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The Role of Life Cycle Structural Engineering in the Transition towards a Sustainable Building Renovation: Available Tools and Research Needs

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Abstract: Given the current climate emergency and the ambitious targets of carbon emissions reduction, retrofitting strategies on existing buildings typically include reducing energy demand, decarbonising the power supply, and addressing embodied carbon stored in materials. This latter point redefines the role of engineers in the transitions towards a sustainable construction sector, being they responsible for designing low impact, sustainable and carbon neutral solutions. A Life Cycle Structural Engineering (LCSE) approach, inspired by the principles of Life Cycle Thinking (LCT), should thus be adopted for the sustainable renovation of existing buildings. Only recently have pioneering approaches been proposed, tackling multifaceted buildings' needs, such as those related to energy consumption as well as seismic safety, but often disregarding LCT principles. This study presents a redefinition of the concept of LCSE for sustainable construction and a comprehensive review of available methods and tools to operationalise the LCSE approach in practice, focusing on the consideration of LCT principles in the retrofitting design process, integration of seismic loss estimation and environmental impact assessment, and implementation of integrated retrofitting strategies. The greatest ambition of this work is thus to boost a paradigm shift for building engineers towards an interdisciplinary perspective in building assessment and retrofitting.

Keywords: sustainable building renovation; life cycle structural engineering (LCSE); life cycle thinking (LCT); life cycle tools; environmental impact assessment; seismic loss estimation; integrated retrofitting strategies; multi-criteria decision making

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1. Introduction

The Paris Agreement on Climate was adopted on 12 December 2015 by 195 countries at the 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris. It represents an international commitment to mitigate impacts of climate change by keeping the rise in the global average temperature ideally below 1.5 °C above pre-industrial levels. In this context, the European Green Deal [1], being one of the six European Commission's priorities for the five-year term 2019–2024, is the new growth strategy to turn the European Union (EU) into a sustainable, resource-efficient, and competitive economy. The Commission recommends a comprehensive climate, energy and industrial policy aiming at a target reduction of greenhouse gas (GHG) emissions by 2030 to at least 55% compared to those in 1990 and at carbon-neutrality by 2050. The accomplishment of such ambitious targets requires a move away from coal, oil and natural gas as well as a complete transformation of all sectors of the economy. The recently implemented Next Generation EU recovery fund includes such a vision as one of its underlying principles and thus aims to contribute to a decisive boosting of a sustainable modernisation of the European existing building stock.

The recent COP26 summit (Glasgow, 31 October–12 November 2021) constituted a first checkpoint of this ambitious decarbonisation process and, most regrettably, left the scientific community doubting the feasibility of achieving the net-zero objective in more than 140 countries (covering 90% of total carbon emissions), notwithstanding the pledges for 2030 made at the event. Indeed, under current policies, the Climate Action Tracker (CAT) [2] predicts an end-of-century average warming equal to 2.7 °C based on current policies (as seen in Figure 1). In the most optimistic scenario, i.e., if all the announced net-zero commitments are implemented, an end-of-century average warming equal to 1.8 °C is expected, which is still not compliant with the 1.5 °C target. Much more needs to be done.

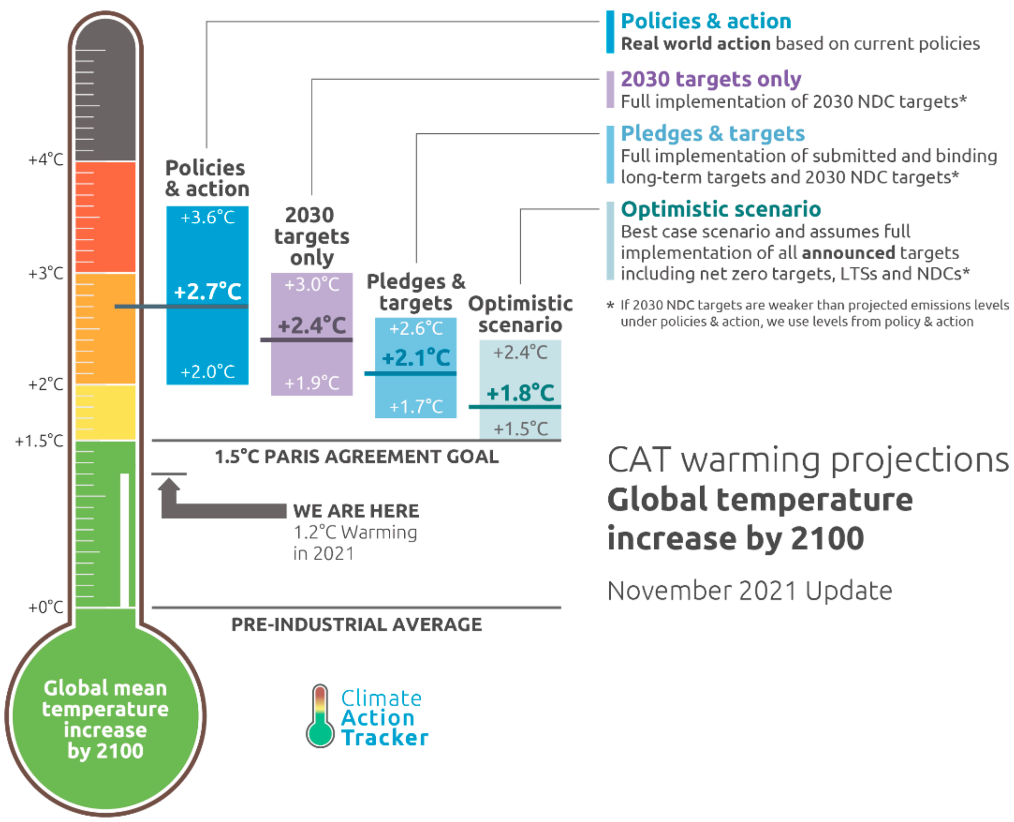

Figure 1. Climate Action Tracker (CAT) warming projections by 2100 (reprinted with permission from Ref. [2]. 2021, Climate Analytics and NewClimate Institute).

It is already well-known that the building sector in the EU is responsible for about 36% of the global GHG emissions [3]; hence, since the 2015 Paris Agreement, several countries have adopted policies and regulations that are expected to have a future impact on long-term emissions and energy efficiency of buildings. GHG emissions are typically expected to be reduced along buildings' life cycle through a triple strategy: reducing energy demand (improved energy performance and efficiency), decarbonising the power supply (e.g., electricity supply from renewable sources and increased use of other zero-carbon technologies) and adopting construction materials with reduced equivalent embodied carbon [4], while possibly also enhancing their comfort, safety and resilience.

In addition to GHG emissions, the construction sector also generates other significant environmental and social impacts that should not be disregarded. It is responsible for 50% of raw material depletion and 35% of waste production (that is the larger stream of waste in Europe). In addition, GHG emissions are responsible for increased freshwater consumption, water pollution, virgin soil exploitation and deforestation, especially in unspoiled regions of the world, and of other harmful emissions which may aggravate, in addition to climate change, other environmental issues. As for social effects, GHG emissions are responsible for impacts throughout the building life cycle on different social categories related to, e.g., health and indoor comfort.

Finally, additional environmental and social impacts are connected to the multiple natural hazards to which the large obsolete European building stock is exposed, such as earthquakes, floods, or, more recently, superstorms. In this scenario, it is clear how reducing/avoiding all the potential impacts associated with each phase of constructions' life cycle is critical to pursue sustainability in the building sector.

Life Cycle Thinking (LCT) and holistic concepts in structural engineering practices through the definition of 'new' target performances are major objectives of current (and future) research. In 2011, Cost Action C25 [5], which was dedicated to the sustainability of construction, introduced the concept of Lifetime Structural Engineering and proposed some target performances to be considered in the design of structural retrofitting solutions, i.e., eco-efficiency, durability, maintenance, dismantlement, etc., ensuring that such requirements would be fulfilled over the entire building service life.

More recently, Marini et al. [6] introduced a more comprehensive vision of the problem, further expanded by Passoni et al. [7], extending and redefining the concept of Life Cycle Structural Engineering (LCSE). In those studies, the need to renovate the existing building stock to reduce the impact of construction, especially adopting an integrated approach, was emphasised. In addition, some guidelines to pursue a sustainable renovation inspired by LCT principles, were defined. These guidelines introduced new principles and design targets to achieve objectives such as reparability, durability, flexibility and adaptability, deconstruction, etc. and including the concept of incremental rehabilitation and the requirement to work from the outside to address some major barriers to renovation.

