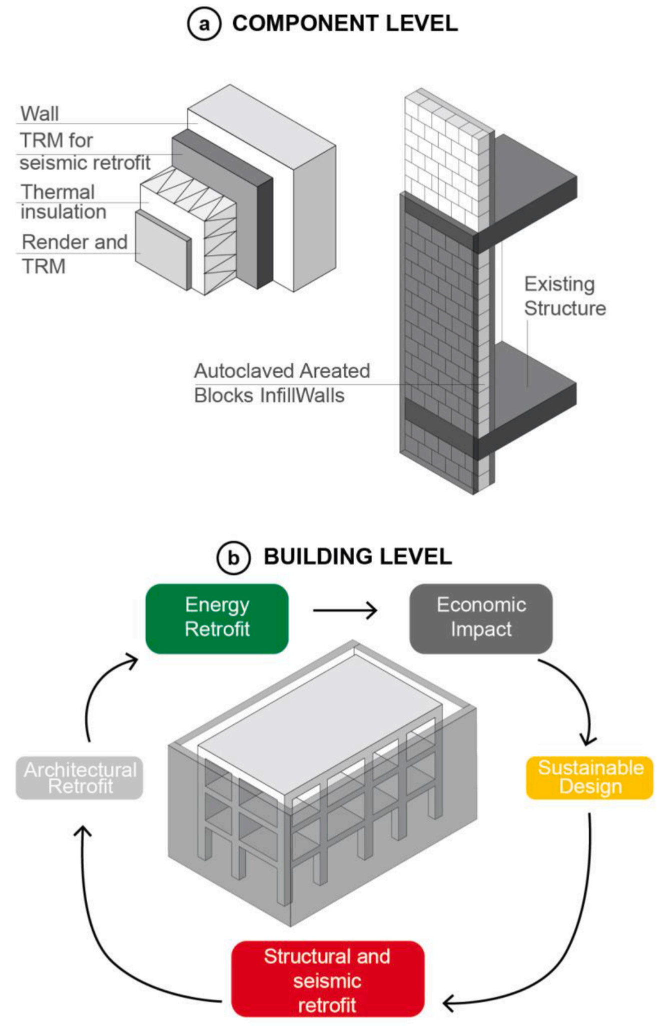

Fig. 5. (a) Examples of combined technologies for seismic and energy retrofit at the component level (a). Readapted from Bournas D.A., 2018, and Artino, A et al., 2019. (b) seismic strengthening and energy efficiency towards an integrated approach at the building level. The visualisation has been readapted by the authors based on data from Marini, A et al., 2017.

compared to most existing ones; at the global scale, replacement decreases the fundamental period of the structure and, in turn, might induce larger seismic forces and trigger possible stress concentrations on the beam-column joints.

When more effective combined solutions are required, especially from a structural viewpoint, that is, when higher levels of seismic upgrading are necessary, additional structures should be considered in the retrofit process. Although higher seismic/energy efficiency targets can be pursued with this approach, additional structures certainly require significant economic effort, a high quantity of material resources, and additional external space for installation. External structures can be added to the as-built configuration in combination with new panels with improved thermal insulation, resulting in a 'double-skin' solution. Following this approach, to achieve a complete seismic rehabilitation even in high seismic prone areas, Masi et al. (Manfredi & Masi, 2018) proposed an external RC frame connected to the existing RC structure through shear connectors and in combination with 200 mm-thick cored bricks insulating infill walls. In recent years, the double-skin technique has been further developed towards steel 'exoskeleton' solutions (D'Urso & Cicero, 2019; Labò, Passoni, Marini & Belleri, 2020; Passoni, Guo, Christopoulos, Marini & Riva, 2020) with the scope of conveniently adapting this solution to different geographical, climatic and urban conditions, and to different seismic hazard levels. In addition to thermal insulation, the resulting enlargement of the existing structure has the potential to guarantee a minimum impact on the inhabitants being applied from the exterior of the building. Additional sustainability targets, such as adaptability, reparability and maintenance, and total demountability-recyclability/reuse at end-of-life, can be achieved through steel-adaptive diagrids making use of over-resistant shell structures combined with dissipative rigid-plastic supports, which can also avoid any damage at the operational limit state. The interest in such a combined technique has recently increased; indeed, different research groups are currently working on double-skin technologies made of prefabricated elements (e.g. plug and play prefabs or high-energy performing envelopes) with the final goal of achieving higher performance in terms of energy requirements, structural safety, and social sustainability.

Moving from the building scale to large-scale integrated retrofit proposals, the issue of selecting proper combined structural and energy retrofit techniques for large-scale interventions has been addressed mainly in the case of historic load-bearing masonry structures characterised by similar structural and energy characteristics and architectural constraints for renovation. For instance, in the renovation process of the historic centre of Enna in Italy, the overall retrofit performance targets were first defined in compliance with the minimum level foreseen by the Italian regulations on energy efficiency and seismic improvement (Basiricò & Enea, 2018). Then, due to the historical value, the technological constraints of non-invasiveness, reversibility, and compatibility with traditional materials resulted in a set of possible combined interventions, which were only local for the structural improvement and used passive insulation measures throughout the building envelope. A similar approach of a non-invasive retrofit was implemented for ancient masonry buildings located in the historical centre of 'Sassi of Matera' (E. Nigro, D'Amato, & Cardinale, 2019) by particularly implementing a bio-composite material based on Kenaf/PLA.

3.2.2. Component-level integrated assessment methods

Component-level integrated assessment methods are mostly implemented to determine the initial cost-effectiveness of refurbishing/ renovation processes applied to existing masonry buildings (rather than existing RC structures) that require structural and energy improvements or also in conjunction with a seismic retrofit of buildings damaged by earthquakes (La Greca & Margani, 2018). The masonry components considered for such an assessment commonly belong to the building envelope, for example, masonry walls or whole façades. This circumstance entails that the structural and energy performance evaluation is limited to the component itself rather than the whole building, to which a more complex analysis is typically associated.

Focusing on a single masonry wall requiring integrated retrofit, a simple assessment method consists of the evaluation of the thermal transmittance (U-value) reduction (expressed in% with respect to the non-retrofitted masonry) versus the global (initial) investment costs (Fig. 6a) for a set of combined and technologically compatible seismic/ energy solutions applied to different masonry wall typologies (De Vita, Mannella, Sabino & Marchetti, 2018); which are indicated as Option A, B,…, n in Fig. 6a, and each of them results in different wall thickness values t_1, …, t_n depending on the achievable targets. Even though long-term performance is not accounted for, this method is useful for quantifying the economic savings linked to the combined labour works or even for highlighting the influence of raw material costs associated with the achievable insulating capacity of the wall.

