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ORIGINAL ARTICLE

The evolution of sustainable renovation of existing buildings: from integrated seismic and environmental retrofitting strategies to a life cycle thinking approach

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Abstract

The sustainable renovation of existing buildings is currently at the top of the agenda of the European Union. Sustainability is typically defined as the result of the interaction of environmental, economic, and social aspects, and it is now considered a major target objective in all sectors of our economy, including the construction one. The concept of sustainable renovation has changed significantly over time, leading to the current interpretation that considers the need to simultaneously improve safety and resilience against natural hazards and minimise energy and resource consumption, as well as to reduce impacts along the life cycle of the building. This manuscript presents insights into combined/integrated environmental and seismic retrofitting techniques and assessment methods for the sustainable renovation of the existing building stock, specifically focussing on those conceived according to a Life Cycle Thinking (LCT) approach. This manuscript goes beyond the current available state of the art by highlighting the evolution of the concept of building sustainability throughout time, as well as defining a comprehensive taxonomy of available retrofitting strategies, while also identifying common clusters among available research papers. This research effort is part of the mission of the European Association of Earthquake Engineering (EAEE) Working Group 15 (WG15), which focusses on 'combined seismic and environmental upgrading of existing buildings".

Keywords Sustainable building renovation · Life cycle thinking · Integrated retrofit · Sustainability · Structural safety · Seismic risk · Resilience · Energy efficiency · Literature review · Environmental impact

1 Introduction

The renovation of existing buildings is presently at the top of the agenda of the European Union, as an opportunity to build a sustainable and resilient environment along the objectives of the Green Deal (European Commission 2019), and to create sustainable, inclusive, and beautiful living spaces along the dimensions of the New European Bauhaus initiative

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(European Commission 2021a). The European Association for Earthquake Engineering (EAEE) is currently contributing to this important goal and Working Group 15 (WG15) on ‘combined seismic and environmental upgrading of existing buildings’ (Felicioni et al. 2022; Felicioni and Negro 2023) was established to encourage this contribution. This paper provides a description of the work conducted by the WG15 towards the proposal of a position paper.

The resilience of the existing building stock against natural hazards is now recognised as a prior target towards the achievement of a sustainable society. The concept of sustainable development that is capable of ‘meeting the needs of present generations without compromising the ability of future generations to meet their own needs’ was first addressed in 1987 in the *Brundtland Report* (Brundtland Commission 1987). Considering the construction sector, sustainable targets have traditionally been associated with building energy efficiency or durability, thus being primarily intended to limit the carbon footprint of the building itself due to its operational energy consumption or maintenance. On the other hand, structural safety has always been treated independently, focussing mainly on seismic risk and/or on other natural, or human-made, risks. However, throughout the last decade, the concept of sustainability has finally been broadened, incorporating building safety and resilience against hazardous events, including earthquakes and climate change (Lizarralde et al. 2015; Roostaie and Nawari 2022; Felicioni et al. 2023). In 2015, namely, the United Nations defined the goal of “making cities and human settlements inclusive, safe, resilient, and sustainable” as one of the 17 *Sustainable Development Goals (SDGs)* (United Nations 2015), and they also published the *Sendai framework for disaster risk reduction 2015–2030* (UNISDR), which was conceived based on the idea that effective disaster risk management is essential towards the sustainable development of our cities.

The challenge of including safety and resilience in a broadened concept of sustainability was swiftly accepted by the scientific community. In 2016, for instance, the Joint Research Centre (JRC) of the European Commission, as part of the project ‘Safe and Cleaner Technologies for Construction and Buildings’, organised the *SAFESUST* (safety + sustainability) workshop, where experts belonging to different fields of the building sector discussed possible methods for the sustainable integrated renovation of the existing building stock, and developed a *Roadmap for the improvement of earthquake resistance and eco-efficiency of existing buildings and cities* (Caverzan et al. 2016).

Following this evolution process of the concept of sustainability, several research studies were published in recent years. A few aimed at developing either combined/integrated retrofitting techniques for the sustainable renovation of existing buildings, while others at proposing frameworks and methods for the integrated assessment of retrofitted buildings. However, the adoption of retrofit solutions aimed at improving the energy and structural behaviours leads to the sole minimisation of the impacts during the operating life (e.g., by reducing seismic losses or energy consumption), while disregarding, or even worsening, the impacts during the other building’s life cycle stages (Passoni et al. 2021). When the whole life cycle of a building is considered, indeed, five main phases are to be considered, i.e., production, construction, use, end of life, and beyond end of life (EN 15978) (European Standards 2011). At the same time, the impact of the retrofit materials and components should also be addressed, from their production to their end-of-life treatment.

The need to embrace such a Life Cycle Thinking (LCT) approach during the building retrofitting intervention design process is finally recognised as the only way to design truly sustainable solutions, which are able to minimise impacts all along the building's whole life cycle and to boost circularity in the construction sector. This concept was recently discussed by several authors and within different projects, including, for instance: (i) (Huang et al. 2020) who introduced some LCT-based criteria to reduce the impacts of building construction materials, though disregarding the potential consequences of hazardous events; (ii) the European framework for sustainable buildings Level(s) (Dodd et al. 2021) that defined some sustainable objectives, including resilience against climate change-induced hazards, but disregarding seismic risk, as discussed in the following section in some detail; and (iii) the European EFIResources project (Gervasio and Dimova 2018) that outlined some design objectives aimed at reducing the impacts of seismic retrofitting solutions for the development of a comprehensive life cycle model for the assessment and benchmarking of buildings. At the same time, some other researchers defined and discussed individual LCT-based design objectives. As an example, a comprehensive framework of LCT-inspired design targets and criteria was presented in (Passoni et al. 2022b), those being applicable to different life cycle stages of the building. In the production and construction phases, for instance, sustainability can be pursued by adopting eco-efficient materials or by reducing raw material extraction, transportation distances, and energy needed for the construction activities. Accordingly, easily repairable/replaceable, dry-assembled, and demountable solutions should be preferred, enabling the adaptability of the structure to possible future needs or climate conditions, while also facilitating the possible replacement with new components. At the same time, the possibility of concentrating structural damage in specific sacrificial components (e.g., demountable dampers or connections), allowing for ease of repair or replacement in case of strong hazardous events, can also be impactful since it would avoid the partial or total demolition of the damaged structural elements. Lastly, regarding the end-of-life phase, retrofitting techniques should be conceived to minimise, if not to avoid, demolition waste, downcycling, and landfill disposal. It is noted that such LCT-based targets may be distinguished in (i) criteria that are applicable at the material level (e.g., use of recycled/reused materials, renewable biomaterial, local materials, durable materials, recyclable materials), and (ii) criteria that can be adopted at the level of technique (e.g., dry technique, prefabrication, modularity/standardisation, material optimisation, damage minimisation, damage concentration).

In this context, this study aims to discuss the most updated state-of-the-art practices in the sustainable renovation of existing buildings, by going beyond the sole combined/integrated retrofitting strategies, covering in fact the most recent studies about LCT-based combined/integrated renovation techniques and assessment methods. Specifically concerning combined/integrated retrofitting interventions only, interested readers can refer to the state-of-the-art reviews recently published by (Ademovic et al. 2022), (Menna et al. 2022), (Pohoryles et al. 2022b), and (Romano et al. 2023b), among others.

The objectives of this work are, however, multifaceted. The paper outlines the evolution process of the concept of buildings' sustainability throughout the past decades, including resilience against earthquakes and other hazards, and it defines a comprehensive taxonomy of available buildings' retrofitting strategies. Based on this taxonomy, a systematic state-of-the-art literature review was carried out to map the currently available LCT-based retrofitting strategies and assessment methods and to highlight possible future research needs towards a truly sustainable renovation of buildings.

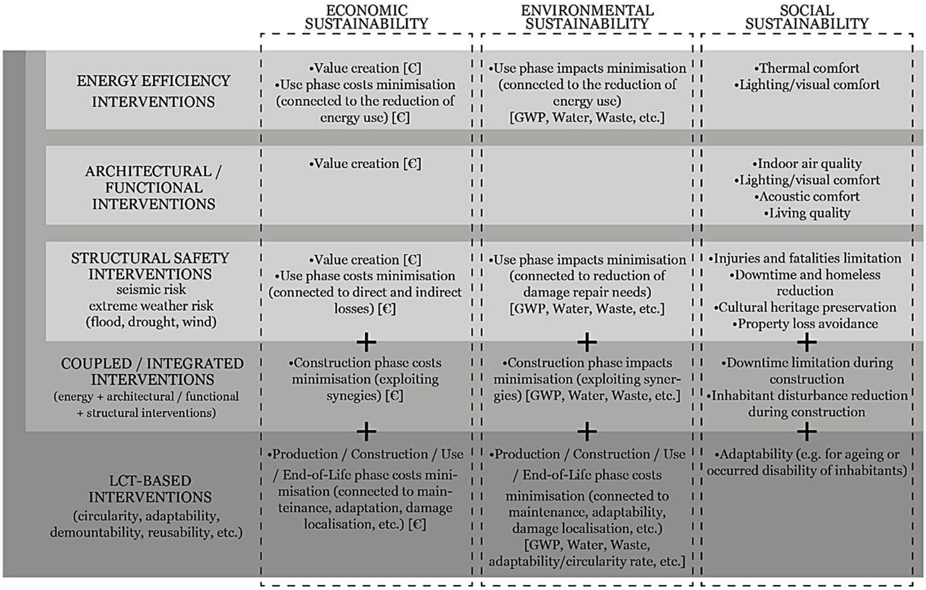
2 Taxonomy of available buildings' retrofitting strategies

The three main pillars of sustainability are represented by (i) environmental issues, usually expressed in terms of resource utilisation, energy consumption, greenhouse gas emissions (GHG), etc., which may be estimated through life cycle assessment (LCA) procedures; (ii) economic issues, typically referring to the associated costs from production and construction, throughout repair and maintenance, to end of life, which can be quantified through life cycle cost (LCC) analyses; and (iii) social issues, mainly related to impacts such as human health, indoor environmental quality, social inclusion, standard of living, etc., which can be quantified through social LCA (s-LCA).