Sustainable renovation strategies should target at least the mitigation of buildings structural vulnerability and the improvement of their energy efficiency, ensuring the highest savings in both hazard-induced damage repair (and consequent environmental impact) and energy consumption. The definition of low-invasive retrofitting techniques coupling energy and seismic upgrade strategies is thus another of the major objectives of current research in the structural/building engineering field. For instance, the Joint Research Centre (JRC) pilot project [8] and the ReLUIS work package 5 (WP5) research project [9] envisage integrated retrofitting solutions for seismic strengthening and energy efficiency (including both traditional and innovative techniques) at different buildings' dimensional scale, evaluating costs and duration of work needed to employ those solutions in real applications.

The above notwithstanding, the adoption of integrated energy and seismic retrofitting interventions, although ambitious, may not be enough to reach the envisioned target of carbon neutrality. Such solutions are indeed aimed at minimising impacts during the building operational phase, including seismic risk, but disregard the impacts of other life cycle stages (e.g., embodied carbon) and of the different nature of costs and carbon emissions. Stemming from this consideration, authors such as Marini et al. [6], Passoni et al. [7] and Huang et al. [10] recently proposed new approaches for the sustainable design and retrofitting of buildings. In the traditional approach, retrofitting solutions, even when integrated and technologically advanced, are first designed and then assessed to validate their compliance with sustainability and circularity principles, usually by applying ex post life cycle (LC) tools to calculate costs and carbon emissions. Instead, the aforementioned new approaches propose an inversion in the retrofitting workflow, introducing LCT principles at the beginning of the design procedure to conceive a truly sustainable LCT-based solution, i.e., effectively minimising the impact along the whole building life cycle.

The new LCT-based framework introduced by Passoni et al. [7] for the design of sustainable and integrated retrofitting interventions has been coined as Sustainable Building Renovation (SBR). The proposed framework may serve all stakeholders at different stages of the design process and consists in four steps: (1) the multidisciplinary assessment of the building in the as-is condition with identification of the major retrofitting needs and of the minimum target performances to be achieved through the retrofitting intervention; (2) the pre-screening of possible uncoupled and coupled retrofitting solutions, allowing for the selection of the most suitable solutions according to qualitative LCT and holistic principles (such as duration of work, renovation cost, need for occupants' relocation, fast assembling, waste generation, expected losses due to seismic hazard, etc.); (3) the preliminary design of the selected integrated solutions adopting a multi-performance based design; and (4) the choice of the optimal retrofitting strategy on the basis of quantitative criteria of different nature.

The SBR framework was intentionally conceived to be as general as possible to provide general guidelines for the design of sustainable and integrated solutions but also to allow professionals to select the most suitable tools for each step based on their skills and practice. In addition, such freedom conferred in the framework allows the substitution of possibly obsolete tools with updated ones, avoiding the obsolescence of the framework itself. On the other hand, the authors acknowledge that the generality of the framework and the lack of specific tools to be adopted in each step may reduce its applicability in current practices, keeping it limited to the solely academic sphere. Further specifications are thus needed to increase the applicability of the framework as a practical tool for the design of sustainable solutions.

It is thus within the above context that with a view to provide a contribution to Life Cycle Structural Engineering, this study presents a comprehensive and critical review of available methods and operative tools for the sustainable renovation of buildings which may be included in the various steps of the SBR framework. Such review is aimed at highlighting strengths and weaknesses of available approaches and the major research needs towards the application of the LCSE approach in actual engineering practices.

2. Available Tools for a Sustainable Building Renovation: State of the Art Literature Review and Research Needs

In recent years, a growing number of research endeavours have focused on methods and operative tools for improving building sustainability. This concept has recently been broadened to include eco-efficiency, safety, and resilience. Passoni et al. [7] presented a state-of-the-art review on sustainable renovation, distinguishing between those studies proposing sustainable techniques/solutions from those developing tools and frameworks for sustainable design. Those studies were then further classified according to the three pillars of sustainability: economic, environmental, and social, where the concept of social was extended to include safety against hazard risks. More recently, Menna et al. [11] presented a literature review of available tools, international sustainability protocols, and ad hoc methods for the combined assessment of seismic resilience and energy efficiency of buildings with a view to highlight the complex nature of retrofitting when energy/structural issues are considered in a combined manner. They distinguished two main groups of works: (i) methods where the assessment is independently carried out according to available codes related to energy performance and seismic safety; and (ii) methods where the integrated evaluation of building's seismic and energy performance is attained considering an 'equivalent' cost (monetary, environmental, or other) indicator, which may be initial or life-cycle-based.

The present review is instead organised in sections dedicated to each relevant topic to be considered in the holistic LCSE approach for sustainable construction (Figure 2). In the first section, tools for a preliminary qualitative evaluation of eligible retrofitting interventions are presented. In the second section, decision-making tools for the selection of the most sustainable solutions among the pre-designed ones are collected based on quantitative indicators. In the third section, classification and rating systems to be applied at the end of the design process to have access to incentives, premiums or certificates are discussed. The Level(s) framework [12], i.e., the new European framework for sustainable buildings, is also introduced. Finally, in Section 2.4, the compatibility of these tools with the LCT-based SBR framework is discussed and possible research needs are highlighted. A synthesis of all the available tools for the design and selection of the most sustainable retrofit solutions is graphically shown in Figure 2.

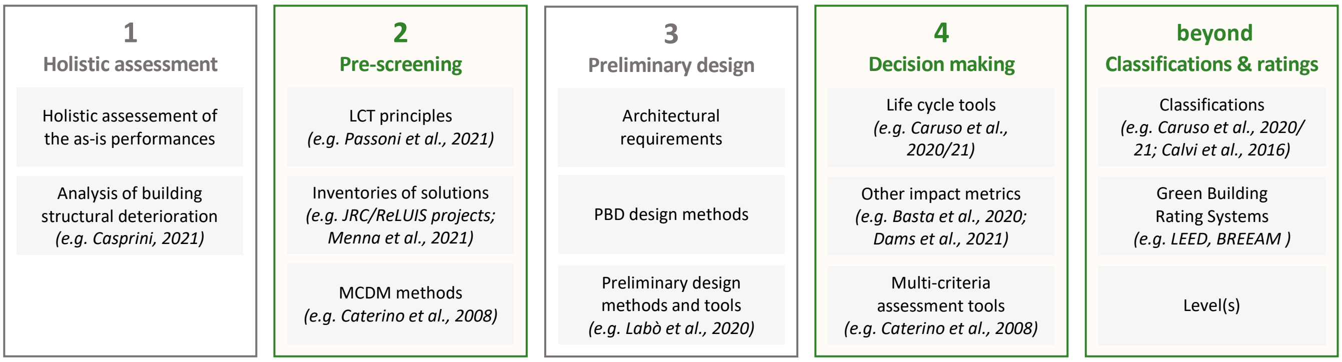

Figure 2. Sustainable Building Renovation (SBR) framework: graphical state of the art.

2.1. Pre-Screening Procedure (Step 2)

When considering alternative retrofitting solutions, their suitability should be evaluated based on three kinds of criteria: (i) technical feasibility, depending on building features and restrictions including building typology, technical characteristics, materials and the presence of urban, architectural or historical constraints; (ii) compliance with decision-maker (DM) requirements, such as budget limitations, particular expectations and needs, the possibility to temporarily close the building during retrofitting work or after a hazardous event and so on; and (iii) compliance with LCT principles, i.e., solutions with limited environmental, social, and economic impacts along the building life cycle.

Given the above boundaries, the pre-screening of alternative retrofitting solutions for a given building may be carried out through a two-phase process as shown in Figure 3:

1. Reference to available inventories of alternative retrofitting measures, including uncoupled and coupled solutions, with the characterisation of their technical, environmental, economic and social features;
2. Choice of the most suitable retrofitting solutions with the support of available multi-criteria decision-making (MCDM) tools.

In the following sections, existing inventories of retrofitting techniques and of available MCMD tools are presented and consequent research needs are highlighted.

2.1.1. Inventories and Characterisation of Retrofitting Solutions

The recent interest in combining energy and structural solutions to concurrently solve more than one building deficiency and exploit the advantages of integrated/combined interventions (e.g., shared construction site, optimisation of resources, limited duration of works, logistics management, etc.) has laid the basis for many multidisciplinary studies and research projects aimed at defining new integrated upgrading technologies and at establishing new inventories of available techniques.