A different assessment method is based on the relationship between the relative increment of structural resistance and the relative variation in the thermal properties of a single unitary (1 × 1 m) masonry wall subjected to a set of possible integrated retrofitting scenarios, and each scenario is developed assuming that the initial investment cost (expressed in $€/m^2$) or CO_2eq produced mass (expressed in kg_{CO2}/m^2) is constant (Mistretta et al., 2019b). As Eq. (1) shows, the improvement of

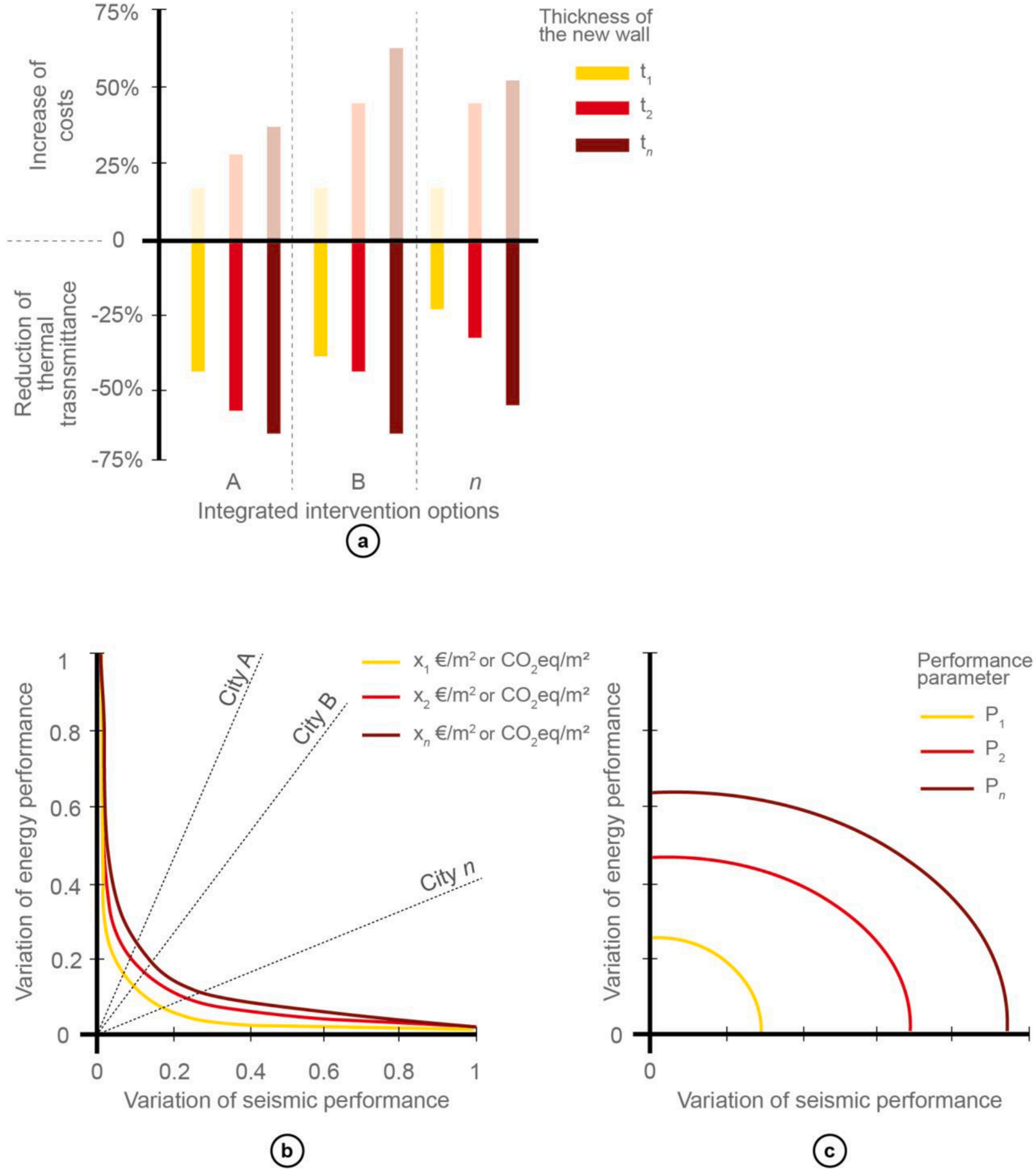

Fig. 6. (a) Integrated retrofit of a single masonry wall considering the thermal transmittance (U-value) reduction (expressed in% with respect to the non-retrofitted masonry) vs the global (initial) investment costs. (b) Integrated cost-analysis approach (or carbon emission approach) for seismic and energy improvement of masonry building façades. (c) The assessment method for combined structural and energy retrofitting in masonry buildings. The visualisations have been readapted based on data from (a) De Vita, M. et al., 2018, (b) Giresini, L. et al., 2020, and (c) Sassu, M. et al., 2017.

the structural and energy performance can be quantified in terms of the masonry wall bending moment, ΔM (or in-plane shear strength, ΔV), and thermal resistance ΔR (or the thermal inertia ΔT). In contrast, the same cost (or CO_2eq mass) of the intervention was guaranteed by tuning the thicknesses of the retrofitting layers (reinforcement and insulation) in different technical solutions. The resulting analytical relationship is a hyperbolic regression curve (with α_1 and α_0 as fitting parameters) for a given initial and normalised (per square metre of the wall) investment cost or CO_2eq produced mass:

$$\Delta \mathrm{R}(\alpha_1 - \Delta \mathrm{M}) = \alpha_0 = \alpha_0 \text{ or } \Delta \mathrm{R}(\alpha_1 - \Delta \mathrm{V}) = \alpha_0 \quad [-] \tag{1}$$

The result is typically represented in terms of isocost (economic or ecological cost) performance curves, as schematically shown in Fig. 6b. The usefulness of these curves lies in the possibility of matching predefined ratios of thermal and structural performance improvements according to the building site seismic and climatic characteristics, that is, by means of the following relationships:

$$\Delta \mathrm{R} = \alpha \frac{C_R}{C_u} \Delta \mathrm{M} \text{ or } \Delta \mathrm{R} = \alpha \frac{C_R}{C_u} \Delta \mathrm{V} \quad [-] \tag{2}$$

where $c_R = \frac{PGA_i}{PGA_{max}}$ and $c_U = \frac{DD_i}{DD_{max}}$ represent the ‘weight’ of the structural and energy needs in a given area, in which

1. PGA_i and PGA_{max} represent the peak ground acceleration for the location of the building and the maximum PGA of a given geographic area, respectively.
2. DD_i and DD_{max} are the HDD values for the given i th location and the maximum value for a given geographic area, respectively.
3. α is a tuning parameter that can be assigned by the political decision-makers.