With the objective of creating a shared set of indicators for the evaluation of buildings' sustainability performance, the European Commission launched the framework Level(s) (Dodd et al. 2021), which is a voluntary framework based on the LCT approach. Unlike other green building rating systems (GBRS), such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB), among others, Level(s) does not issue certifications defining minimum target requirements, rather it outlines six macro-objectives, representing the strategic priorities of the European Union policy objectives related to buildings performance, those being: (1) GHG emissions along the life cycle of a given building, (2) resource efficient and circular material life cycles, (3) efficient use of water resources, (4) healthy and comfortable spaces, (5) adaptation and resilience to climate change, and (6) optimised life cycle cost and value. The first three macro-objectives are related to the environmental performances, the fourth to social impacts, the last one to economic issues, and the fifth to the potential adaptation to future risks related to climate change. Thus, specific indicators are suggested to measure the given building's performance under each individual macro-objective, including, for example, operational energy performance and global warming potential (GWP) (for macro-objective 1), sustainability of materials and circular economy (for macro-objective 2), optimisation of water consumption (for macro-objective 3), indoor air quality, lighting, visual and acoustic comfort (for macro-objective 4), increased risk of weather events (for macro-objective 5) and life cycle cost tools (for macro-objective 6). It should be noted that this framework, however, does not explicitly consider mitigation against seismic hazard, although it only refers to climate change-related risks.

Based on the evolution of the concept of sustainable renovation outlined in the Introduction, a detailed taxonomy of available retrofitting measures is presented herein. In the following, retrofitting solutions are classified in a sustainable perspective, highlighting their contribution to the improvement of the economic, environmental, and social sustainability of buildings, using some of the indicators proposed within the Level(s) framework (Fig. 1).

The proposed taxonomy can be conceptually divided into three main groups (highlighted by the colour scale in Fig. 1), which reflect the chronological evolution and the progressive expansion of the concept of buildings' sustainability. The first group refers to the uncoupled/sectorial retrofitting interventions, which provide benefits in terms of each individual pillar of sustainability, but only solve a single deficiency of a given building. Coupled/integrated retrofit interventions instead constitute the second group, leading to the same benefits of the uncoupled solutions, as well as to possible additional co-benefits (Marini et al. 2014, 2017), including, for example, the shared construction site. Lastly, the most inclusive group



	ECONOMIC SUSTAINABILITY	ENVIRONMENTAL SUSTAINABILITY	SOCIAL SUSTAINABILITY
ENERGY EFFICIENCY INTERVENTIONS	•Value creation [€] •Use phase costs minimisation (connected to the reduction of energy use) [€]	•Use phase impacts minimisation (connected to the reduction of energy use) [GWP, Water, Waste, etc.]	•Thermal comfort •Lighting/visual comfort
ARCHITECTURAL / FUNCTIONAL INTERVENTIONS	•Value creation [€]		•Indoor air quality •Lighting/visual comfort •Acoustic comfort •Living quality
STRUCTURAL SAFETY INTERVENTIONS seismic risk extreme weather risk (flood, drought, wind)	•Value creation [€] •Use phase costs minimisation (connected to direct and indirect losses) [€]	•Use phase impacts minimisation (connected to reduction of damage repair needs) [GWP, Water, Waste, etc.]	•Injuries and fatalities limitation •Downtime and homeless reduction •Cultural heritage preservation •Property loss avoidance
	+	+	+
COUPLED / INTEGRATED INTERVENTIONS (energy + architectural / functional + structural interventions)	•Construction phase costs minimisation (exploiting synegies) [€]	•Construction phase impacts minimisation (exploiting synergies) [GWP, Water, Waste, etc.]	•Downtime limitation during construction •Inhabitant disturbance reduction during construction
	+	+	+
LCT-BASED INTERVENTIONS (circularity, adaptability, demountability, reusability, etc.)	•Production / Construction / Use / End-of-Life phase costs minimisation (connected to maintenance, adaptation, damage localisation, etc.) [€]	•Production / Construction / Use / End-of-Life phase costs minimisation (connected to maintenance, adaptability, damage localisation, etc.) [GWP, Water, Waste, adaptability/circularity rate, etc.]	•Adaptability (e.g. for ageing or occurred disability of inhabitants)

Fig. 1 Taxonomy of available retrofitting solutions: potential benefits towards sustainability

refers to the fully integrated retrofitting interventions inspired by the principles of life cycle thinking.

Starting from the uncoupled interventions, the benefits of the sole energy, sole architectural, and sole structural interventions are first addressed. It is known that the poor energy performance of the existing building stock is mostly due to the lack of thermal insulation of opaque components (e.g., external walls, ground floor, roof, etc.), the high thermal transmittance of windows and doors, the presence of thermal bridges, and the obsolescence of the mechanical equipment (e.g., heating, ventilation, and air conditioning). For these reasons, energy efficiency upgrading measures generally aim at (i) reducing the energy demand of the building by improving the thermal insulation of the envelope (e.g., walls/floors/roof insulation, replacement of windows, etc.) or by introducing a new energy-efficient equipment (e.g., condensing boiler, heat pump, etc.); (ii) decarbonising the energy supply by using renewable energy resources (e.g., photovoltaic system, solar thermal system, biomass, etc.); or (iii) introducing control systems that follow the energy consumption patterns of occupants (e.g., smart control systems, etc.) (Marini et al. 2014). Therefore, energy efficiency retrofitting interventions contribute to the building's economic value increase, the minimisation of operational costs and environmental impacts related to the operational energy consumption, and the improvement of the indoor thermal comfort, as well as of the lighting and visual comfort, depending on the type of retrofit. On the other side, architectural and functional interventions in buildings, including, for instance, the sole introduction of new lighting systems or acoustic insulation layers, increase the economic value of the building, while also improving the air, lighting, visual, acoustic, and living quality indoors.

Lastly, when dealing with the vulnerability to natural hazards (for example, wind, fire, etc.), and more specifically to earthquakes, inadequate structural detailing, poor quality of construction materials, age corrosion, and brittle failure mechanisms (for example, shear failure or soft-storey) are among the main deficiencies observed in existing buildings. Seismic strengthening interventions, indeed, are typically intended to (i) improve the capacity of individual structural members with local interventions (e.g., reinforced concrete jacketing, steel jacketing, fibre-reinforced polymer sheets or textile-reinforced mortars, etc.); (ii) increase the global capacity of the building by creating lateral force resisting systems (by adding shear walls/bracings or shell facade systems); or (iii) reduce the seismic demand (e.g., by adopting seismic isolation, tuned mass dampers, energy dissipation devices, etc.) (Marini et al. 2014). Local measures on individual structural members affect their strength or deformation capacity, rendering them more adequate for structures with good overall resistance, but limited ductility. On the contrary, global interventions lead to an increase of the resistance of the entire building, being more effective when the existing capacity of the building is relatively low. Thus, structural interventions contribute to the increase of the economic value of the building, but more importantly, to the limitation of hazard-induced direct and indirect economic, environmental, and social losses (for instance, potential injuries and casualties, business inactivity and downtime, risk of property loss in case of buildings' severe damage, etc.) by improving life safety and resilience. It is noted that, in recent years, the scientific community has made relevant efforts to quantify the additional contribution of natural hazards in life cycle evaluations, especially those related to earthquakes (e.g., (Hossain and Gencturk 2016; Chhabra et al. 2018; Anwar et al. 2020), among others).

The extension of the concept of sustainability by including safety and resilience finally led to the definition of combined/integrated retrofitting measures, i.e., structural + energy + (possibly) architectural interventions, whose integration was first proposed by (Takeuchi et al. 2009). Taking into account the benefits of such measures with reference to the three pillars of sustainability, these solutions provide all the economic, environmental, and social improvements described above for each of the sectorial retrofitting techniques, while also taking advantage of the reduction of costs, environmental impacts, and duration of construction activities, with consequent limited disturbance to the occupants. For the sake of clarity, *combined* retrofit strategies refer herein to scenarios where energy efficiency upgrading measures and structural strengthening techniques are adopted at the same time in a given building, employing different materials and components (for example, the construction of reinforced concrete shear walls coupled with the installation of new windows). On the other hand, *integrated* retrofitting strategies make use of the same component to improve seismic resistance and energy efficiency simultaneously (e.g., a new shell system with both a structural strengthening layer and a thermal insulation coat).