In the JRC Pilot Project [8], a first major inventory in which energy amelioration measures and structural retrofitting solutions were classified with respect to compliance to LCT principles, construction costs, duration of work and integrability with other retrofitting measures was presented. An extensive survey of both traditional and innovative techniques, also with reference to actual engineering applications, was carried out in the ReLUIS WP5 research project [9] as well.

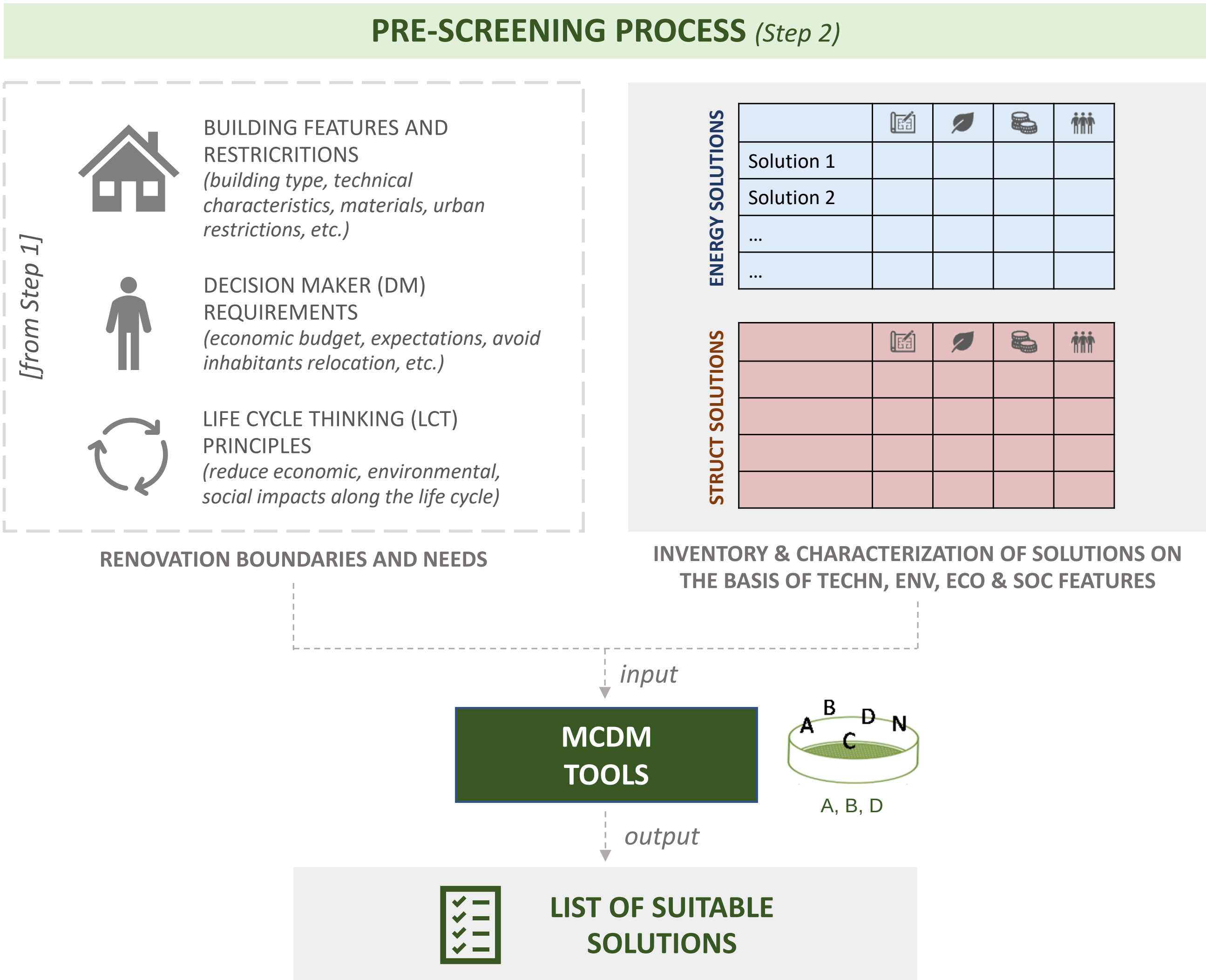

Figure 3. Workflow of the pre-screening process to select the most suitable strategies.

The state of the art of the currently available uncombined and combined seismic and energy upgrading measures is also presented in Menna et al. [13]. In particular, they proposed a technical/economical classification of energy and structural retrofitting interventions, based on their level of invasiveness. Three increasing levels of disruption were identified: (i) Level 1, addressing low-invasive energy retrofits (e.g., modification of existing systems, new coverings, small components substitutions, substitution of windows and roof thermal insulation, etc.) and local seismic strengthening (e.g., external beam column joints or exterior beams and columns strengthening through fibre-reinforced polymers, steel or textile reinforced mortars jacketing); (ii) Level 2, addressing thermal improvement of the existing envelope and/or replacement of HVAC systems and in-plane and/or out-of-plane infills strengthening or strengthening of reinforced concrete frame; and (iii) Level 3, addressing more invasive interventions, such as the application of an exterior insulation layer and/or finishing system as well as highly energy-efficient or renewable energy systems and global structural strengthening (e.g., steel bracing, shear walls, etc.).

In addition, in recent years, innovative integrated solutions have been proposed, expanding the concept of holistic renovation to also include architectural and functional renovation and urban regeneration. A pioneering research project, inspired by the energy efficiency upgrade and architectural renovation projects proposed by Lacaton and Vassals architects (such as the “Bois-le-Prêtre” tower renovation), but also including seismic retrofitting, was presented in the Eutopia research project [14] in which the conceptual design of holistic retrofit exoskeletons was first introduced. Similar proposals were then developed by ProGETonE (https://www.progetone.eu/project/, accessed on 24 July 2022) [15] and by Reggio et al. [16]. A first example of seismic, energy and architectural deep renovation, also including LCT principles such as macro-prefabrication, demountability, damage concentration, etc., was completed in Brescia (Italy) and financed by Regione Lombardia for the holistic renovation of a public school gym hall [17]. An enhancement of this technique is now under development, also including additional sensors for IoT and smart monitoring, as well as new mechanical systems applied from the outside of the building [18].

All these studies are valuable to define a comprehensive inventory and a classification of available holistic solutions; however, some limitations should still be overcome. First, despite all the efforts, it is difficult to provide a general classification of retrofitting techniques based on their economic and environmental impact. Prices are dependent on regional markets, seismic and climatic zones and peculiar building features and project specifications. As for environmental impacts, the sole carbon emissions are usually addressed, disregarding some other important impacts such as water consumption or waste production. A strong dependency of the results on the adopted assessment procedures, functional units, inventories and databases should also be considered. At this stage, such studies are useful to retrieve a raw estimate of average impacts, but the price and environmental impact ranges for each solution are still very wide. Furthermore, it should be considered that the evaluation of costs and impacts for innovative combined solutions is mostly based on simulations or, in the most optimistic scenario, on pilot projects which may have peculiar characteristics; such evaluations should thus be validated with additional data to obtain more robust reference ranges of data.

2.1.2. Multi-Criteria Decision-Making (MCDM) Tools

MCDM methods are intended to support stakeholders while evaluating and comparing different alternatives to identify optimal strategies according to multiple criteria. Several decision-making procedures have been proposed in recent years to aid the selection of optimal retrofitting solutions for buildings.

As an example, a decision-making tool for seismic retrofitting was conceived by Caterino et al. [19] for comparisons between different options. Relevant evaluation criteria (qualitative and/or quantitative and of very different nature as well) are first defined depending on building-specific features and scope and then weighted based on a pairwise comparison (i.e., relative importance of one variable with respect to another). The choice of the best and worse solutions is then made by calculating the distances of each retrofit solution to fictitious positive and negative solutions. An applicative study of this MCDM tool was carried out by Clemett et al. [20], also including environmental impacts amongst the decisional variables considered. In addition, recently Caterino et al. [21] proposed an update of this work, implementing a BIM-based framework that considers both the DM profile and data retrieved from a BIM model of the given building.

Other valuable MCDMs have been developed in the energy retrofitting field to select the best retrofitting solutions according to the three sustainability pillars. Among others, Pons et al. [22] introduced the MIVES method, which is able to rank the alternative solutions on the basis of a sustainability index (SI), and Bragança et al. [23] proposed a multicriteria building rating tool, i.e., the MARS-H Tool, which ranks the alternatives according to a global sustainable score (SS). A comprehensive overview of MCDM decision-making tools applied to the building sector can be found in Si et al. [24].