If graphically represented on the same ΔRvsΔM or ΔRvsΔV plane for different locations (see dashed lines in Fig. 6b), the intersection of one of the two curves of Eqs. (1) and (2) represent a possible criterion for designing a masonry panel retrofitting intervention that is characterised by a given cost and environmental impact. The evolution of this assessment method at the mesoscale level of analysis was recently introduced by Giresini et al. Giresini, Paone & Sassu, 2020) and referred to building façade elements undergoing combined retrofit (i.e. instead of 1×1 m^2 of masonry wall). At the mesoscale level, the seismic performance indicators were the variation of base shear capacity ΔV and the corresponding variation of ductility capacity $\Delta\mu$, both determined through non-linear static analyses; for the thermal evaluation, the performance parameter is represented by the variation of thermal transmittance ΔU computed with a simplified approach in terms of an equivalent wall (existing wall and insulation/reinforcement layers), considering the openings and doors of the façade. In addition to the different performance parameters adopted, the economic and environmental isocost curves at the mesoscale can be obtained using Eq. (1) and ((2). A generalised approach following a similar integrated assessment method was proposed by Sassu, Stochino and Mistretta (2017) with reference to a set of reinforcements and energy scenarios for masonry walls. For each combined retrofit solution, the relative increment of structural resistance ΔR (in a plane or out-of-plane strength) and the relative increment in the thermal resistance ΔU (reciprocal of the transmittance) can be related to a 'performance parameter' P, generally associated with monetary terms (but also to other targets such as CO_2eq emissions) and is defined as the ratio between the investment cost of refurbishment C_i and the total cost of the building C_{tot}, as shown in Eq. (3).

$$g_R(c_R\Delta \mathrm{R})^{\alpha_R} + g_U(c_U\Delta \mathrm{U})^{\alpha_U} = \mathrm{P} = \frac{C_i}{C_{tot}} \quad [-] \tag{3}$$

where $g_{R,U}$ are specific weights that can be assumed for the structural and thermal improvement depending on the use of the building, whereas $\alpha_{R,U}$ are dimensionless adaptive coefficients depending on the site location. Starting from the pre-defined values of the performance parameter P, several combined performance curves can be drawn according to the equation above (Fig. 6c).

In general, the methods mentioned above are advantageous for selecting local retrofit solutions or simplified/rapid evaluations within a retrofit decision-making process. Indeed, for a fixed economic budget or environmental target that a private owner or a public administration has, it is possible to relate the level of thermal/seismic performance of a building component to the different retrofit scenarios applied in a specific geographical site. Although it appears that there is a lack of component analysis for RC structures, it is more common to have methods for masonry maybe because the masonry walls appear directly in seismic calculation, whereas non-structural walls (infills) are of particular interest in RC structures. Table 2 summarises the main features of the component-level integrated assessment methods.

3.2.3. *Global-scale integrated assessment methods*

In general, when a more intensive retrofit is required because of the significant thermal and seismic deficiencies of the existing building, a global approach to the design/assessment of the intervention is required. This is the case, for instance, of the double-skin solution described in Section 3.2.1, where the structural effects in terms of variation of strength, ductility, and dissipation capacity are quantified through a global building analysis. Indeed, in that case, the evaluation of a single portion of the building might not be representative of the overall performance outcome. Similar considerations can be drawn for the energy efficiency evaluation owing to the complex changes generated in the entire building envelope. It should be pointed out that several frameworks were recently proposed to approach the global retrofit from a holistic perspective by focusing on manifold sustainability-related concepts such as life cycle thinking (Passoni et al., 2021). These approaches aim to comprehensively consider the contributions of the construction phase, use-phase energy consumption, earthquake-induced damage and related repairing operations, retrofitting, and end-of-life management. Even though holistic frameworks can provide a general evaluation of the retrofit process, the complexity of the calculation has also encouraged researchers to focus on a limited number of sustainability aspects, for example, methods combining environmental and economic sustainability, safety and economic sustainability, safety and environmental sustainability, and safety, economic and environmental sustainability (Menna et al., 2013; Belleri & Marini, 2015; Caruso et al., 2017; Passoni et al., 2021). For the sake of clarity, in this review, we only focus on assessment methods developed to explicitly compute the effects of combined seismic retrofit and energy retrofit measures. In this circumstance, the evaluation of the combined thermal-seismic performances should be approached by focusing on a global metric (common to both the interventions) that represents the overall improved efficiency (thermal, seismic, or, more generally, sustainability efficiency) of the retrofitted structure. However, performing a global analysis of the retrofitted building within a given discipline (e.g. energy analysis, structural analysis, or life cycle assessment) would provide performance quantities in different units that cannot be summed up to obtain a single global parameter representative of the integrated intervention. A typical solution to this issue is to convert the outputs of the seismic, energy, and environmental impact analyses into monetary units (i.e. 'equivalent' costs), which are then used as a basis for comparing different retrofitting scenarios.

Table 2

Main features of combined assessment methods applied at the building component level.

Reference of the study	Structural Typology	Method for seismic analysis	Method for energy analysis	Method for environmental analysis	Overall integrated assessment
(De Vita et al., 2018)	Masonry walls	Considering the current national code for structural verifications	U-value of heterogeneous structures UNI EN ISO 6946:2008 and EN ISO 12,567–1	NA	Thermal transmittance reduction (% variation) and initial investment costs vs retrofit options
(Mistretta, Stochino & Sassu, 2019a)	Masonry walls	Resistant bending moment of a masonry wall retrofitted with FRP; or shear force strength of the wall panel	Thermal insulation resistance considering the properties of each layer of the panel	The ecological cost in terms of kg CO_2eq produced to retrofit a single 1×1 m^2 masonry panel.	Cost (economic and CO_2eq) regression lines for different initial costs per m^2 (for different techniques)
(Sassu et al., 2017)	Masonry walls	Increment of structural resistance (compressive strength and in-plane shear strength)	The relative increment in the thermal resistance	NA	Single dimensionless performance parameter P as a function of refurbishment type, building location, dimensionless adaptive coefficients
(Giresini et al., 2020)	External façades	Non-linear static (pushover) analyses on the entire façade to determine maximum base shear and ductility of the façade	Variation of thermal transmittance - UNI EN ISO 6946:2008 (for new buildings) considering an entire façade with openings	The ecological cost in terms of kg CO_2eq produced to retrofit a single 1×1 m^2 façade panel.	Economic and environmental isocost curves

In contrast to component-level integrated assessment methods, which mainly consider the initial investment cost of the combined intervention, at the global scale, these 'equivalent' costs are computed over the extended life cycle of the retrofitted building. The life-cycle aspect allows the method to include the long-term operational energy consumption or even the effects of damage-related economic and environmental costs due to natural hazards (e.g., earthquakes) or exceptional climatic events (e.g., floods) in the assessment. Consequently, the building performance associated with seismic resilience can be assessed by considering the predicted values of seismic expected annual losses (*EALs*), that is, the average value of economic loss that a building will sustain annually over its (remaining) service life due to the potentially occurring seismic damage. In contrast, the energy efficiency performance of existing buildings can be related to the total annual energy consumption, which determines the mean annual energy cost. Other performance parameters (e.g. CO_{2eq}) can also be quantified and associated with the retrofit process using proper transformations into monetary terms to consider the 'equivalent' annual environmental losses.

Within this common economic assessment framework, the effectiveness of any implemented integrated retrofitting solution can also be related to the payback time, that is, the time needed (in years) to equal the initial investment cost for retrofit. In detail, a lower payback time is associated with a higher economic efficiency of the combined intervention. The determination of this performance parameter is associated with the breakeven point for a building subjected to seismic, energy, or seismic and energy retrofitting, reporting total costs (including consumption and losses) over time.