In this context, three relevant safety issues should be addressed. The first one is related to the more generic structural vulnerabilities of buildings, including the capacity of carrying out code-specified operational loads; the second one is connected to the building's capacity of withstanding the consequences of natural risks, such as earthquakes, strong wind, or fire; while the third one is instead represented by the increasing occurrence of extreme events related to the current climate change emergency (e.g., floods, drought, etc.). It should be noted, once again, that the European framework Level(s) only mentions climate change-related risks, while, for the other ones, it refers to European, or national, codes. In fact, in several countries, risk mitigation activities and code prescriptions are usually mandatory for the construction of new buildings only and not for the retrofit of existing buildings, which are indeed most of the time renovated under an energy and architectural point of view, despite their structural vulnerabilities.

The third group of retrofits finally includes LCT-based retrofitting interventions, which are conceived as being fully compatible with a life cycle thinking approach. In addition to all the advantages of the combined/integrated strategies described above, these solutions also allow for the minimisation of the economic, environmental, and social impacts of retrofit components, rather than those related to the sole use of the building (e.g., those related to production, construction, maintenance, and end-of-life treatment), while also guaranteeing adaptability to climate change and potential future needs of occupants. These retrofit solutions are nowadays considered as those that maximise buildings' sustainability and are expected to be adopted more and more frequently in the near future. The state-of-the-art literature search described in the following sections is specifically focussed on LCT-based solutions that have been proposed for different structural typologies in the most recent years, as well as on LCT-inspired assessment methods.

3 Overview of lct-based combined/integrated building retrofitting strategies

The overview of the current state-of-the-art literature on combined/integrated retrofitting strategies and assessment methods for existing buildings conceived according to LCT principles is presented in this section. The literature search was initially intended to include research works addressing a variety of natural hazards (e.g., floods, heavy storms, fires, etc.). However, only a few relevant research works were found in the literature dealing with hazards other than solely earthquakes. For such a reason, this manuscript mainly focusses on LCT-based combined/integrated energy and seismic retrofitting techniques and methods. Several other state-of-the-art reviews have been published in the scientific literature covering combined energy/seismic retrofit interventions (e.g., (Ademovic et al. 2022; Menna et al. 2022; Pohoryles et al. 2022b); however, this work is expected to go beyond the precedent reviews, due to the specific focus on LCT-driven approaches. Similarly, the outcomes of the literature search predominantly featured publications concerning reinforced concrete (RC) and masonry structures over other types, although the research string was not limited to such typologies.

3.1 Systematic literature review: keywords and methods

In order to map the scientific production on the combined/integrated assessment and retrofitting of buildings according to LCT principles, a systematic literature research was conducted in July 2023 in Web of Science (WoS) and Scopus databases, which are well known for indexing high-quality, peer-reviewed papers and that are managed by third parties. Data types were limited to “reviews”, “articles”, “conference papers”, and “books/book chapters” to ensure quality and uniformity among records, and English was indicated as the preferred language. The time frame for this investigation was established from 01/2012 to 06/2023. Considering 2015 as a milestone for the research on combined renovation of existing buildings, and considering previous analyses of the state of the art about green retrofitting (Tetteh et al. 2022), the last decade was indeed elected as the most significant time frame.

Based on the evolution of the concept of sustainability and of the taxonomy previously introduced, six different domains were examined in the literature research. Figure 2 illus-

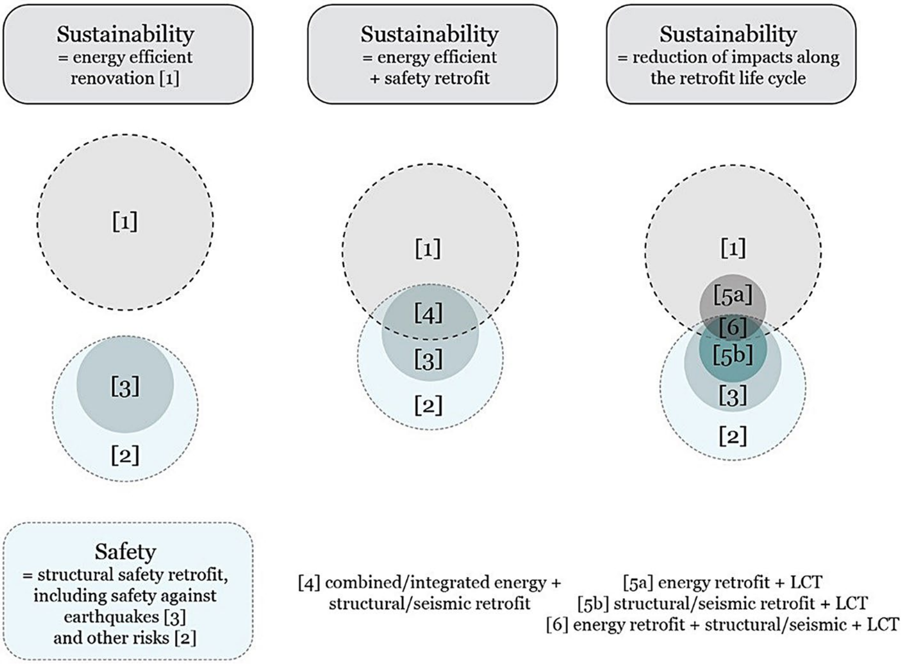


Fig. 2 Evolution of the concept of sustainable renovation in the construction sector: qualitative analysis of the state-of-the-art scientific literature

trates these domains and their interrelations, with the size of circles qualitatively representing the number of scientific papers found on each specific topic from the research engines. The following strings were used in each database to characterise each domain, searching within titles, keywords, and abstracts of candidate papers:

- Domain [1] - “Energy retrofitting” | (building*) AND (renovation OR retrofit* OR upgrad* OR refurbishment) AND (energy OR efficiency OR environment*);
- Domain [2] - “Stuctural retrofitting and hazard mitigation” | (building*) AND (renovation OR retrofit* OR upgrad* OR refurbishment) AND (structur* OR safety OR resilien* OR seismic* OR earthquake* OR wind* OR hurricane* OR flood* OR loss* OR natural risk* OR natural threat* OR natural hazard* OR climate-related risk*);
- Domain [3] - “Structural retrofitting and seismic hazard mitigation” | (building*) AND (renovation OR retrofit* OR upgrad* OR refurbishment) AND (structur* OR structural-safety OR structural-resilien* OR seismic* OR earthquake*);
- Domain [4] - “Combined/integrated energy and structural/seismic retrofitting” | (building*) AND (renovation OR retrofit* OR upgrad* OR refurbishment) AND (structur* OR structural-safety OR structural-resilien* OR seismic* OR earthquake*) AND (energy OR efficiency OR environment*);
- Domain [5a] - “LCT-based energy retrofitting” | (building*) AND (renovation OR retrofit* OR upgrad* OR refurbishment)) AND (energy OR efficiency OR environment*) AND (LCT OR LCC OR LC OR durability OR Life cycle OR sustainab*);

- Domain [5b] - "LCT-based structural retrofitting and seismic hazard mitigation" | (building*) AND (renovation OR retrofit* OR upgrad* OR refurbishment) AND (structur* OR structural-safety OR structural-resilien* OR seismic* OR earthquake*) AND (LCT OR LCC OR LC OR durability OR Life cycle OR sustainab*);
- Domain [6] - "LCT-based combined/integrated energy and structural/seismic retrofitting" | (building*) AND (renovation OR retrofit* OR upgrad* OR refurbishment) AND (structur* OR structural-safety OR structural-resilien* OR seismic* OR earthquake*) AND (energy OR efficiency OR environment*) AND (LCT OR LCC OR LC OR durability OR Life cycle OR sustainab*).

This review carried out herein is focussed on the scientific publications belonging to the domain [6] of LCT-based combined/integrated retrofitting activities and evaluation methods, which are only a limited portion of the domain [4] that is not covered here. Namely, the PRISMA diagram (Page et al. 2021), presented in Fig. 3, illustrates the second-phase review process of works in the domain [6]. The initial search yielded 906 results from both Web of Science and Scopus. Upon completion of the data search, 7 additional records were identified by hand searching, 214 duplicate records were removed, and a total of 701 candidate records were filtered for screening (i.e., reviewing titles and abstracts). After that, the full texts of the remaining papers fulfilling the study's criteria were properly reviewed; at the end of the review, a few of the selected records were disregarded as well, since considering only marginally either seismic safety or life cycle thinking. The remaining 51 records were finally deemed eligible for the detailed state-of-the-art review, which is discussed in Sect. 4.