2.2. Decision-Making Procedure (Step 4)

Once candidate solutions are identified and preliminarily designed, the best option should be selected for the detailed design development. Decision-making tools should thus be adopted to define the optimal retrofitting strategy based on quantitative economic, environmental and social metrics. The procedure for the identification of the best strategy can be articulated in two main phases:

1. Identification and quantification of relevant economic, environmental and social metrics (e.g., costs, carbon emissions, seismic losses, waste generation, water consumption, etc.);
2. Selection of the best strategy by adopting multi-criteria assessment tools, based either on equivalent costs, cost-benefit analyses, MCDM procedures or similar.

A representation of this decision-making process is shown in Figure 4. It should be noted that all these evaluations must be carried out based on available data from a preliminary design of the considered retrofitting measures, where the retrofit components are just preliminary proportioned.

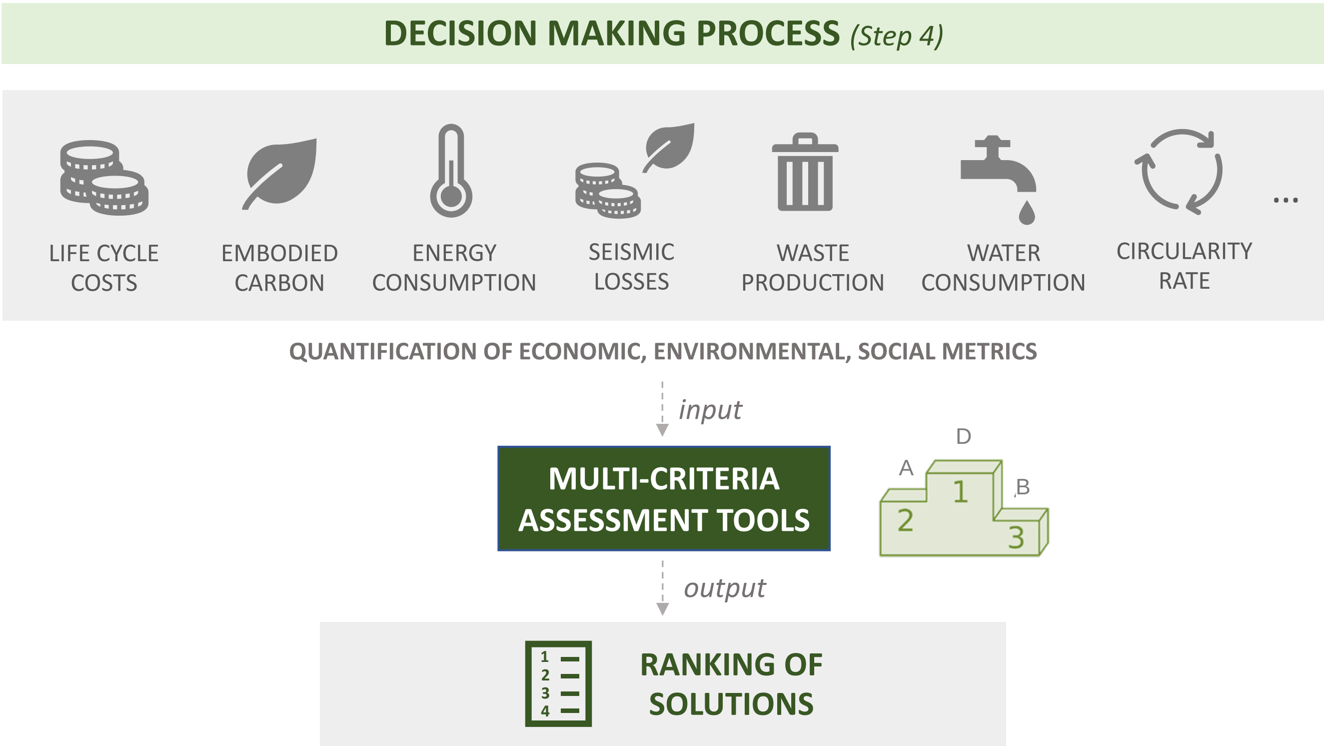

Figure 4. Workflow of the decision-making process for the selection of the best retrofitting option.

In the following sections, a review of existing tools for the quantification of relevant metrics and available multi-criteria assessment tools for the selection of the best strategy are presented and research needs highlighted.

2.2.1. Quantification of Economic, Environmental and Social Metrics

Relevant economic, environmental and social metrics should be estimated to allow for a quantitative comparison between all candidate solutions. Possible relevant metrics are, for example, seismic losses in terms of both costs and carbon emissions, life cycle impacts, embodied carbon, energy consumption, hazardous and non-hazardous waste production, water consumption, circularity rate, flexibility rate, etc. The evaluation of such metrics requires the adoption of different assessment tools as further discussed below for some of those metrics.

- Earthquake-induced losses

An important indicator to evaluate the effectiveness of a retrofitting intervention is the evaluation of earthquake-induced losses in economic (i.e., repair or reconstruction costs and downtime), social (i.e., injured people and casualties) and more recently, environmental terms (e.g., equivalent carbon emissions). To quantify seismic risk in terms of representative and easily understood performance metrics, several indicators have been proposed in the last decades. Amongst these, the average annual loss (AAL), i.e., the average loss that a building is going to experience during its service life due to seismic hazard, is becoming more and more widely used. Accurate and simplified procedures are available for the quantification of such expected losses, some of them being discussed below in further detail.

The most refined seismic loss assessment method is the PEER performance-based earthquake engineering (PBEE) methodology [25,26], developed by the Pacific Earthquake Engineering Research (PEER) Center, which is a fully probabilistic approach to estimate earthquake-induced damage and corresponding losses depending on the site-specific seismic hazard and on the building-specific structural response. As illustrated in Figure 5, it has a four-step main structure: (1) seismic hazard quantification at the site of interest, (2) evaluation of building structural performance under seismic action, (3) estimation of damage in different building components conditioned on the estimated structural response, and (4) calculation of losses due to repairing the damaged components. Simplified procedures for seismic loss assessment are also available in the literature as alternatives to the PEER PBEE approach, e.g., [27–29], amongst others. Another example is the simplified approach prescribed in the Italian guidelines for seismic risk classification [30,31].

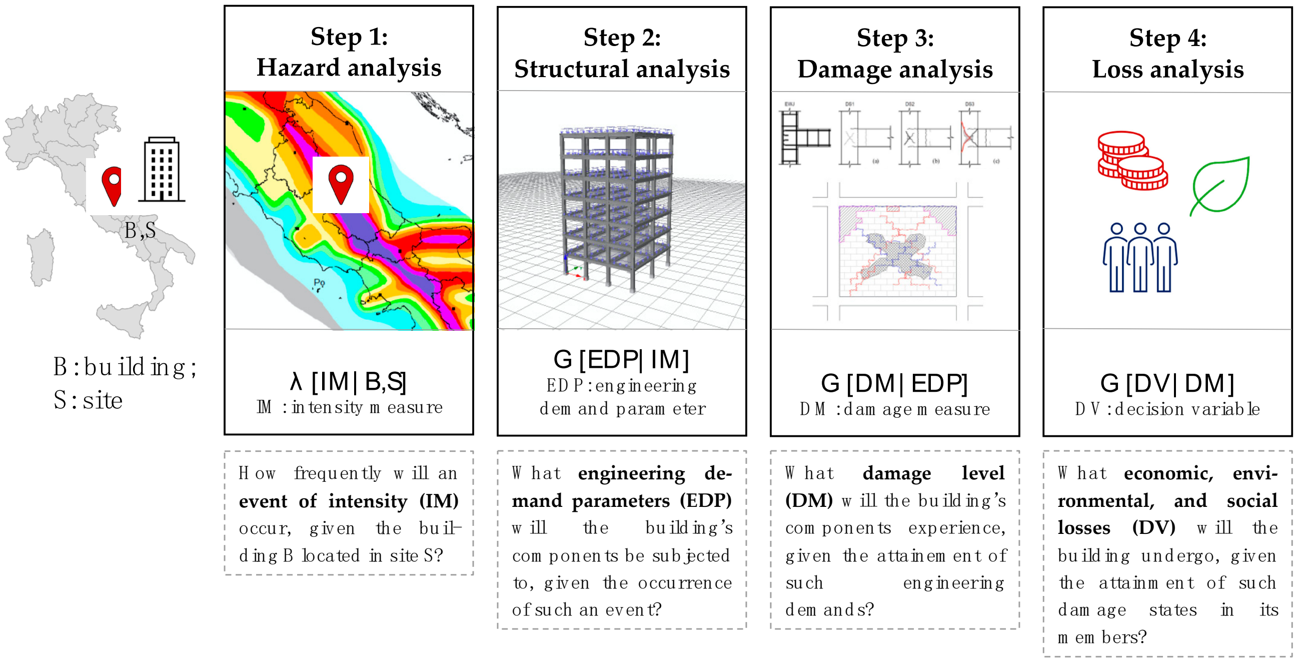

Figure 5. PEER PBEE loss assessment procedure (ATC [26,27]).