In the following discussion, the main features of integrated assessment methods/tools available to date are reported, highlighting the possible advantages and disadvantages of their implementation.

Generally, global-level assessment methods are structured in multi-step/stage procedures characterised by three main blocks:

1. definition of energy retrofit measures and/or seismic improvement techniques based on pre-defined selection criteria
2. execution of energy and/or structural simulations according to well-established tools;
3. definition and quantification of integrated performance parameters for the retrofitted building.

For example, Güleroğlu et al. (Güleroğlu, Karagüler, Kahraman & Umdu, 2020) first defined a set of integrated retrofit packages compatible with regulatory boundaries, building preservation, and seismic rehabilitation codes; then, for each retrofit scenario, only the energy simulation results were used to quantify the economic performance parameter given by the sum of both the initial investment cost and the life cycle operation cost (i.e. associated with the primary energy consumption after retrofit). Based on this performance parameter, the cost-optimal energy/structural retrofit measure can be determined using the net present value (NPV) of the retrofit investment given by the discounted sum of all cash flows received, C_n, for each time period, n, with discount rate, i, as shown in Eq. (4).

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+i)^n} \quad [\text{any currency}] \tag{4}$$

Even though the life-cycle economic performance of the retrofitted building is quantified through this method, other sources of economic costs are neglected, especially those related to structural and environmental performance.

A more comprehensive multi-step integrated assessment approach was proposed by (Mauro et al., 2017; Menna et al., 2019; Menna et al., 2021). In particular, after determining the cost-optimal energy retrofit measures (ERMs) by minimising the thermal energy demand and thermal discomfort of the target building, the future costs related to the seismic-induced damages (i.e. corresponding to the economic investment to restore the damaged components) were quantified in terms of the expected economic losses in the building lifetime. In this regard, the economic loss assessment procedure was based on a simplified version of the well-consolidated approach developed by PEER-PBEE, in which the structural analysis was performed through static non-linear analysis instead of a non-linear time-history structural analysis (Vitiello, Asprone, Di Ludovico & Prota, 2017). The energy-structural aspects were integrated by linking the operational and damage levels of ERMs to the structural performance (in terms of engineering demand parameters EDPs) of the building components onto which they are applied (e.g. walls, floor, windows, etc.). The resulting integrated performance indicator was expressed as the overall economic life cycle cost (*LCC*) in the selected time interval τ, defined as Eq. (6) as follows:

$$\mathrm{LCC} = \mathrm{GC}(\tau) + \mathrm{EAL}(\tau)\ [\in /\mathrm{m}^2 / \mathrm{yr}] \tag{5}$$

The first term of the summation is the global cost (GC) which considers the investments for the ERMs as well as the discounted running costs for energy services over the building life-cycle, which is assessed according to the European Union (EU) Guidelines using Eq. (6):

$$\mathrm{GC}(\tau) = \sum_{\mathrm{j}} \left[\sum_{i}^{\tau} \left(\mathrm{RC}(i) \times \mathrm{D_R}(i) - \mathrm{V_{f,\tau}}(j) \right] + \mathrm{IC}\ [\notin /\mathrm{m}^2] \tag{6}$$

where

1. j is an index that denotes a given ERM;
2. i is an index that denotes the year;
3. τ is the considered time horizon, set equal to 30 years for residential buildings and 20 years for not residential buildings [19, 20];
4. *RC(i)* is the annual running cost for energy needs;
5. D_R is the actualisation factor;
6. $V_{f,\tau}$ is the residual value of the investments at the end of the evaluation period;
7. *IC* is the total investment cost for ERMs and strengthening measures (if these are implemented).

In contrast, the expected annual losses (*EALs*) due to the occurrence ofi earthquakes are assessed according to the procedure taken from Vitiello et al. (2017) and expressed by Eq. (7) in terms of total losses over the selected time interval τ:

$$EAL(\tau) = D_R \times \sum_{i}^{\tau} [C(i) \times \lambda(i)]\ [\notin /\mathrm{m}^2 / \mathrm{yr}] \tag{7}$$

where

1. *EAL(τ)* is the total loss computed over the selected time interval τ;
2. C is the replacement or restoration cost of the building after a seismic event in year i (i.e. the expected loss);
3. λ is the probability of occurrence of a seismic event in year i;
4. $C(i) \times \lambda(i)$ is the *EAL* in the year *i*.

The outcomes of this energy-seismic integration (commonly represented in an *LCC* vs. *year* diagram and shown schematically in Fig. 7 demonstrate that, for some seismic locations, the economic effort required to improve the energy efficiency of the building might be partially neutralised by yearly seismic losses because a significant shift of payback time can be experienced. Further development of this assessment method (Menna et al., 2019) consists of coupling the cost-optimal ERMs with cost-effective seismic strengthening solutions characterised by a pre-defined strengthening level (i.e. a given safety level defined as the ratio between the seismic capacity and the demand value). In this case, Eq. (4) showed that a combination of ERMs with the structural retrofit could keep the payback significantly reduced