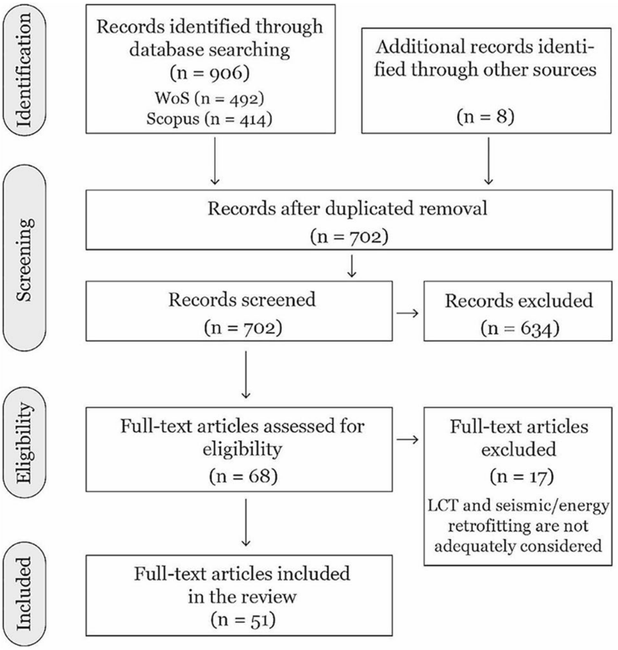


Fig. 3 Search strategy for review of the literature based on the PRISMA workflow

3.2 Statistics

As a result of the systematic review of the 51 filtered records, two main clusters were identified, as shown in Fig. 4, namely (i) LCT-based combined/integrated retrofitting techniques (29 publications), and (ii) integrated assessment and retrofitting methodologies embracing a life cycle thinking approach (22 publications). The first cluster refers to scientific papers where retrofitting solutions are proposed for the combined/integrated renovation of buildings under an LCT perspective. The second one, instead, gathers research works that suggest methods and procedures to carry out the evaluation of buildings' performances and their retrofitting activities in an integrated manner, while also using life cycle tools. Thus, it was observed that the literature search yielded a number of scientific papers, not only limited to those focussing on LCT-based retrofitting measures, but also including more methodological research works embracing a life cycle perspective. For such a reason, both clusters of papers were reviewed, as discussed in more detail in Sect. 4.

A significant observation derived from the analysis of the annual distribution of the selected publications, shown in Fig. 4, is that the papers from Cluster 1 (green columns) appeared considerably earlier if compared to those belonging to Cluster 2 (blue columns). More specifically, methodologies within Cluster 2 began to be investigated in 2017, approximately five years after the first publications on LCT-based combined/integrated retrofitting techniques.

Another critical and interesting consideration lies in the geographical coverage of these publications and works. Investigating indeed the affiliations of the authors of each article, it was observed that most of them belong to Italian universities, as both Figs. 5 and 6 show. It is important to note that papers with authors from different affiliation countries/cities have been counted more than once.

This result is unsurprising, given that Europe is particularly committed to sustainable building renovation, and that Italy is a seismically vulnerable country that has experienced

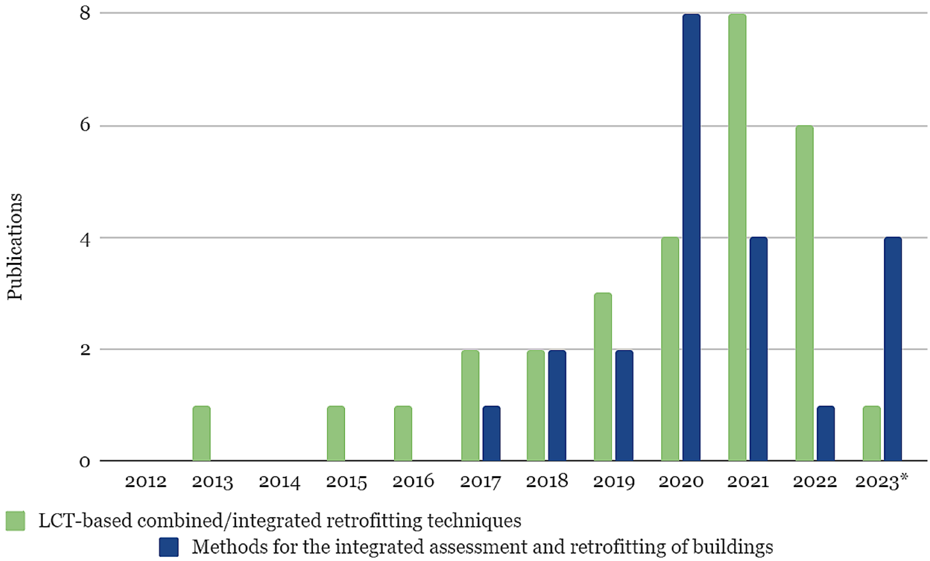


Fig. 4 Annual distribution of the publications included in the review divided by cluster. (*) The 2023-review focussed only on results published within the first half of that year

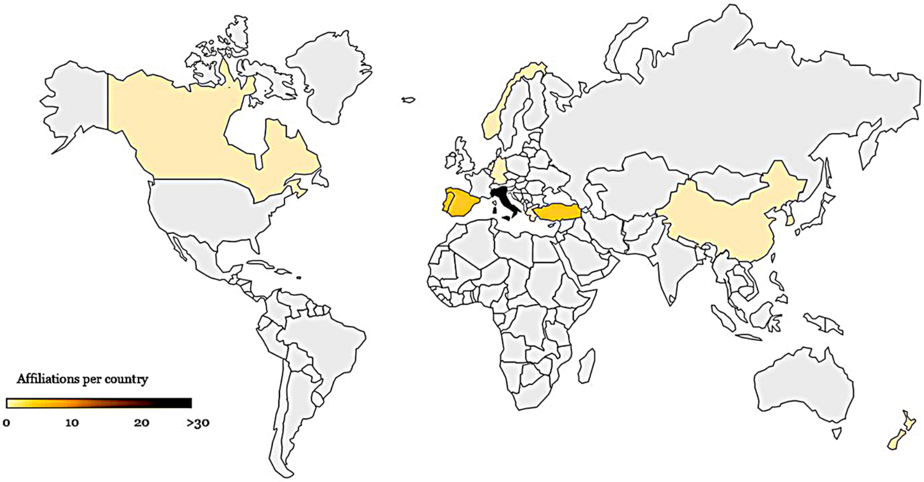


Fig. 5 Global distribution of selected publications based on the affiliations of all authors, with colour intensity proportional to the number of affiliations in each country

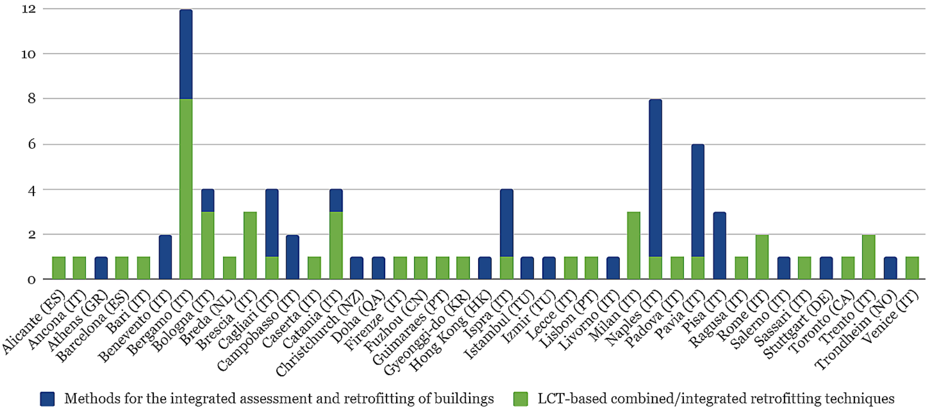


Fig. 6 Worldwide geographical distribution of the selected publications by affiliation, categorised by cluster

substantial damages and losses attributable to natural hazards, thus being interested in coupling energy and structural retrofitting solutions while also addressing LCT principles.

4 Critical discussion on the selected retrofitting techniques and assessment methods

4.1 Cluster 1 - LCT-based combined/integrated retrofitting techniques

The first cluster comprises 29 records, where one or more LCT design criteria are adopted to design LCT-based combined/integrated retrofitting techniques. The selected studies can be distinguished into two main groups. In the first group (10 records), the adoption of an

LCT approach for the design of integrated retrofitting interventions is conceptualised from scratch, new LCT-based design objectives are defined, and alternative solutions are proposed to directly respond to the LCT criteria. In the second group (19 records), instead, the integrated solutions are designed considering single or multiple general LCT criteria, thus not necessarily embracing a full LCT approach.

The need to design integrated interventions according to LCT design criteria was first introduced by (Feroldi et al. 2013) and (Marini et al. 2017). In these studies, the authors, inspired by the *camouflage* technique that enhances the energy, functional, and aesthetic performances of existing buildings, initiated the reengineering of exoskeletons to also improve the safety and resilience of post-second world war RC buildings. The proposed structural system is an additional exoskeleton, whose installation can be carried out outside of the building to avoid the relocation of the inhabitants. Such exoskeletons, laying on new foundations, could be conceived as either a wall system, introducing shear walls or braced frames, or as a shell system, by exploiting the whole new external envelope shell. Furthermore, to minimise costs and environmental impacts throughout the building life cycle, the authors also introduced a number of criteria based on LCT, suggesting an accurate selection of materials and technologies to allow for adaptability, reparability, maintenance and total recyclability/reuse at the end of life. The potential barriers and benefits of such an LCT-based combined approach were also discussed, proposing possible structural exoskeleton solutions to be coupled with energy refurbishment solutions, and carrying out an application to a reference building as a proof of the concept.