- Life cycle impacts

For the evaluation of life cycle economic, environmental and social impacts, LC tools, namely life cycle costing (LCC), life cycle assessment (LCA) and social life cycle assessment (S-LCA) procedures, are usually adopted, respectively. LC tools are standardised by the ISO 14040 series [32,33], which provide a technically rigorous framework for the calculation of impacts that requires skilled professionals for its application. Recently, simplified procedures have also been proposed to allow the estimation of those impacts even by unskilled professionals and designers. An example is represented by the adoption of environmental product declarations (EPDs) for the evaluation of the most commonly used environmental impact metrics of products (e.g., global warming potential, waste disposal, water consumption, amongst others) (Passoni et al. [34]). EPDs also entail the adoption of specific data for the calculation of impacts, thus overcoming one of the main drawbacks of LCA analyses, which is the difficulty in selecting the most suitable data from available databases. On the other hand, EPDs are available for just a limited number of products and often report data for the sole production and end-of-life stages, which are the only mandatory phases according to EN 15804:2012 + A2:2019 [35].

Traditional LCA models for buildings have customarily neglected the potential occurrence of earthquakes during the building's life cycle, disregarding a possible considerable contribution in terms of environmental impact due to post-earthquake repair and retrofitting activities [36]. Hence, recent research works focused on the integration of seismic loss estimation and environmental impact assessment, emphasising the need to also consider the effects of earthquake-induced damage and consequent repair activities in the building operational phase, especially in regions characterised by a high level of seismic hazard. Some of them [36–40] investigated how to translate seismic risk in environmental impacts and explored different approaches to quantify the environmental impacts associated with repair activities. They also demonstrated the convenience and the importance of risk mitigation strategies not only to guarantee safe structural performance levels, but also to reduce environmental impacts of seismic damage and repair activities in buildings. Some other researchers [41–48] instead proposed alternative approaches to quantify the life cycle environmental impacts of buildings located in high seismic hazard regions, thus incorporating the environmental impacts of seismic damage and repair within the operational phase in standard LCA procedures.

Caruso et al. [41,42] presented a life cycle framework for the integrated assessment of buildings which accounts for the contributions of initial construction, operational energy consumption, earthquake-induced damage repair activities, potential retrofitting interventions and demolition (considering also its associated potential material recycling) in terms of both monetary costs and environmental impacts. Gencturk et al. [45] proposed a life cycle sustainability assessment (LCSA) framework for buildings that are subjected to earthquakes. Sustainability is quantified through the various stages of the building's life cycle (however, not including operational use contributions, e.g., energy, water, maintenance, retrofit, loss of contents) in terms of costs and downtime, environmental impacts and waste generation, as well as fatalities, including the impact of seismic repair. Menna et al. [46] developed a probabilistic life cycle assessment of buildings that considers the seismic risk-based time-dependent expected loss. Their results are presented in terms of four damage categories (i.e., CC: climate change, HH: human health, EQ: ecosystem quality and RD: resource depletion) and showed that the rehabilitation phase due to seismic events contributes approximately 6–7% of the overall impact and around 25% of pre-use environmental impact (i.e., the one related to initial construction). Wei et al. [47] instead proposed an LCA framework based on the HAZUS methodology to convert seismic risk into carbon emissions and showing the convenience of risk mitigation in terms of reduction of environmental impacts with a cost-benefit analysis. Belleri and Marini [36] proposed a probabilistic "PBEE-Green" approach based on the PEER-PBEE method and adopted this method to show the inefficiency of the sole energy refurbishment of vulnerable buildings. With a different approach, Di Bari et al. [49] proposed to adopt a probabilistic approach to consider seismic hazard in LCA.

- Other impact metrics

In addition to costs and environmental impacts, some other indicators have been recently proposed aimed at calculating the rate of circularity and flexibility of the proposed retrofitting solutions with the aim of reducing the embodied carbon, especially connected to the maintenance and end-of-life stages of buildings, according to the LCT approach. Among others, Basta et al. [50] proposed a deconstructability assessment scoring (DAS) methodology for quantitative assessment of steel structures deconstructability. The proposed methodology takes into consideration a number of parameters such as the type of connections, the ratio of prefabricated elements, the presence of secondary finishing or of toxic materials, etc. The methodology is then implemented in a BIM-based environment. Deconstruction and flexibility scores may also be calculated according to indications contained in Green Building Rating Systems such as DGNB, among others and in the Level(s) Framework, as discussed in Section 2.3. Similarly, Dams et al. [51] proposed a circular construction evaluation framework (CCEF) to assess and quantify the circularity of a construction project. Based on LCT principles for the design for disassembly and adaptability (i.e., simplicity, standardisation and modularity in design, sustainably-sourced materials, transparent and accessible mechanical connections and the adoption of durable and reusable standardised components and materials), the CCEF allows users to evaluate circularity at both whole building and elemental levels at the early design and planning stages for a new construction, refurbishment or renovation project.

From the above state of the art, it is clear that the large number of available indicators and the skills required to calculate each one of the metrics may hinder the adoption of these methods in actual practice. A careful selection of the most significant metrics should thus be proposed and simplified calculation methods developed.

2.2.2. Ranking of Alternative Solutions

New proposals of life cycle frameworks emerged recently with the aim of developing methods and tools for the integrated assessment of existing buildings, including earthquake-induced repair activities into traditional LCA evaluations, and envisaging the importance of integrated retrofitting. Such approaches may either adopt scoring/rating systems, defining an equivalent index that considers all the calculated metrics, cost-benefit analyses, or MCDM procedures. Most of them adopted LC metrics and tools for the quantification of economic and environmental impacts of buildings to compare alternative retrofitting solutions (e.g., Caruso et al. [41,42]), whilst others (e.g., Caterino et al. [19]) also used additional qualitative criteria (e.g., functional compatibility, skilled labour requirement/technology level, needed intervention at the foundation level, etc.).

The results of different types of assessment (e.g., energy, structural or environmental) are typically expressed in terms of different performance metrics (e.g., seismic losses, energy consumption or carbon emissions), which need to be converted into common variables for a comprehensive integrated evaluation. Most researchers focused indeed on life cycle monetary estimates as an individual performance metric, with a view to also aid the decision-making process. For instance, Lamperti Tornaghi et al. [52] proposed the Sustainable Structural Design (SSD) method, considering both environmental and structural parameters in a life cycle perspective. The comparison between different design or retrofitting solutions and the selection of the most suitable option is cost-based since the proposed global assessment parameter is the sum of the costs of energy, building carbon footprint (which is converted into an assumed equivalent monetary cost), seismic repair and downtime. Calvi et al. [53] proposed an integrated assessment of energy efficiency and earthquake resilience in which both energy and seismic metrics are translated into a common monetary decision variable. As for average annual losses due to seismic hazard, the energy average annual cost is assumed to be equal to the ratio between the cost of consumed energy and the total building replacement cost. In this framework, classes of both energy efficiency and earthquake resilience are proposed as a function of a unique green and resilient indicator (GRI). For all these studies, doubts arise on the efficiency and the rightness of translating environmental impacts, i.e., the main responsible for climate change, and social impacts such as casualties, into monetary costs.

MCDM methods can instead consider different metrics of both quantitative and qualitative nature without converting them into a unique parameter. In these methods, the possibility to include weights for each criterion is also envisioned, and the best solution is usually defined as the closest to a fictitious optimal solution. Some examples of MCDM tools, which were previously introduced in Section 2.1.2, may also be adopted in Step 4 (e.g., Caterino et al. [19]).