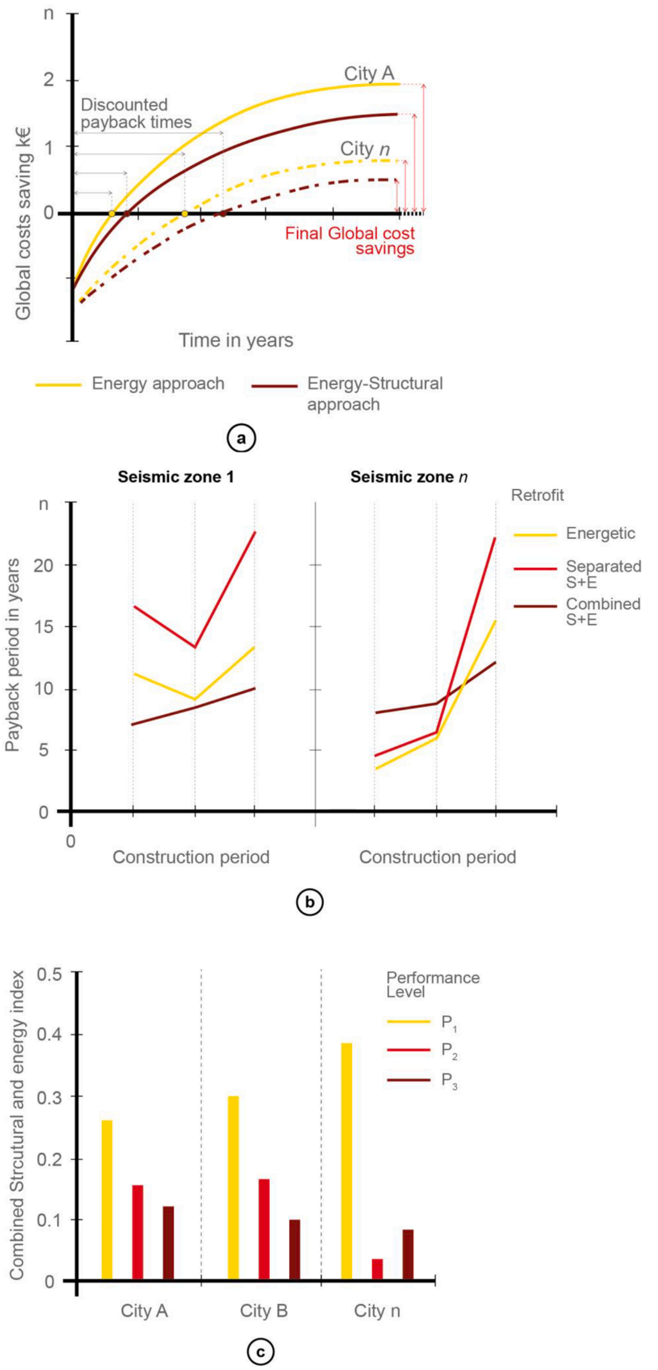

Fig. 7. (a) Trends by city of the GC savings vs time for the building energy retrofit. (b) Payback period in years for a determined construction period for the energetic, seismic, or combined retrofit analysed in different seismic zones. (c) Combined structural and energetic index by city. The visualisations have been readapted by the authors based on data from (a) Mauro, G.M. et al., 2017, (b) Pohoryles, D.A. et al., 2020, and (c) De Angelis, A. et al., 2020.

depending on the particular building site.

The importance of coupling structural analyses with the thermal performances of retrofitted buildings has also been highlighted Manfredi & Masi, 2018). In particular, the authors emphasised the role of masonry infills in the structural-energy modelling approach and the corresponding outcomes. This is because the infill walls in existing RC structures commonly need to be upgraded to satisfy the requirements in terms of energy savings and, at the same time, they can potentially increase the stiffness and resistance of the entire structure. In the study by Manfredi and Masi (2018), the seismic performance of the existing/-retrofitted building was evaluated through incremental dynamic analyses (IDA), considering the influence of the infill panels using an equivalent diagonal strut in the structural model, whereas the energy assessment was carried out according to the Italian standard UNI/TS 11, 300–1,2 which provide as output, respectively, the useful energy need for space heating and cooling and the energy demand associated with non-renewable resources. The integrated assessment method (adopted to compare different infill scenarios, including double-skin solution) considered, as building performance indicators, the following dimensionless quantities, α and β, which are evaluated in a specific building location, as shown in Eq. (8) and ((9):

$$\alpha = \frac{S_{e,C}}{S_{e,D}}\,[-] \tag{8}$$

$$\beta = \frac{U_D}{U_C}\,[-] \tag{9}$$

where

1 $S_{e,D}$ is the seismic demand value of the building;
2 $S_{e,C}$ is the seismic capacity value of the building (commonly as the maximum base shear obtained from each IDA analysis) evaluated for both damage limitation (DLLS) and life safety (LSLS).
3 U_D is the heat transmittance threshold value prescribed by national regulations in a given geographic location (i.e. demand value);
4 U_C is the heat transmittance evaluated for the considered infill type (i.e. capacity value).

Performance parameters greater than 1 identify a building with adequate seismic-energy performance for a given climatic/seismic zone.

Recently, integrated indicators were proposed to consider the economic performance of the retrofitted building, resulting from the seismic-induced damage and the energy consumption over its extended life cycle. The green and resilient indicator (GRI) (Calvi, Sousa & Ruggeri, 2016) introduced the idea of a practical and equivalent quantification of seismic and energy performances in terms of 'expected annual losses'. Accordingly, the value of the energy expected annual loss (EAL_E) can be determined as the ratio between the average annual cost of consumed energy and the total building value, making possible a direct comparison with its expected seismic loss counterpart (EAL_S).

Following the approach of integrated energy and expected seismic losses, the additional costs and savings linked to combined retrofit using innovative technologies were quantified in previous studies (Bournas, 2018; Pohoryles et al., 2020). In particular, the authors proposed an integrated assessment method to evaluate the effectiveness of a TRM jacketing technique combined with thermal insulation for the seismic and energy retrofit of masonry and existing RC structures, which was tested against different combinations of climatic (classified by HDDs) and seismic zones (classified by the expected PGA for a return period of 475 years, 10% exceedance in 50 years). The structural and energy performances of the retrofitted buildings were determined from representative typologies of the European building stock, generally identified by the construction period, the main structural system or material (e.g. RC or masonry), dimensions, and number of stories, because the seismic vulnerability and the U-values of envelope elements vary with these key parameters. Within this assessment framework, the energy retrofit target can be defined in terms of the U-value of the envelope elements that are required by the EU directives in each climatic location. Then, as shown in Eq. (10), the energy retrofit effectiveness is quantified in terms of expected annual costs (or losses), EAL_E, computed from the primary energy use due to the heating and cooling demands per unit of conditioned floor area (kWh/m^2):

$$EAL_E = \frac{Annual\ cost\ for\ heating\ +\ cooling}{Total\ building\ value}\,[\%] \tag{10}$$

where the building value is expressed in €/m^2 and depends on the building type and location.

With regard to the structural aspects, the seismic retrofit target is represented by the improvement in the performance by two categories, defined in terms of seismic design level (no code, low, medium, and high level of seismic design) after seismic retrofitting and in accordance with the framework of PBEE. Then, as Eq. (11) shows, the seismic retrofit effectiveness was quantified in terms of expected annual losses, EAL_S, evaluated in line with the PEER PBEE methodology and using fragility curves and damage-to-loss functions of the building typology. Then, the combined energy-seismic losses, EAL_C, can be given as (Bournas, 2018; Calvi et al., 2016):

$$EAL_C = EAL_E + EAL_S \quad [\%] \tag{11}$$

Alternatively, as Eq. (12) describes, the overall assessment of the integrated retrofit can be expressed in terms of the economic savings due to retrofit, that is, as the difference in the initial annual combined losses, $EAL_{C,i}$, and those after retrofit implementation, $EAL_{C,r}$:

$$\Delta EAL_C = EAL_{C,i} \ - \ EAL_{C,r} \, [\%] \tag{12}$$

This parameter can also be used to determine the payback time of the retrofitting intervention, which is defined as the ratio between the initial cost of the investment for the combined retrofit and the annual cost savings. Fig. 7b shows the results of such a methodological approach in terms of payback time obtained from the economic savings of Eq. 8 and as a function of the construction period of the existing building, for a specific seismic zone, and by comparing separated or combined approaches. The evaluation of energy consumption and seismic loss reductions achievable by applying combined retrofitting interventions has also been carried out on a larger scale using dedicated tools (Leone & Zuccaro, 2016).

Within the context of the expected annual loss approach, semi-probabilistic methodologies have also been recently proposed based on the definition of seismic fragility curves (suitable for a macro-classification of building stock) coupled, with the energy assessment curves defined as 'energetic fragility curves'. Their use is based on introducing a well-defined building stock classification, the selection of the intensity measures of a specific site, and the definition of seismic and energy performance levels. These can be useful for determining the interaction points for evaluating intervention strategies according to a pre-defined level of performance representative of a given building location (Fig. 7c).