On the basis of these preliminary conceptual studies, in the following years, the same research group proposed further significant developments. As an example, the architectural potentials and social benefits connected to LCT-based integrated solutions applied to social housing buildings were investigated by (Bellini et al. 2018) and (Bellini 2020). Alternative seismic retrofitting techniques to be integrated into holistic exoskeletons were also studied in more detail. In particular, different wall or shell, dissipative or over-resistant solutions (Passoni et al. 2020), and steel diagrid solutions (Labò et al. 2020) were proposed, also providing practical design procedures; while exoskeletons implementing shape memory alloys-based devices for passive seismic dissipation were conceived by (Scuderi 2016). More recently, (Passoni et al. 2022b) validated the sustainability of such LCT-based solutions compared to more traditional retrofitting interventions. Namely, the authors carried out simplified LCA analyses, based on Environmental Product Declarations (EPDs), on four different structural exoskeleton technologies, two shells (timber shell and steel diagrid exoskeletons) and two wall systems (steel and RC wall exoskeletons), also investigating different end-of-life scenarios. Lastly, new integrated retrofit techniques conceived to respond to a large number of LCT design objectives and criteria were developed and applied to real buildings. (Zanni et al. 2021) proposed the AdESA (Adeguamento Energetico Sismico ed Architettonico, in Italian) system, consisting of a dry, modular and flexible shell exoskeleton with multiple layers, i.e., cross-laminated timber (CLT) panels for the structural retrofit, thermal insulation panels for the energy efficiency amelioration, and claddings for the architectural restyling. The system is designed for easy installation and disassembly, facilitating the reusability and recycling of its components at the end of their lifespan. Such an objective is achieved through the incorporation of macro-prefabricated dry components and standardised dry connections. At the same time, the expected seismic damage is minimised by considering reduced inter-story drift targets and lumping the potential damage into sacrificial, replaceable, and dissipative connections. (Zanni et al. 2023) also conceived the re-engineering of the AdESA system, by enhancing the connections between the exoskeleton and the foundations to improve the demountability of the additional façade. The new plants, which are completely installed from the outside, are integrated into the timber shell to upgrade the existing obsolete plants. Lastly, a continuous performance monitoring system ensures safety, efficiency, and durability. Both of these solutions were used in real retrofitting projects to effectively validate the efficiency of the investigated construction systems. The ADESA system was indeed employed in a precast RC gym hall of an elementary school, while its updated version was applied to a masonry building adhibited to social housing, both buildings being located in Northern Italy.

In the same years, (Margani et al. 2020) investigated a novel approach for renovating RC framed buildings by adopting an LCT approach, incorporating CLT panels along with wooden-framed panels onto the outer walls. The additional pre-assembled and customisable panels integrate thermal insulation and cladding materials, aiming to enhance both the energy performance and the aesthetic appeal of the renovated structure. In addition, innovative seismic dissipation devices connect the CLT panels to the existing RC beams. In case of an earthquake occurrence, these devices, combined with the CLT panels, are expected to decrease the building drift demand, mitigating the structural damage and the subsequent repair consequences. This retrofitting solution, thanks to prefabricated panels and the dry connection system, allows for a quick and easy installation. Although the solutions proposed by (Margani et al. 2020; Zanni et al. 2021, 2023) may look similar, they are based on different structural systems. Indeed, the former is conceived as a global shell system, featuring a new lateral force resisting system, where panels are connected one to the other to create a continuous outer layer, laying on new foundations; the latter is instead a local stiffening system of selected RC frame bays, where panels are connected to RC beams.

Another example of LCT-inspired retrofitting technique is the sustainable seismic coat contrived by (Lombardo 2021). The system, aimed at improving energy performance, seismic safety, sustainability, functionality, and aesthetic quality, is composed of modular, prefabricated, and dry-assembled panels made of natural lava stone blocks, which are coupled with a thermal insulation layer. Such panels are prestressed with steel reinforcement bars, both in the factory at the panel level, and on-site to ensure a global behaviour of the system. They act as a bracing system, which may be concentrated in some building's portions, constituting a wall system, or diffused throughout the whole building's envelope, exploiting instead the box effect. The panels are connected to the building in correspondence with the perimeter floor beams and are placed on new foundations. All connections are installed using dry processes, facilitating the demountability of the system. Regarding the design choices at the material level, this solution envisions the adoption of recycled/recyclable components, durable elements that require no maintenance, and local materials, which do not need long-distance transportation and employment of local manpower. At the technique level, the industrial prefabrication and modularity of the prestressed panels, the very fast execution times, the easy maintenance due to the easy removability of the panels, and the possibility of deconstruction at the end of the building's life cycle are amongst the LCT criteria that the seismic coat successfully fulfils.

The largest number of records resulting from the literature search was found to belong to the second group of this cluster, which includes all research works proposing integrated retrofitting solutions not totally inspired by an LCT approach but designed according to one or more LCT-based design criteria. The selected studies are described in the following, distinguishing those adopting LCT criteria at the material level and those that are LCT compatible at the technique level.

As for LCT criteria at the material level, several retrofitting solutions were found considering the use of renewable and/or bio-based materials. In addition to some of the solutions above (i.e., (Margani et al. 2020; Zanni et al. 2021, 2023), 6 other studies proposed integrated retrofitting solutions made of timber, which is a good example of a renewable, bio-based, and recyclable/reusable material. As an example, (Valluzzi et al. 2021) explored the approach of nested buildings for the strengthening of unreinforced masonry (URM) buildings, by installing a new inner structural system made of CLT panels, connected to the existing walls by means of traditional steel connectors. The system can be applied to the entire building envelope or to some floors only, and may require the demolition of the roof and internal walls. When applied inside the building, this technique aims to preserve the external architectural appearance of the existing structure. Similarly, (Busselli et al. 2021) conceived an integrated retrofitting system to be installed on the interior surfaces of existing masonry walls. The structural layer is provided with timber-based products, either panels or strong-backs, or a combination of the two, which are fixed to the walls using point-to-point mechanical or adhesive connections. The panels, made of CLT or LVL-X (laminated veneer lumber with veneers orientated transversally to the main direction), are connected to the floors, employing traditional hold-downs and angle brackets, and are linked one to each other either by simple contact or with screwed shear connections. The effectiveness of the system in improving the energy and seismic performances was validated through numerical analyses of the retrofitted walls.

(Stazi et al. 2019), (Contiguglia et al. 2021) and (Smiroldo et al. 2021) proposed alternative examples of reinforcing systems using timber panels, which are conceptually similar to that proposed by (Margani et al. 2020) from a structural point of view. (Stazi et al. 2019) carried out a preliminary experimental and numerical study focussed on the mechanical behaviour of CLT panels used as a bracing system. In these simplified analyses, a single RC bay was considered, and a perfect bonding at the interfaces between the CLT panel and the RC frame was assumed. In (Contiguglia et al. 2021), CLT panels were secured to the original RC frame from the outside using hold-downs and brackets, and screwed to the upper and bottom beams. The system was applied to a 100 m-tall Chinese RC building, featuring internal concrete cores and glazed surfaces along the facades. In this case, the architectural potentialities of the integrated system were also exploited by re-designing the internal spaces and the existing facades with a view to also improve energy efficiency and indoor comfort (quality of the air, natural lighting, etc.). Lastly, the system proposed by (Smiroldo et al. 2021) was conceived for the integrated retrofitting of RC infilled frames, especially those featuring double-wythe masonry infills, typical of the Italian building stock. In this study, the technical specifics and implementation procedures of the investigated retrofitting strategies were carefully examined, proposing two alternative configurations with varying degrees of invasiveness. The more invasive configuration involves replacing the external masonry wythe with CLT panels, while the less invasive one entails positioning the CLT panels externally, without removing the wythes. The seismic and thermal effectiveness of the system was then validated with reference to a single-story, single-bay frame. The architectural potential of adopting CLT panels in urban regeneration strategies for “parasitic architecture” interventions was also explored by (Frunzio et al. 2022), those allowing for the realisation of volumetric additions to existing buildings.

It is thus observed that the use of timber for the combined renovation of buildings may be surely considered as sustainable for the material’s well-known properties, as well as because it allows for the employment of dry and prefabricated renovation systems; however, in the above studies, any other LCT-based design criterion was taken into account to further reduce the potential impacts of the buildings along their life cycle.

Considering integrated techniques adopting bio-based materials, other than timber, 2 other studies were found in the literature search. (Majumder et al. 2022) proposed and characterised jute-reinforced textile-reinforced mortars (TRM), including raw jute fibres and jute threads, for thermal and seismic upgrading of existing masonry buildings. (Lombardo 2021), who was already previously described, proposed instead the use of panels made of Etnean basalt, which is easily available on site, being naturally produced by the volcano, and processed in a natural way.

As for the use of recycled materials, (Longo et al. 2021) proposed a fabric-reinforced geopolymer mortar (FRGM), including waste materials, such as fly ash and expanded glass (acting as a matrix) to be adopted as plaster and serving the double scope of thermal insulation and seismic strengthening. Experimental, mechanical, and thermal tests were carried out on reinforced masonry prototypes to evaluate the efficiency of the retrofitting system. For the rehabilitation of RC buildings, instead, (de Sousa et al. 2022) proposed a sandwich panel with the outer wythes made of recycled steel fibre reinforced micro-concrete and a core layer of extruded polystyrene. The installation of the investigated strengthening solution requires the demolition of the existing masonry infill walls. The panels are connected to the existing frame using steel angle profiles, which are adhesively bonded along the perimeter though proper anchor bolts. In turn, the steel angle profiles are linked to the frame through mechanical anchors. The structural efficiency of this reinforcing system was assessed by performing in-plane quasi-static cyclic tests on single bay specimens.