As another example, Caruso et al. [41,42] proposed a life cycle framework for the integrated assessment of buildings and the identification of the optimal retrofitting solution based on life cycle economic and environmental impact estimates, as well as the payback period (PB) of the retrofit investment and the average loss of life (AALL) due to earthquakes, as further discussed in other sections below. Similar to MCDM tools, another approach may consist of calculating such different metrics which are then normalised and represented on a unique radial graph, allowing for a graphical comparison between the considered options, as further discussed in Section 3.4. Similarly, González et al. [54] proposed a circularity assessment methodology. This system allows the graphic selection of the best option on the basis of multiple criteria, i.e., energy circularity (%) and total life cycle energy consumption (kWh of primary energy), materials circularity (%) and total materials consumption (kg of materials), water circularity (%) and total water footprint of the building (m^3), social added value (% of maximum achievable social impacts) and Life Cycle economic value, incorporating positive and negative externalities (EUR, USD or similar).

2.3. Classification and Rating Systems (Beyond SBR Framework Boundaries)

Some other tools available in literature are intended to assess various performances of buildings. However, different from the tools discussed in previous sections, they are usually adopted neither at a preliminary design stage, nor after the preliminary design of the retrofitting measurers, but only at the very end of the design process. They are aimed at classifying or rating buildings to have access to potential financial incentives, premiums or certificates. Those tools include classification systems which allow the definition of seismic classes, energy classes or combined seismic energy classes and the green building rating systems (GBRS), which are used to certify the sustainability of a building on the basis of credits in different disciplines (e.g., energy, indoor environment, water, material, waste, site, etc.). It should be noted, however, that, even if classes and rates are certified only at the end of the design process, they can also represent performance objectives to be included at the beginning of the design stage, i.e., in Steps 2, 3 and 4 of the SBR design framework.

Classification systems for buildings were introduced in the EU countries about 10 years ago following European directives aimed at reducing energy consumption of the building stock. Energy classes are calculated based on non-renewable energy consumption (expressed in kWh/m^2 per year) and are represented by an alphanumeric value, where A4 stands for the most energy efficient (lower energy consumption), and G represents the least energy efficient (highest energy consumption).

Similarly, a seismic classification of buildings was recently introduced in Italy to certify the seismic performance of a building, aimed at improving the resilience of the built environment against seismic risk [30,31]. In this case, the seismic risk class is calculated on the basis of both the AAL, i.e., in terms of monetary losses, and of a safety index, i.e., in terms of structural performance. The classes are expressed similar to the energy classification, with a letter from A+ to G. In Italy, both these tools were adopted by the government to provide financial incentives for the energy and seismic renovation of existing buildings in the framework of the Ecobonus and Sismabonus schemes. In both cases, it is required that the retrofitting intervention leads to a minimum of two classes of improvement.

More recently, Caruso et al. [41,42] proposed a combined seismic-energy classification system aimed at rewarding integrated interventions as opposed to non-integrated ones. This study will be further discussed in Section 3.6.

GBRSs are instead intended for the assessment and certification of buildings that meet certain green requirements or standards. According to the World Green Building Council (GBC), rating tools, often voluntary, recognise and reward companies and organisations that build and operate greener buildings, thereby encouraging and incentivising them to push the boundaries on sustainability. These tools are based on a credit system that allows the building of interest to acquire credits in different sustainability areas as long as some prerequisites are satisfied. The sum of those credits gives the total rating for the building on the basis of which a certificate of excellence is awarded. Some examples of GBRSs are the LEED, DGNB and BREEAM systems, among others. Considering combined seismic and energy assessment tools, Menna et al. [11] presented a review and a comparison of the three GBRSs above, concluding that in the current configuration they are still not satisfactory for the assessment of combined interventions, especially for areas prone to seismic risk and characterised by high energy demands.

Finally, another important framework that was recently introduced and represents the future reference for sustainability in the construction sector is the Level(s) framework [12]. Similar to GBRSs, it provides a set of indicators and common metrics for measuring the sustainability performance of buildings throughout their life cycle, assessing the following aspects: environmental performance, health and comfort, life cycle cost and value and potential risks to future performance. However, different from all the previously introduced tools, this framework guides designers and other stakeholders along the entire process, from the conceptual design to the building management. The framework is organised into three levels corresponding to three different stages of a building project, which define the level of detail to be used in the reporting on sustainability. Level 1 is the conceptual design of the building project, thus entailing early-stage qualitative assessments for the conceptual design and reporting on the concepts that designers intend to apply in the project. This level would correspond to Step 2 of the SBR framework. Level 2 represents the detailed design and construction performance of the building, entailing the quantitative assessment of the designed performance and monitoring of the construction according to standardised units and methods. Finally, Level 3 is the as-built and in-use performance of the building, and it entails the monitoring and surveying of activities both on the construction site and of the completed building. Levels 2 and 3 thus lay beyond the SBR framework boundaries. The Level(s) framework is by far the most updated method for the design of sustainable retrofitting solutions, including among its macro-objectives and indicators many of the LCT principles previously introduced. However, when considering safety and resilience, it only considers possible risks induced by climate change, disregarding the vulnerability of the existing building stock against other natural and manmade hazards, such earthquakes, hurricanes, flood, etc.

2.4. Integration of the SBR Framework in the Design Process

In Figure 6, the steps required to foster sustainability in building retrofitting (i.e., holistic assessment, pre-screening, schematic design, selection of best options) are integrated and merged within the traditional phases of the design process—i.e., assessment of the building in the as-is condition, schematic design, design development, construction documents and post-construction management.

As previously discussed, existing tools for the sustainable and holistic assessment of retrofitting solutions may indeed be applied at three different levels of the design process: at Step 2, before the preliminary design, to select a range of candidate solutions and discard unsuitable techniques; at Step 4, when the selected solutions are designed at a conceptual level and the components of the retrofitted systems are only preliminarily calculated, to aid the process of identification of the optimal solution; and at Step 6, to provide an official class or rating to certify the proposed retrofitting measure and obtain access to potential financial incentives. A final additional level related to the management and operational phase of the building is defined by the Level(s) framework.

The SBR framework [7] only considers phases from one to four: (1) assessment, (2) pre-screening, (3) design, and (4) choice, thus covering only the initial phase of the design process and disregarding other phases related to design development, classification and rating, construction and management, which are instead a fundamental (and complementary) part of the process. Namely, Step 6 is of critical importance since especially today, energy and seismic classes represent the most important financial leverage for the economic feasibility of renovation projects and define the performance targets for the actual design of structural and energy retrofitting interventions. It is noted, however, that rating systems may also be useful in defining possible sustainable performance objectives (Step 2) and providing tools for the assessment of economic, environmental and social metrics of alternative solutions (Step 4).

In the following sections, possible enhancements of the current state of the art are discussed with the aim of providing a contribution to the field of sustainability of the construction sector and to the advancement of Life Cycle Structural Engineering.