From a sustainability perspective, which also focusses on the environmental performance of integrated retrofits, a sustainable structural design method (SSD) should also be considered (Lamperti Tornaghi and Negro, 2017; Caverzan et al., 2018; Lamperti Tornaghi et al., 2018). The European Commission - Joint Research Centre has developed the SAFESUST, an acronym which means SAFEty and SUSTainability, which identifies a research work package on the impact of sustainability and energy efficiency requirements during the design phase of buildings (Caverzan et al., 2018). The need to pursue is the renovation/reconstruction integrated with the SAFESUST approach: the best design solution can be recognised to improve structural safety and, at the same time, energy and environmental performance, considering the life cycle perspective. In detail, the framework of the SSD is based on three main evaluation steps schematically reported in Fig. 8: i) energy performance assessment to quantify the operating energy of a retrofitted building; ii) life cycle assessment to quantify the total CO_2eq emissions associated with the renovation process; and iii) structural performance assessment to quantify all the costs associated with a retrofit solution, as well as the expected losses (including also the downtime losses) that may occur in the building during its service life; these are calculated through a simplified performance-based assessment (sPBA) (Negro & Mola, 2017) based on the correlation of the PGAs and corresponding interstorey-drift-ratio of a given building typology. The main outcome of the SSD procedure is the global assessment parameter, R_{SSD}, expressed in equivalent monetary terms as the total sum of environmental and structural impacts, as follows in Eq. (13):

$$R_{SSD} = C_{TOT} + R_E^{Energy} + R_E^{CO2\mathrm{eq}} \tag{13}$$

where

1. C_{TOT} is the total cost of the building and corresponds to the sum of the initial investment and the expected total loss over the building life cycle.
2. R_E^{Energy} is the total energy cost associated with the life-cycle energy consumption of the retrofitted building calculated for a specific country;
3. R_E^{CO2eq} is the equivalent cost associated with the amount of the CO_{2eq} emissions calculated in the life cycle of the retrofitted building (i.e. converted into costs by means of a unitary cost of carbon dioxide (Romano, Negro & Taucer, 2013)).

Following a more comprehensive sustainability-orientated approach, that is, considering environmental issues into the integrated assessment of the combined seismic and energy retrofit, a life cycle-

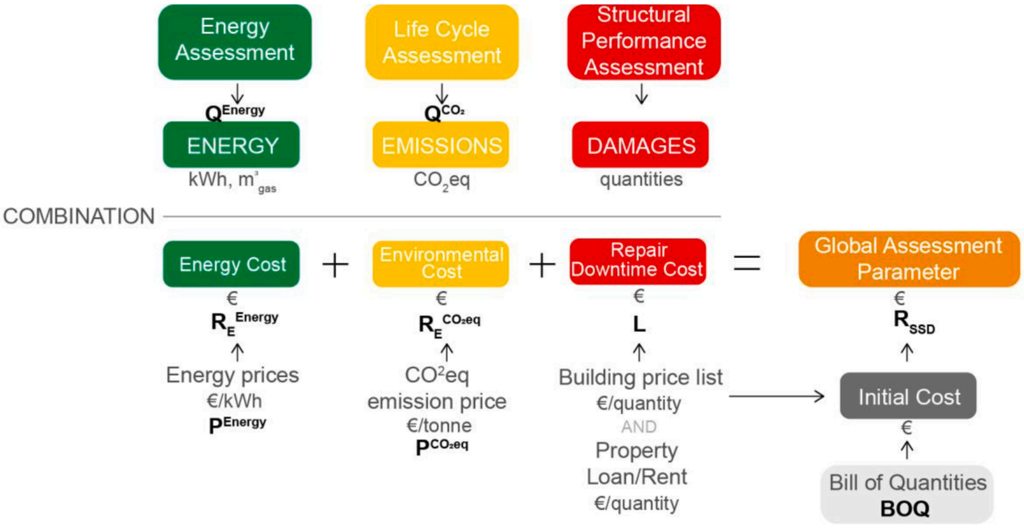

Fig. 8. Breakdown of the SSD method. The visualisation has been readapted by the authors based on data from Tornaghi, Loli, and Negro, 2018.

based framework was recently proposed (Caruso et al., 2020) and is schematically shown in Fig. 9. This study attempted to quantify the combined seismic/energy retrofit in terms of both monetary costs and environmental impacts, accounting for the following building life cycle contributions: initial construction, operational energy consumption, earthquake-induced damage repair activities, potential retrofitting interventions, and demolition (also considering its associated potential material recycling). Regarding the probability of seismic event occurrence, the authors proposed a damage-to-impact conversion to estimate the corresponding environmental impacts. As a result of this method, the authors proposed a particular representative classification made based on the normalised total annual costs and carbon emissions that could be adopted for a new classification system. The system integrates the life cycle economic and environmental impacts considering both the seismic vulnerability and energy efficiency of a specific building (Fig. 10).

Table 3 summarises the main features of global-scale integrated assessment methods.

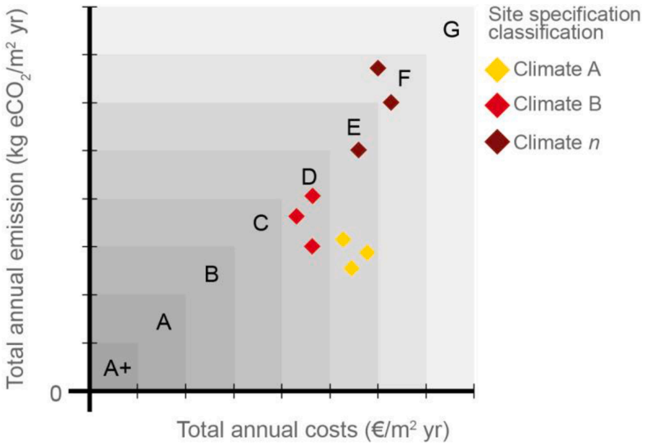

Fig. 10. The framework integrates the life cycle economic approach and environmental impacts, such as carbon emission, considering both seismic vulnerability and energy efficiency in a site-specific classification. The visualisation has been readapted based on data from Caruso, M. et al., 2020.

4. Discussion

The previously described tools might be addressed to different stakeholders, such as architects and engineers, municipalities, or construction companies. To be successful and handy, these rating systems and methodologies should be easy to use and able to approach different aspects related to energy efficiency, sustainability, and resilience. Table 4 shows a comparison between the studied protocols/techniques and the 'optimum' tool, highlighting the main aspects which should be covered to be recognised as appropriate. Considering the first group of methods, that is, sustainability protocols, it is evident that they consider numerous aspects, such as energy and the building context, and because they are usually based on a point system, they are also considered easy to use and apply to a specific case. In contrast, the resilience aspects, especially the seismic hazard, are not considered in detail; for example, only LEED BD+C New Construction recognises the geophysical risk, while the existing building version does not have criteria related to this matter, and it might be a limit for the tool.