Recyclable materials, or reusable components, were adopted in many of the studies discussed, including, for example, all the solutions employing timber panels; however, the sole adoption of recyclable materials does not necessarily correspond to a high rate of recycled/reuse material at the end of life of the building. Such an objective may be pursued only if the proposed solutions are designed to be easily disassembled at the end of life, or if selective dismantling of the building components is allowed. The benefits connected to the recyclability and reusability of the components beyond life are comprehensively discussed in (Passoni et al. 2022b), where different end-of-life scenarios are considered for alternative steel and timber retrofitting solutions.

When looking at a technique level, and considering the use of dry techniques and prefabricated components, all the solutions already presented that employ timber as the main structural material should be mentioned as relevant, together with the solutions proposed by (Lombardo 2021; de Sousa et al. 2022). Moreover, (Romano 2015) designed a combined seismic/energy retrofitting intervention on a school building, implementing prefabricated modular façade elements, including thermal insulation, shading devices and air vents, with the aim of reducing the time and cost of the realisation. (Ferrante et al. 2020) and (Guardigli et al. 2019), in the framework of the European Pro-GET-onE project, proposed an integrated retrofitting system combining different prefabricated elements. In particular, additional steel walls are added to the building façade and linked to the pre-existing RC frame with rigid slotted connections at the column-beam joints, allowing for vertical sliding. Such walls are transversally connected leading to different façade configurations, and allowing for the inclusion of integrated modular systems composed of manufactured off-site elements for the addition of balconies, loggias, etc. (Pozza et al. 2021) conceived an RC-framed skin, rigidly connected to the RC existing structure at each floor level. The additional system is poured on site, employing prefabricated expanded polystyrene (EPS) modules that serve as both the formwork system and the thermal insulation layer of the building, and which include a steel mesh aimed at reinforcing the finishing plaster layer. Lastly, (Baek et al. 2022) discussed the use of prefabricated textile reinforced concrete panels with an embedded radiant capillary tube system combined with high-strength textiles and mechanically connected through mortar or adhesives to the envelopes of the existing building, allowing them to improve the thermal and seismic performance of existing masonry-filled RC frames. The efficiency of the system was validated by means of experimental analyses on scaled building prototypes.

At the same time, the criteria of modularity and standardisation were considered by different authors, such as (Marini et al. 2017; Labò et al. 2020; Passoni et al. 2020; Lombardo 2021; Zanni et al. 2021, 2023), for both the additional façade elements and the connection systems, (Ferrante et al. 2018) and (Guardigli et al. 2019), for the elements of the exoskeleton, (Romano 2015) for the energy upgrading system, and (Pozza et al. 2021) for the formwork system.

Lastly, the concept of damage minimisation/concentration applied to integrated interventions was first introduced by (Marini et al. 2017). Such an LCT major target may be achieved by following two alternative approaches, i.e., by designing dissipative solutions, which are able to dissipate the seismic energy and, possibly, to lump the damage into sacrificial replaceable structural fuses, or by designing over-resistant solutions, able to withstand the whole seismic action without damage (Passoni et al. 2020). All of the solutions discussed above that implement dissipative connection systems respond to this LCT-based requirement. A state of the art of low damage structural systems and an overview of possible next-generation technologies for integrated low-damage building systems can be found in (Pampanin 2022).

The last two works included in this first cluster are those of (Echarri et al. 2017; D'Urso and Cicero 2019). The former (D'Urso and Cicero 2019) draws from the assumption that the search for beauty represents an important, though often neglected, dimension of sustainability, which is in accordance with the vision of the New European Bauhaus (European Commission 2021b). In this study, the authors further expanded the concept of sustainability to include beauty. Moreover, they combined the use of parametric design and the structural shape of steel exoskeletons to renovate a typical Italian apartment block from the 1960s. The results showed that the proposed parametric approach can provide different effective renovation solutions. (Echarri et al. 2017), instead, is the only study found from the literature review, where energy refurbishment is coupled with structural improvement against fire. In this study, the integrated renovation of a hotel in terms of fire safety, envelope improvement and air conditioning replacement is conceived following some LCT-based design criteria, such as the improved use of resources by embracing the approach of 'reduce/rethink/reuse', industrialisation and prefabrication, energy savings, and waste treatment.

Table 1 summarises all the reviewed theoretical contributions belonging to this cluster described above, highlighting the following aspects:

- the typology of the building, to which the retrofitting strategy is applicable (e.g., buildings, masonry structures, all types of building, etc.);
- the structural concept and the level of invasiveness of the retrofitting strategy (e.g., construction from the outside, with limited disturbance of occupants, vs. construction from the inside, with potential need for demolition of buildings portions);
- the approach of the study (conceptual, numerical or experimental structural/energy analyses on case-study buildings or on component/building prototypes, real applications of the retrofitting technique to existing buildings);
- the adoption of life cycle tools (such as LCA or LCC analyses) for the estimation of environmental impacts and costs of retrofitting solutions over the life cycle;
- the LCT design criteria adopted in the conceptualisation of the retrofitting technique at the material level and/or at the technique level

Table 1 Summary of selected records resulting from step 6 of the literature research - Cluster 1: integrated retrofitting strategies

Authors	Year	Building typology (RC, masonry, steel buildings, or others)	Structural concept & Invasiveness (from the outside or inside of the building, possible need for demolitions)	Methodology of the study (conceptualisation, technology, case study, numerical analyses, experimental testing, real application)	LC Tools (LCA, LCC)	LCT principles								
						Recycled/ reused materials	Renewable biomaterials	Recyclable materials	Dry technique	Pre-fabrication	Modularity/ standardisation	Material optimisation	Damage minimisation	Damage concentration
(Feroldi et al. 2013)	2013	RC buildings	Exoskeleton (outside)	Conceptualisation, case study					x					x
(Romano 2015)	2015	Not specified (real application: RC/ steel buildings)	Structural intervention (inside) + Energy upgrading (outside)	Real application (school)						x	x			
(Scuderi 2016)	2016	Not specified	Exoskeleton (outside)	Conceptualisation, case study, numerical structural analyses					x		x	x		
(Echarri et al. 2017)	2017	Not specified	Energy upgrading (inside) + Fire prevention (inside)	Conceptualisation, case study	LCA, LCC	x		x		x	x	x		
(Marini et al. 2017)	2017	RC buildings	Exoskeleton (outside)	Conceptualisation, case study, numerical structural and thermal analyses		x	x	x	x	x	x	x	x	x
(Bellini et al. 2018)	2018	Not specified	Exoskeleton (outside)	Conceptualisation, case study		x	x	x	x	x	x	x	x	x
(Ferrante et al. 2018)	2018	RC buildings	Exoskeleton (outside)	Conceptualisation, case study, numerical structural and thermal analyses						x	x			
(D'Urso and Cicero 2019)	2019	Not specified	Exoskeleton (outside)	Conceptualisation, case study, parametric design, numerical structural analyses										
(Guardigli et al. 2019)	2019	Not specified	Exoskeleton (outside)	Conceptualisation, technology, case study	LCA, LCC					x	x			
(Stazi et al. 2019)	2019	RC buildings	Bracing system (outside)	Experimental structural testing, numerical analyses			x							
(Bellini 2020)	2020	Not specified	Exoskeleton (outside)	Conceptualisation, case study		x	x	x	x	x	x	x	x	x
(Labò et al. 2020)	2020	RC buildings	Exoskeleton (outside)	Conceptualisation, design method, case study, numerical structural analyses		x	x	x	x	x	x	x	x	x

Table 1 (continued)

(Margani et al. 2020)	2020	RC buildings	Bracing system (outside)	Conceptualisation, technology, case study, thermal analyses		x	x	x	x	x	x		x	x
(Passoni et al. 2020)	2020	RC buildings	Exoskeleton (outside)	Conceptualisation, design method, case study, numerical structural analyses		x	x	x	x	x	x	x	x	x
(Busselli et al. 2021)	2021	Masonry buildings	Bracing system (inside)	Conceptualisation, technology, structural and thermal analyses			x		x	x				
(Contiguglia et al. 2021)	2021	RC buildings	Bracing system (outside)	Conceptualisation, technology, structural and thermal analyses			x		x	x				
(Lombardo 2021)	2021	Not specified	Exoskeleton (outside)	Conceptualisation, technology, experimental testing, case study, structural and thermal analyses	Embodied CO2		x		x	x	x			
(Longo et al. 2021)	2021	Masonry buildings	Plaster (outside & inside)	Conceptualisation, technology, experimental testing		x								
(Pozza et al. 2021)	2021	RC buildings, but also steel, masonry buildings	Bracing system (outside)	Conceptualisation, technology, numerical structural and thermal analyses	LCA, LCC						x			
(Smiroldo et al. 2021)	2021	RC buildings	Bracing system (outside), with or without demolition of external masonry wythe	Conceptualisation, technology, structural and thermal analyses			x		x	x				
(Valluzzi et al. 2021)	2021	Masonry buildings	Endoskeleton (inside), may require demolition of roof and walls	Conceptualisation, technology, structural and thermal analyses			x	x	x	x				
(Zanni et al. 2021)	2021	Not specified (real application: RC building)	Exoskeleton (outside)	Conceptualisation, technology, case study, structural and thermal analyses, real application (school gym hall)			x	x	x	x	x	x	x	x
(Baek et al. 2022)	2022	RC and masonry buildings	Bracing system (outside)	Conceptualisation, technology, experimental testing						x				
(de Sousa et al. 2022)	2022	RC buildings	Bracing system (outside), demolition of existing masonry infill walls	Conceptualisation, technology, experimental testing		x				x				