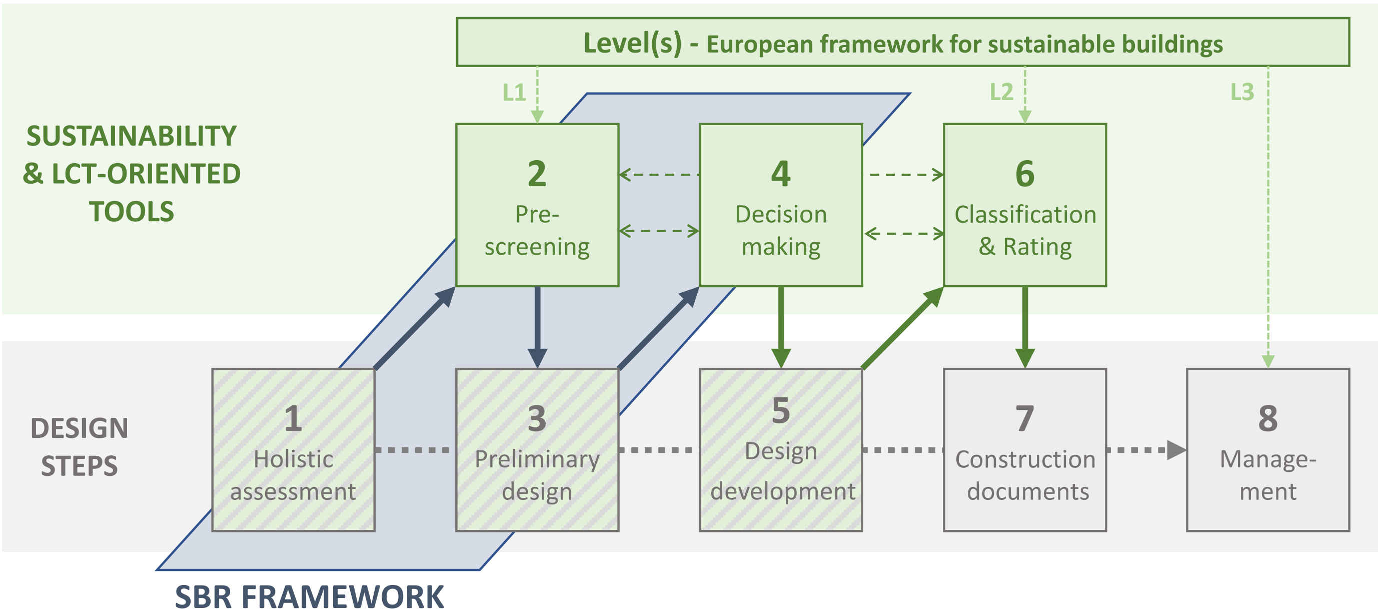

Figure 6. Visual representation of the workflow of a design procedure aimed at fostering the sustainability of the retrofitting intervention (steps 1 to 8) obtained by integrating SBR steps, sustainability and LCT-oriented tools, as well as Level(s) metrics and criteria, into the workflow of the traditional design procedure (commonly limited to steps 1, 3, 5, 7, 8).

3. Advancement in Life Cycle Structural Engineering (LCSE) Approach for Sustainable Construction

All the research endeavours reviewed in the previous sections are of utmost importance since they provide most of the tools that are needed to develop a comprehensive framework for the integrated assessment and retrofitting of buildings oriented towards sustainability. However, none of them individually comply with all sustainability targets for buildings (i.e., economic, environmental and social), given that they focus independently on the engineering process of integrated retrofitting techniques, the quantification of the environmental impact due to seismic risk, the implementation of 'ex post' assessment tools (thus, possibly enabling the adoption of unsustainable retrofitting techniques due to the lack of a pre-screening before the actual design phase) or the identification of relevant sustainability and LCT principles to be ideally included in the design process. In addition, most of these existing methods still find themselves at an academic stage of development and implementation and thus need to be further improved to be rendered fully suitable for actual applications. The main challenges to be addressed in future research are thus:

- Overcoming the sectorial and non-coordinated approach in current engineering applications by providing building engineers with guidance for a shift into a multi-disciplinary perspective with insights on earthquake engineering, energy efficiency, architecture, comfort, economy/finance and life cycle analysis, amongst others;
- Including pre-design evaluations in terms of specific performance targets oriented to sustainability and based on LCT principles to allow the consideration of sustainable retrofitting measures only from the very beginning of the renovation process;
- Meeting the current drive for a holistic and sustainable retrofitting of existing buildings in the EU through the definition of a standardised procedure for the identification of optimal retrofitting solutions based on sustainable LCT-based performance metrics and of a classification tool that will allow the introduction of new financial incentives for building renovation.

Given the gaps in the state of the art of the current literature highlighted above, the previously introduced new LCSE approach for sustainable construction is discussed herein in further detail based on the SBR framework [7] and improved by its integration and harmonisation with other available tools (e.g., Caruso et al. [41,42]). The major goal of this proposal is reconsidering the role of structural engineering in light of this new concept of sustainability and of suggesting a shared common methodology for the design of sustainable holistic interventions that will bring buildings into the circular economy, encouraging LCT and accounting for ecoefficiency, safety and resilience.

The workflow of the proposed LCT-based structural design framework is illustrated in Figure 6, covering all steps from the multi-performance assessment of buildings to the identification of the optimal renovation strategy (and consequent accessibility to financial incentives based on a novel integrated classification scheme). This LCSE approach to building renovation thus consists of multiple stages obtained from the integration of LCT-oriented tools (green boxes in Figure 6) into the steps of the design, which are revised to foster holistic renovation and include new LCT-based design objectives and targets (green and grey boxes in Figure 6): (i) multi-performance holistic assessment of the building in the as-built configuration; (ii) identification of retrofitting solutions that satisfy a suite of performance targets (through a pre-screening based on qualitative and quantitative performance criteria), including seismic resistance and energy efficiency, as well as other sustainable requirements; (iii) preliminary design of the retrofitting techniques identified in the previous step, including schematic design and preliminary proportioning of the retrofit components; (iv) selection of the optimal retrofitting strategy for the given building based on meaningful performance metrics; (v) design development of the selected optimal retrofitting solution according to new LCT-based design objectives and targets; (vi) use of tools/classification that facilitate accessibility to potential financial incentives; (vii) advanced design of the retrofitting solution and construction, adopting LCT-inspired technical detailing; and (viii) management of building in-use performance and its end of life. The first six steps of the proposed procedure are further described in the following sections in some detail.

3.1. Step 1—Multi-Performance Assessment

This step encompasses the assessment of the building in the as-is situation, evaluating possible deficiencies in all relevant areas (safety, energy, functional, comfort, etc.), as well as the societal and economic constraints of the intervention (e.g., occupants' relocation, urban planning, budget restrictions, etc.). This allows the clear identification of the major building needs under a holistic and multidisciplinary point of view, which in turn results in the selection of the minimum performance objectives to be targeted in the renovation process. To this end, traditional energy/acoustic performance assessment and structural/seismic vulnerability assessment may be adopted.

Feasibility of the retrofitting intervention as opposed to a demolition and reconstruction approach is also assessed with the analysis of the state of preservation, structural decay, residual service life and cost–benefit evaluations. Most existing buildings requiring renovation have exhausted or nearly exhausted their design nominal service life (typically 50 years), and their structural residual life should be assessed as a function of the possible degradation of the structural components and/or materials (in case of RC structures due to carbonation, corrosion, etc.) prior to carrying out important and expensive renovations. In some cases, demolition and reconstruction might be the only viable solution. A protocol to evaluate the level of deterioration of existing RC structures to include the presence of corrosion patterns in structural models and to estimate the residual life of RC buildings has been recently proposed by Casprini et al. [55].

In this first step of the framework, the main actors involved are design professionals and building stakeholders, whose collaboration is crucial to define the shared objectives of renovation.

3.2. Step 2—Pre-Screening of Retrofitting Solutions

According to the LCSE approach, the suitability of eligible retrofitting solutions (either coupled or uncoupled) is evaluated by analysing their specific features with respect to a set of requirements and constraints defined on the basis of the multiple building needs, LCT principles and possible barriers to renovation (e.g., inability to relocate the inhabitants during the construction works, low budget, etc.). By comparing different solutions based on qualitative and eventually quantitative estimations, designers and decision makers are enabled to select the best set of alternatives (and to discard those not complying with the envisioned criteria) from the very beginning of the design stage without carrying out unnecessary calculations, thereby optimising the design process in terms of time, resources and results. In fact, by applying this filter before the preliminary design phase, unsustainable solutions are discarded from the beginning of the process, while innovative holistic and sustainable solutions are encouraged. In addition, adopting an LC perspective in the renovation process will foster the proposal of new renovation models and the conceptual design of new technical solutions, such as the exoskeleton proposed in [6,18].

To make building renovation truly sustainable, concerted seismic risk mitigation and energy efficiency upgrading (i.e., aimed at reduced seismic expected losses and energy consumption) should be considered to enable an integrated reduction of running costs and environmental impacts throughout the building life cycle. Other performance objectives (as well as LCT and circular economy principles) are to be included while designing retrofitting strategies, examples of those being [7,34]:

- Design for material sustainability: limitation of raw material depletion, waste and pollution production, adoption of socially sustainable materials, i.e., limitation of life cycle impacts of construction materials from their extraction and manufacturing to their end-of-life stages;
- Design for easy assemblage: prefabrication and off-site production, standardisation and dry and modular techniques to reduce the impacts at the construction stage;
- Design for health, comfort and indoor environmental quality: quality of air, thermal comfort, amount of daylight and artificial light, acoustics, and accessibility to and quality of potable water are aspects that influence the physical (and sometimes also mental) health of building's occupants.
- Design for reparability: dry connections which act as structural fuses and are easily replaceable in case of damage;
- Design for durability: maintenance of acceptable performances over the building's life cycle, for instance, against deterioration phenomena (thus reduced need for maintenance);
- Design for adaptability and flexibility: ease of dismantling and replacement, adaptability to future building needs (e.g., change of building final use or property, implementation of advanced technologies, etc.) and to future climate change (extreme weather events, rising temperatures, floods, fires, etc.);
- Design for deconstruction: dry and modular techniques, easily demountable connections, standardisation, light materials to allow for an easy disassembly of the construction at the end of life;
- Design for recycle and reuse: prefabrication, standardisation, modularity, dry techniques, recyclable and/or reusable materials to allow for circularity of materials beyond the end of life of the building.