From the discussion above, it appears that the assessing capability of sustainability protocols with regard to combined seismic and energy retrofits is still not satisfactory, especially for areas prone to seismic risk and characterised by high-energy demands. In contrast, the recent development of combined techniques/technologies as well as the national incentives associated with sustainable building renovation have fostered the release of more appropriate assessment methods. These methods are still at an academic/research level of maturity and need to be further improved for final use by the different stakeholders of the existing building renovation. Generally, these methods are based on the preliminary definition of site-specific parameters, that is, PGA and HDD, to characterise the seismic risk and energy demand. A significant feature is that the 'ad hoc' methods differ from each other in terms of four main key points:

1 *Dimensional scale of the application*: either component or global integration can be pursued in the evaluation process. In the former case, the assessment methods are mostly implemented to determine the cost-effectiveness of refurbishing/renovation of a portion of the building envelope, for example, masonry walls or whole façades. In the latter case, the integrated assessment requires a more detailed structural/energy analysis of the whole building.
2 *Time of application*: In some cases, the ad hoc integrated methods aim to quantify the initial cost (or environmental impact) effectiveness of the combined intervention, that is, at the construction stage. This could be very useful for interventions at the component level and/or for a preliminary selection of techniques and technologies to be applied to existing buildings. However, a more robust evaluation is represented by the quantification of combined performances throughout the extended life cycle of a building after a retrofit.
3 *Integrated parameters*: The approach to integrate the outcomes of both the seismic and energy analyses (at a local or global scale) varies amongst the different methods. The simplest approaches include the quantification of a specific energy performance parameter (e.g. U-value) as a function of different options of the intervention. However, these approaches neglect possible mechanical/physical/economic interactions derived from combined techniques. A more reliable and promising approach quantifies the energy, seismic, and

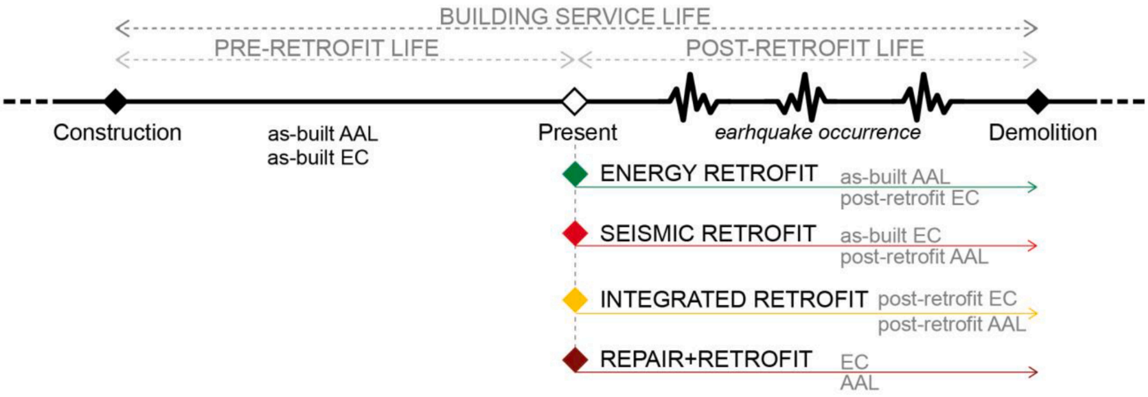

Fig. 9. Life-cycle framework with identifications of retrofit strategies considering economic and environments aspects. The visualisation has been readapted based on data from Caruso, M. et al., 2020.

Table 3
Main features of combined assessment methods applied at the global level.

Reference of the study	Energy analysis	Seismic analysis	Environmental analysis	Output parameters	Overall integrated assessment
(Leone & Zuccaro, 2016)	Simulations with dedicated energy analysis software on two sub-sets of building samples (masonry and RC structures)	Time-dependant vulnerability model	NA	Vulnerability distribution and expected economic impact at a regional scale	Cost-benefit analysis of a building retrofitting scenario based on the expected economic impact
(Calvi et al., 2016)	EP—primary energy as the amount of energy needed to heat the building, according to the calculation criteria of the UNITS 11,300, expressed in kWh/m^2	PEER methodology to estimate losses in a probabilistic framework by constructing building-specific loss assessment curves	NA	Energy expected annual loss that can directly be compared with its seismic counterpart, i. e. seismic expected annual losses	Two directly comparable and cumulative components of a comprehensive green and resilient indicator (GRI)
(Güleroğlu et al., 2020)	Selected building elements for U-value calculation using dynamic simulations	Structural analysis by using SAP2000 software; the need for strengthening exterior walls	NA	Initial investment cost and total cost of combined retrofit packages using NPV	Life cycle costing and annual heating and cooling energy consumption for all renovation scenarios
(Mauro et al., 2017)	Cost-optimal energy dynamic analyses by minimising the thermal energy demand and thermal discomfort of the target building	Economic loss assessment based on a simplified version of the PEER-PBEE approach; structural analysis performed through static non-linear analysis	Calculation of CO$_2$eq emissions associated with energy consumptions; not used for overall integrated assessment	GC consider the investments for the ERMs as well as the discounted running costs for energy services; EALS due to the occurrence of earthquakes	Integrated performance indicator expressed as the overall economic LCC; overall payback time
(Menna et al., 2019)	Cost-optimal energy dynamic analyses by minimising the thermal energy demand and thermal discomfort of the target building	Economic loss assessment based on a simplified version of the PEER-PBEE approach; structural analysis performed through static non-linear analysis	Calculation of CO$_2$eq emissions associated with energy consumptions; not used for overall integrated assessment	GC considering the investments for the ERMs as well as the discounted running costs for energy services; EALS due to the occurrence of earthquakes	Integrated performance indicator expressed as the overall economic LCC; overall payback time
(Manfredi & Masi, 2018)	Incremental dynamic analyses (IDA) and considering the influence of the infill panels	Energy assessment according to the Italian standard UNI/TS 11,300–1	NA	Seismic demand/capacity value of the building;heat transmittance prescribed by national regulations vs heat transmittance of the considered infill type	Dimensionless performance parameters to verify the adequate seismic-energy performances with respect to a given climatic/seismic zone
(Lamperti Tornaghi et al., 2018)	Simplified performance-based assessment (sPBA) by Safety and Security of Buildings Unit of the Directorate Space Security and Migration-European Commission, Joint Research Centre	Operating energy defined as the energy required for maintaining comfort conditions and day-to-day maintenance of the buildings	Life cycle assessment is performed (cradle to grave approach) to determine the CO$_2$eq emissions	Monetary costs computed separately for the expected seismic losses, energy consumptions and environmental impacts	Global assessment parameter expressed in equivalent monetary terms
(Bournas, 2018)	Non-linear time-history analyses (OpenSEES software); through the integration of the 'Annual Probability of Exceedance vs. Loss' curve	Energy needs for space heating (QH,ND) with a thermal energy balance and the indicator of energy performance (Epi)	NA	Sum of seismic and energy expected annual loss, expressed by the ratio of the average annual cost (of consumed energy or expected seismic loss) to the total building value	The total reduction in EALS as the total economic benefit of the combined retrofitting; payback time
(Pohoryles et al., 2020)	The expected annual loss due to seismic events evaluated in line with the PEER PBEE methodology	Dynamic energy simulations in EnergyPlus to calculate the energy demand for space heating and cooling per conditioned floor area (kWh/m 2) for a specific location	CO$_2$eq emissions calculated from heating and cooling demands	Seismic EALS, annual heating and cooling costs, and equivalent costs for CO$_2$eq emission	Combined losses and savings due to retrofit as the difference of the initial annual losses and the losses after retrofit application
(De Angelis et al., 2020)	Fragility curves using analytical, empirical or hybrid methods according to the type of input data	Results of the dynamic energy simulation for the definition of energetic fragility curves	NA	Primary energy for heating vs HDD; Structural and fragility curves for building	Combined structural and energetic index
(Caruso et al., 2020)	Loss assessment method following the fully probabilistic PBEE methodology	Energy analyses through EnergyPlus	Damage-to-impact conversion to get an estimate of the corresponding environmental impacts	Life cycle associated costs for seismic losses, energy consumptions and CO$_{2eq}$ emission	Monetary expenses and carbon emissions (total annual costs or total annual emissions) calculated through a summation that accounts for the contributions of the building life cycle phases