Table 1 (continued)

(Frunzio et al. 2022)	2022	Not specified	Exoskeleton (outside)	State of art, conceptualisation			x		x	x				
(Majumder et al. 2022)	2022	Masonry buildings	Plaster (not specified)	Experimental testing			x							
(Pampanin 2022)	2022	Not specified	Exoskeleton (outside)	State of art, conceptualisation									x	x
(Passoni et al. 2022b)	2022	All building typologies	Exoskeleton (outside)	Conceptualisation, case study, structural analyses	EPD-based LCA	x	x	x	x	x	x	x	x	x
(Zanni et al. 2023)	2023	Not specified (real application: masonry building)	Exoskeleton (outside)	Conceptualisation, technology, case study, structural and thermal analyses, real application (social housing)			x	x	x	x	x	x	x	x

4.2 Cluster 2 - methods for the integrated assessment and retrofitting of buildings

When performing different types of assessment (e.g., energy, structural, or environmental), performance quantities are typically expressed in different units that cannot be summed up (e.g., primary energy consumption, expected seismic losses, etc.); hence, in order to deal with them in an integrated manner, such quantities need to be converted into common and shared variables. Several alternative methodologies and approaches were proposed in the literature to solve this gap, some of them using individual parameters (e.g., global costs), while others considering a variety of parameters, describing different aspects of the building. Such individual or multiple parameters are meaningful decision-making criteria for the comparison of alternative combined/integrated retrofitting solutions, and, finally, for the identification of the best renovation strategies. Among such methodologies available in the literature, those belonging to the second cluster of this research (22 records) represent the limited number of works that adopt a life cycle and sustainable perspective for the integrated assessment of multiple buildings' performances, as well as for the identification of the optimal retrofitting strategies. Each of those methodologies is described in some detail in the following.

The approach developed as a result of the above-mentioned SAFESUST workshop (Caverzan et al. 2016), joining safety and sustainability, has led to the implementation of the so-called Sustainable Structural Design (SSD) method (Caverzan et al. 2018; Lamperti Tornaghi et al. 2018). The comparison between alternative design or retrofitting solutions, and consequently the selection of the most suitable strategy, is proposed to be based on the individual 'global assessment parameter', which is the sum of the costs of energy consumption, carbon footprint, seismic repair, and downtime, evaluated throughout the life of the building. Notably, the carbon footprint is converted into an equivalent monetary cost, based on the actual market prices of carbon dioxide, to be included in the economic summation as well. As a further advance of the work on this topic, more recently, the Joint Research Centre, under the mandate of the European Parliament, has also successfully carried out a European pilot project, titled "Integrated techniques for the seismic strengthening and energy efficiency of existing buildings" (Gkatzogias et al. 2023). The available seismic, energy, and combined/integrated renovation technologies were first reviewed (Pohoryles et al. 2022a, 2022b; Romano et al. 2023c). A simplified method for assessing the benefits of combined renovation was proposed and applied to representative buildings (Romano et al. 2023a), and an integrated framework was developed for regional impact analysis. By employing this framework across the European Union, seismic risk, energy performance, and socioeconomic aspects were assessed to identify priority regions and investigate renovation scenarios (Gkatzogias et al. 2022a, b). The Joint Research Centre is currently active in developing an approach to further extend an assessment method to cover the three dimensions of the New European Bauhaus initiative, sustainability, quality of experience and inclusion (Negro and Romano 2022). Similarly to the global assessment parameter above, (Menna et al. 2019) proposed a decision-making framework for retrofitting existing buildings that integrates energy and seismic aspects through the so-called 'total lifecycle cost (LCC)' parameter. LCC is in fact the result of the summation of the global cost (GC) for energy consumption and the expected annual losses (EAL) due to seismic hazard in the building's life cycle. Thus, the methodology can be undertaken to identify the most cost-effective retrofitting solution from an integrated life cycle perspective, i.e., the one that minimises the LCC due to investment in retrofitting, energy running costs and expected losses over the life of the building after retrofit. Global life cycle costs were also used by (Mauro et al. 2017) within a multistep approach for the identification of the cost-optimal energy retrofit for a given building, integrating energy, structural and economic aspects. Namely, this methodology considers the investments and operating costs related to energy usage, as well as the increased seismic economic losses due to the building's added value of the energy refurbishment.

As opposed to individual parameters, several multi-criteria decision-making (MCDM) approaches emerged in recent years for the identification of optimal retrofitting strategies for buildings. The largest number of methodological papers selected here proposed MCDM methods, which typically consider a range of economic, social, technical, and, more recently, life cycle environmental aspects that are assumed to be of interest to decision-makers.

Within the framework of the ReLUIS-DPC (Italian Civil Protection Department - Dipartimento della Protezione Civile) 2019–2021 and 2022–2024 research projects, focussed on the development and verification of integrated seismic and energy retrofitting solutions, several MCDM methods have been developed. For instance, the MCDM approach conceived by (Caruso et al. 2020, 2021), and further extended by (Caruso et al. 2023), is based on the use of the so-called radar plots to, also visually, support the process of identification of optimal integrated retrofitting strategies. Life cycle costs (C) and carbon emissions (CE), the retrofit investment payback period (PB), and the average annual loss of life due to potential earthquakes (AALL) are proposed as unweighted decision-making variables to compare alternative retrofitting solutions from economic, environmental, and social perspectives. In a similar manner, (Clemett et al. 2023) proposed to consider the performance of alternative seismic/energy retrofitting strategies across a broad range of decision variables, including installation costs, life cycle costs and carbon emissions, duration of works, and architectural impact, among others. This methodology uses a weighted average method to identify the optimal retrofitting solution, following the technique for order preference by similarity to the ideal solution (TOPSIS). (Giresini et al. 2020) proposed instead an alternative method to quantify the improvement of seismic and energy performances of retrofitted masonry buildings through the so-called isocost and isoperformance curves, allowing for the quantification of the economic and environmental costs of each retrofitting option considered based on a specific energy or seismic performance target. Namely, in (Giresini et al. 2020), a meso-scale approach (i.e., façade-scale) for integrated interventions was applied to masonry façades, and a preliminary application of this method can be found in (Stochino et al. 2020). As an improvement of the method, (Giresini et al. 2021b) proposed to take into account a more comprehensive life cycle approach when estimating the environmental and economic impacts of retrofitting solutions. Finally, (Giresini et al. 2021a) extended the methodology at the building level, to mitigate the local seismic vulnerability of existing masonry buildings.

Additional examples of multi-criteria decision-making approaches for the retrofitting of individual buildings can also be found in (Artino et al. 2020; Fiore et al. 2020; Güleroğlu et al. 2020), while (Anwar et al. 2023), more recently, proposed a sustainability-oriented approach applicable at a building portfolio level. (Artino et al. 2020) conceived the decision support system (DSS) as a tool that allows for the rapid and effective identification of the best renovation strategy for a given building, based on the definition of a multifaceted priority scale with several weighted criteria, including life cycle costs and duration of operations, occupants' disturbance, environmental sustainability, energy savings and thermal comfort and structural safety. Reference to the Protocollo ITACA (iiSBE Italia; Proitaca 2024) is made for evaluating the life cycle environmental sustainability of buildings, including criteria such as operational primary energy, energy from renewable sources, eco-compatible materials, performance of the envelope, CO_2 equivalent emissions, solid waste, and thermo-hygrometric well-being. Alternatively, (Fiore et al. 2020) proposed the use of the analytic hierarchy process (AHP) method to support the planning of retrofitting interventions in school buildings, by considering a variety of environmental, economic, and social sustainability parameters, that is, seismic safety, energy performance, intervention cost, environmental impact, realisation time, and disturbance. Namely, the environmental impact indicator comprises the quantity of waste produced during the intervention and the percentage of recovered materials. Focussing on historical buildings, instead, (Güleroğlu et al. 2020) proposed a novel methodology to identify the most effective integrated renovation measure, considering energy, seismic and cost performances at the same time. LCC is used as a decision-making support criterion for selecting the optimal strategy. At a larger geographic scale, (Anwar et al. 2023) introduced an optimisation and decision-making framework for community portfolios of buildings, subjected to a high level of seismic hazard, considering multiple performance indicators, including socioeconomic and environmental consequences of earthquakes, as well as retrofit investment costs (e.g., number of injuries, downtime, embodied carbon and energy due to repair activities, etc.).

On a different note, a holistic multidisciplinary approach for comparing alternative architectural solutions was proposed by (Assimakopoulos et al. 2020). It was conceived to evaluate the optimal configuration of building refurbishment by using volumetric additionals, towards the nearly zero-energy building (nZEB) target. The effectiveness of the volume addition strategy was demonstrated through the use of an innovative, quantitative SWOT matrix, including several multifaceted aspects of improvement (e.g., acoustic comfort, seismic risk, etc.).

(Di Bari et al. 2020), instead, presented a methodology to include seismic hazard into novel probabilistic-based approaches for life cycle analyses, considering the possibility of structural enhancement over an extended building lifespan. Therefore, the probabilistic LCA and LCC results can be used as metrics to compare alternative retrofit solutions.

Lastly, an example of a more general and holistic design and assessment framework was proposed by (Passoni et al. 2019, 2021), and extended by (Passoni et al. 2022a), which is based on a comprehensive life cycle thinking approach and which integrates with the Level(s) framework. In fact, it consists of the holistic following steps: (i) the multi-performance assessment of the building in its as-built configuration; (ii) the pre-screening of retrofitting solutions that satisfy a suite of sustainable and LCT-compliant performance targets; (iii) the preliminary design of the retrofitting techniques identified in step (ii); (iv) the selection of the optimal retrofitting strategy for the given building based on meaningful performance metrics; (v) the design development of the optimal retrofitting solution; (vi) the use of tools or classification schemes that facilitate accessibility to potential financial incentives; (vii) the advanced design of the retrofitting solution and construction, adopting LCT-inspired technical detailing; and (viii) the management of the in-use performance and end of life. It is noteworthy that life cycle thinking and sustainability are adopted herein as performance targets starting from the very beginning of the design process.

To summarise all these works, Table 2 collects all the reviewed contributions belonging to this second cluster, as well as a detailed analysis of their contents, which were investigated in terms of:

- the building typology, to which the method is applicable;
- the numerical application to one or more case-study buildings;
- the employment of one or more environmental impact metrics;
- the use of life cycle tools (such as LCA or LCC analyses);
- the application of a classification scheme (e.g., energy efficiency, seismic risk, integrated classes, etc.).

Table 2 Summary of selected records resulting from step 6 of the literature research - cluster 2: integrated methodologies

Authors	Year	Building typology (RC, masonry, steel buildings, or others)	Numerical application (residential building, office, school, or others)	Environmental impact metrics (CO_2e, or others)	LC Tools (LCA, LCC)	Classification schemes (energy, seismic risk, integrated classes, or others)
(Mauro et al. 2017)	**2017**	All building typologies	Residential RC building	CO_2	LCC	
(Caverzan et al. 2018)	**2018**	All building typologies		CO_2e into costs	LCA, LCC	
(Lamperti Tornaghi et al. 2018)	**2018**	All building typologies	New office building (cast in place vs. precast reinforced concrete)	CO_2e (converted into costs)	LCA, LCC	
(Menna et al. 2019)	**2019**	RC buildings	Facility RC building		LCC	
(Passoni et al. 2019)	**2019**	All building typologies			LCA, LCC	
(Artino et al. 2020)	**2020**	All building typologies	Residential RC building	Different criteria from the ITACA protocol (e.g., operational primary energy, energy from renewable sources, CO2e, etc.)	LCA (ITACA protocol), LCC	Vulnerability classes
(Assimakopoulos et al. 2020)	**2020**	All building typologies	Dormitory RC building	CO_2e		NZEB classification
(Caruso et al. 2020)	**2020**	All building typologies	Illustrative example	CO_2e	LCA, LCC	Integrated classes
(Di Bari et al. 2020)	**2020**	All building typologies	Residential RC building (social housing)	CO_2e	LCA, LCC	
(Fiore et al. 2020)	**2020**	All building typologies	School RC building	Quantity of waste production and percentage of recovered material		Energy classes
(Giresini et al. 2020)	**2020**	Masonry buildings (façade-scale)	Municipality masonry building (façade-scale)	CO_2e		
(Güleroğlu et al. 2020)	**2020**	All building typologies	Historical masonry building (actual destination: office, future destination: hotel)		LCC	
(Stochino et al. 2020)	**2020**	Masonry buildings (façade-scale)	School masonry building (façade-scale)	CO_2e		
(Caruso et al. 2021)	**2021**	All building typologies	School RC building	CO_2e	LCA, LCC	Energy, seismic risk, integrated classes
(Giresini et al. 2021b)	**2021**	Masonry buildings (façade-scale)	School masonry building (façade-scale)	CO_2e	LCA, LCC	

Table 2 (continued)

(Giresini et al. 2021a)	**2021**	Masonry buildings	School masonry building	CO_2e	LCA, LCC	
(Passoni et al. 2021)	**2021**	All building typologies	Residential RC building		LCA, LCC	
(Passoni et al. 2022a)	**2022**	All building typologies			LCA, LCC	Integrated classes
(Anwar et al. 2023)	**2023**	All building typologies	Community building portfolio (mixed destinations and structural types)	CO_2e, GJ		
(Caruso et al. 2023)	**2023**	All building typologies	Residential RC building	CO_2e	LCA, LCC	
(Clemett et al. 2023)	**2023**	All building typologies	School RC building	CO_2e	LCA, LCC	Energy classes
(Gkatzogias et al. 2023)	**2023**	All building typologies		CO_2e into costs	LCA, LCC	

5 Conclusions

The concept of sustainable renovation has undergone a progressive evolution in the recent decades, leading to the latest interpretation as the need to simultaneously improve the buildings' structural vulnerability against natural hazards and minimise their consumption of energy and resources, while also addressing environmental, economic and social impacts at different life cycle. In this scenario, the paper defines a comprehensive taxonomy of available strategies that meet LCT criteria and carries out a systematic state-of-the-art literature review to map the currently available LCT-based retrofitting strategies and assessment methods and to highlight possible future research needs towards a truly sustainable building renovation.

This research effort was carried out under the mandate of the European Association of Earthquake Engineering (EAEE), within the framework of Working Group 15 (WG15), focussed on "combined seismic and environmental upgrading of existing buildings". The mission of this group is to support the dissemination of technical retrofit solutions and procedures that are finalised to reduce seismic vulnerability and increase environmental efficiency, leading to a significant reduction of economic, environmental, and social impacts (Felicioni and Negro 2023).

To map the scientific production on LCT-based combined/integrated assessment and retrofitting of buildings, a keyword-based literature research was carried out in July 2023 in WoS and Scopus databases, searching for works published between January 2012 and June 2023. The systematic review resulted in 51 records, which were then distinguished into two main recurring clusters, i.e., (i) integrated retrofitting techniques (29 records) and (ii) integrated assessment methods (22 records). The first cluster collects scientific papers where retrofitting systems are proposed for the combined/integrated renovation of buildings under an LCT perspective, based on one or more LCT principles at the material level (e.g., use of recycled/reused materials, renewable biomaterial, local materials, durable materials, recyclable materials), or at the technique level (e.g., dry technique, prefabrication, modularity/standardisation, material optimisation, damage minimisation, damage concentration). Each technique was described and classified according to common criteria in order to make comparisons amongst the different studies. The criteria considered include the building typology, the structural concept, the level of invasiveness, the study typology, the adoption of life cycle tools (LCA, LCC), and the LCT-based design criteria adopted in the retrofit conceptualisation. The second cluster, in contrast, gathers more methodological research works that suggest procedures to assess the multiple performances and their retrofitting activities in an integrated way and under a life cycle perspective. Similarly to cluster 1, the different methodologies were summarised and classified according to the building typology, the application to case-study buildings, the adoption of alternative environmental impact metrics, the use of life cycle tools (LCA, LCC), and the possible application of sectorial and/or integrated classification schemes.

From the critical analysis of the state-of-the-art papers, some final considerations can be drawn:

- The existing building stock features a variety of structural typologies (e.g., masonry, reinforced concrete, steel, timber, composite structures, etc.), each one with their specific vulnerabilities. However, the literature search resulted in publications mostly covering reinforced concrete and masonry structures over other types, although the research

string was not limited to such typologies. Future research work should also cover retrofitting techniques and assessment methods adaptable to other structural typologies;
- In recent years, several research studies on integrated retrofitting techniques and assessment methodologies were proposed, only considering seismic and energy combined/integrated retrofitting. In order to further increase the resilience of the existing building stock, the mitigation of risks other than earthquakes should be considered as well, such as fire (one paper only was found herein), floods, droughts, and other climate-related risks. Future works should thus be not only tailored on the building typology but also on climate conditions and potential hazards at the building site;
- In order to carry out a truly sustainable renovation of the building stock, adopting an integrated strategy is not enough, rather an LCT approach should be embraced since the very beginning of the design process. The building life cycle goes indeed beyond the initial construction and use stage; for such a reason, LCT-based design criteria should be considered in the conceptualisation of retrofitting techniques and integrated in assessment methods. This would enable the effective minimisation of the impacts along the whole building life cycle. In the reviewed studies, only a few LCT criteria were adopted throughout the design of each retrofit solution; as for the methodologies, the adoption of an LCT approach is often interpreted as the sole application of LC tools. However, LC tools do not inspire the design of sustainable solutions, but just calculate, at the end of the design process (‘ex-post’), the impacts of the proposed retrofitting techniques;
- Most of the collected studies include theoretical demonstrations of retrofitting techniques and assessment methods, while only a few of them report examples of real applications. In the future, the application of available LCT-based techniques and methods, as well as the development of novel ones, should become the standard in current engineering practices, overcoming academia boundaries.

Unless these issues are addressed contextually, renovating the existing building stock, even with an integrated approach, may represent a missed opportunity to contribute to a more sustainable and resilient built environment. Future efforts of EAEE WG15 include the development of a vision document on the LCT-ispired renovation strategy that could go beyond the state-of-the-art practice, and propose guidelines and perspectives to pursue such an ambitouos target, as well as improved dissemination activities.

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