environmental performance in a unique monetary metric encompassing the equivalent expected losses for the different life cycle stages of the retrofitted building.

4 *Aspects of sustainability*: The effort to develop more reliable and comprehensive assessment methods for combined retrofits should focus on all aspects of sustainability, that is, environmental, social, and economic aspects. Simpler approaches mostly refer to cost/benefit analyses for selecting a more economically convenient set of retrofit techniques. In contrast, more sustainability-orientated methods have developed a multicriteria framework that includes equivalent environmental impacts as contributors to the overall economic performance of a building.

To foster sustainable renovation of existing EU buildings and based

Table 4
Comparing the previously analysed tools according to the main aspects highlighted by the 'optimum' tool.

	Multidisciplinary	Seismic Resilience	Energy	Site-Specific Context	Life Cycle Approach	Ease of Use	Economic Evaluation
Sustainability Protocols							
**New Building version presents this*							
BREEAM	NO	YES	YES	YES	YES	YES	NO*
DGNB	NO	YES	YES	YES	YES	YES	YES
LEED	NO	NO*	YES	YES	NO*	YES	NO
SSD	YES	YES	YES	NO	YES	YES	YES
Component-level integrated assessment methods							
(De Vita et al., 2018)	NO	YES	YES	NO	NO	YES	YES
(Mistretta et al., 2019a)	YES	YES	YES	YES	NO	YES	YES
(Sassu et al., 2017)	NO	YES	YES	YES	NO	YES	YES
(Giresini et al., 2020)	YES	YES	YES	YES	NO	YES	YES
Global-scale integrated assessment methods							
(Leone & Zuccaro, 2016)	NO	YES	YES	YES	YES	NO	YES
(Calvi et al., 2016)	NO	YES	YES	YES	YES	NO	YES
(Güleroğlu et al., 2020)	NO	NO*	YES	YES	NO	YES	YES
(Mauro et al., 2017)	NO	YES	YES	YES	YES	NO	YES
(Menna et al., 2019)	NO	YES	YES	YES	YES	NO	YES
(Manfredi & Masi, 2018)	NO	YES	YES	YES	NO	YES	YES
(Lamperti Tornaghi et al., 2018)	YES	YES	YES	YES	YES	YES	YES
(Bournas, 2018)	NO	YES	YES	YES	YES	NO	YES
(Pohoryles et al., 2020)	YES	YES	YES	YES	YES	YES	YES
(De Angelis et al., 2020)	NO	YES	YES	YES	NO	NO	YES
(Caruso et al., 2020)	YES	YES	YES	YES	YES	YES	YES

on the main outcomes of this review, a set of requirements for a novel integrated (energy-structural) retrofit design method can be proposed. The requirements reflect the recent long-term sustainability targets set out by the EU and international institutions and consider the main characteristics of both energy and seismic retrofit techniques . The key aspects of the ideal combined assessment method consider the possibility of considering the particularities and mechanical interactions of both structural and energy retrofit techniques as well as the definition of a single life cycle monetary parameter, which should allow the selection of the most sustainable (in terms of economic, social, and environmental aspects evaluated throughout the residual life cycle of the building) combination of available techniques.

5. Conclusions and directions of future works

The manuscript reports some well-known factors, such as population and energy consumption, both of which have grown in the last decades and centuries. Natural disasters are present in many European and international protocols and policies, such as Sustainable Development Goals (SDGs), to save lives and reduce economic losses due to natural events. Climatological events have always been more frequent, but the results of comparing their economic losses to geophysical events are surprising. Seismic economic losses are approximately four times greater than the climatological economic impact.

In addition, the result of analysing the recorded seismic prone areas is that in Europe, the countries vulnerable to natural earthquakes are along the Mediterranean Sea: Italy, Greece, Albania, and Spain. Concerning HiQuakes (human-induced earthquakes), the vulnerable areas are mostly in Northern Europe, which include the Netherlands and Germany. Moreover, since in Europe, there are other natural stressors, such as floods (coastal and rivers) or wildfires, it is necessary to specify where the assessment system or integrated technique will be used. In fact, it is not reasonable to use one general tool for all Europe; it is fundamental to consider the site-specific context and the boundary conditions for the building assessment.

This manuscript reviews existing methods and techniques for retrofitting existing European buildings that have been assessed considering integrated evaluation methods for seismic resilience and energy efficiency.

Two main categories of methodologies were highlighted. The first is related to sustainability. It is particularly focused on qualitative assessments of European and non-European sustainable protocols (i.e. BREEAM, DGNB, LEED). These have been compared considering seismic, energy, and environmental impacts. The outcomes of these protocols were essentially qualitative. The second category refers to different techniques evaluated considering the integration of seismic and energy aspects applied to existing RC and masonry buildings. This category appears very promising depending on the level of application, time extent of the analysis, and sustainability aspects included.

Future directions in integrated methods should concentrate more explicitly on developing a holistic approach. This might involve all aspects of the design framework, methods, and technological solutions for stakeholders to measure the building system's performance and damage as a whole. Therefore, multi-objective evaluations are desired to demonstrate both the short- and long-term sustainability of the combined intervention itself, which also accounts for a set of existing building-related constraints such as minimum performance target compliance, historical value, non-invasiveness, reversibility and compatibility with traditional materials, reparability and maintenance, and total demountability-recyclability/reuse at end-of-life.

Declaration of Competing Interest

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

Acknowledgements

Part of the analysis was inspired by the activities of the Italian joint programme DPC-ReLUIS 2019–2021, WP5: 'Fast and Integrated Retrofit Interventions' led by Prof. Andrea Prota. Some results of this work come from the non-profit activities of four authors in fib (International Federation for Structural Concrete). This research was partially funded by specific research funds from the Czech Technical University in Prague.

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