This pre-screening process according to such performance targets should be supported by the possibility of developing an inventory of retrofitting technical solutions (distinguished for building typologies, i.e., reinforced concrete, masonry, steel, etc.) classified on the basis of technical, economic, environmental and social features, which would represent a unique source of data for thousands of users. This would represent an enhancement of the classification proposed in the JRC project [8]. In other words, traditional and innovative retrofit techniques may be ranked in terms of their compliance with the envisioned targets (e.g., LCT principles, possible implementation in incremental rehabilitation plans, average environmental impacts and costs over the building life cycle and feasibility with respect to the renovation barriers). Techniques that do not satisfy all requirements (or that exceed specific quantitative thresholds) according to each building's needs and requirements may thus be discarded.

As already stated, all the MCDM tools previously introduced may be adopted for such pre-screening. The main actors in this step are design professionals and stakeholders (owners, investors, users) who are asked to provide requirements and constraints that would lead the design of the retrofit intervention. However, there may still be an insufficient awareness and training of producers and designers towards the performance targets above, thus a potential initial reluctance to include such principles in retrofitting solutions should be overcome. Moreover, simplified tools, ad hoc studied to be applied in this pre-screening step of the framework, are needed and currently under development.

3.3. Step 3—Preliminary Design of the Retrofitting Intervention

This step consists in the conceptual design and preliminary proportioning of the retrofitting solutions identified in Step 2 (or available in currently available or future inventories) and characterised by the same energy, structural, etc., performances. In the design phase, new paradigms and tools are adopted to design the most favourable alternatives. Preliminary design tools, such as design abaci and spectra (e.g., Labò for structural retrofitting [56]), can be adopted for the preliminary design of the retrofitting interventions and to obtain an indicative bill of materials to be used in the calculation of quantifiable sustainability indicators in Step 4.

In this step, the actors involved are design professionals of different disciplines who design the pre-selected retrofitting interventions to be compliant with the performance objectives defined in the previous steps of the design framework, having also in mind the final seismic/energy classes that are needed for the intervention to be eligible for financial incentives (Step 6). It should be noted that it is important that each selected retrofitting solution must entail the retrofitted building achieving the same performance levels to allow a fair comparison among different alternatives in the subsequent step.

3.4. Step 4—Selection of the Optimal Retrofitting Strategy

Existing tools for the choice of optimal retrofitting strategies can be integrated in this step (such as the ones discussed in Section 2.2.2). Among them, MCDM approaches are particularly efficient. For instance, the life cycle-based method proposed by Caruso et al. [41,42] can serve as a decision-making tool for buildings' retrofitting. Based on already existing life cycle assessment and life cycle costing analysis procedures, the tool allows the estimation of two life cycle performance metrics in terms of costs and carbon emissions, respectively, which include the contributions of retrofitting intervention (and consequent demolition of retrofitting materials), energy consumption and earthquake-induced damage and repair activities (with consequent downtime and possible need of occupants relocation) that may occur during the post-retrofit operational life of the building. The identification of the optimal retrofitting solution for a given building is proposed as the one that limits such running economic and environmental impacts through the post-retrofit life of the building, as well as the payback period of the retrofit investment and the average loss of life due to earthquakes. Figure 7 shows illustrative radar charts for a hypothetical building in three potential retrofitted configurations (seismic strengthening option, energy efficiency refurbishment, integrated intervention) in terms of these four decision variables, normalised to the as-built conditions. The optimal solution can be determined as the one associated to the smallest resulting area, i.e., the one that concurrently minimises all the relevant variables.

The tool has been conceived with the intent of introducing a novel criterion for the identification of optimal retrofitting solutions based on multiple and quantifiable performance metrics (including seismic and energy performance evaluations). Such performance metrics noteworthily include environmental, economic and social aspects, as envisaged in the new concept of building sustainability. Interestingly, the tool can be easily implemented to account for other performance metrics, such as those assessing comfort (depending on each building's needs and requirements, one may select air quality, acoustics, smart readiness indicator, etc.).

The main actors in this step are design professionals of different fields (e.g., structural, environmental, etc.), who evaluate the retrofitted configurations according to the performance metrics used for the choice of the optimal retrofitting solution for a given building.

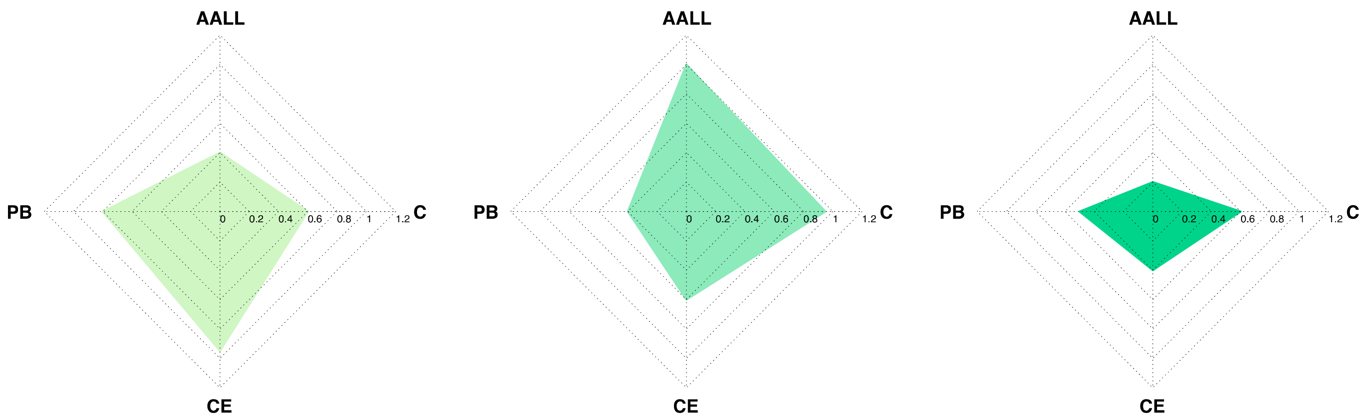

Figure 7. Normalised post-retrofit costs (C), carbon emissions (CE), payback period (PB) and average loss of life (AALL) of three hypothetical retrofitting configurations: seismic strengthening (**left**); energy efficiency refurbishment (**centre**); integrated intervention (**right**).

3.5. Step 5—Design Development

Once the optimal retrofitting intervention is identified, the detailing is conceived to guarantee the effectiveness of the intervention and actual compliance with the LCT principles that were defined just at a concept level in Steps 2, 3 and 4 (i.e., standardised connection typologies may be critical to enable easy assemblage, repair/replacement, selective dismantling, etc.). Maintenance management should be planned based on expected building performance after completion and handover to the client. As an example, if insulating panels are to be installed on the building envelope to improve energy efficiency, their connection to the structural system needs to sustain low intensity frequent earthquakes without damage. Therefore, specific and quite demanding design targets on the maximum lateral deformation capacity of both the insulating envelope and the structural system must be enforced. As another example, considering that work from the inside of the building may not be allowed, specific design targets may be required to limit the in-plane load demand on the existing floors to avoid the need of floor strengthening [6]. Similarly, the details of the structural system should be studied to avoid possible thermal bridges, which may reduce the efficiency of designed energy-saving measures.

In this step, the actors involved are design professionals of different disciplines who should collaborate to define the most sustainable and cost-effective details for the proposed combined intervention and as-built and in-use manuals.

3.6. Step 6—Classification Tool for Accessibility to Financial Incentives

Post-retrofit economic and environmental estimates as defined in Caruso et al. [41,42] can be used as a basis for a new potential seismic vulnerability—energy efficiency integrated classification scheme for building retrofitting, where one or more class upgrades are possible only if an integrated reduction of costs and carbon emissions is pursued (in other words, a reduction of costs or emissions alone would not always be sufficient for a class upgrade).

Figure 8 shows an illustrative example for the same hypothetical building above, assuming it to be located in central Italy, i.e., a region that is characterised by high seismic and energy demands. It is noted that seismic strengthening and energy efficiency refurbishment techniques alone produce a significant reduction of either running costs or emissions, whilst only the integrated option aimed at improving both seismic and energy performance ensures their concomitant reduction.

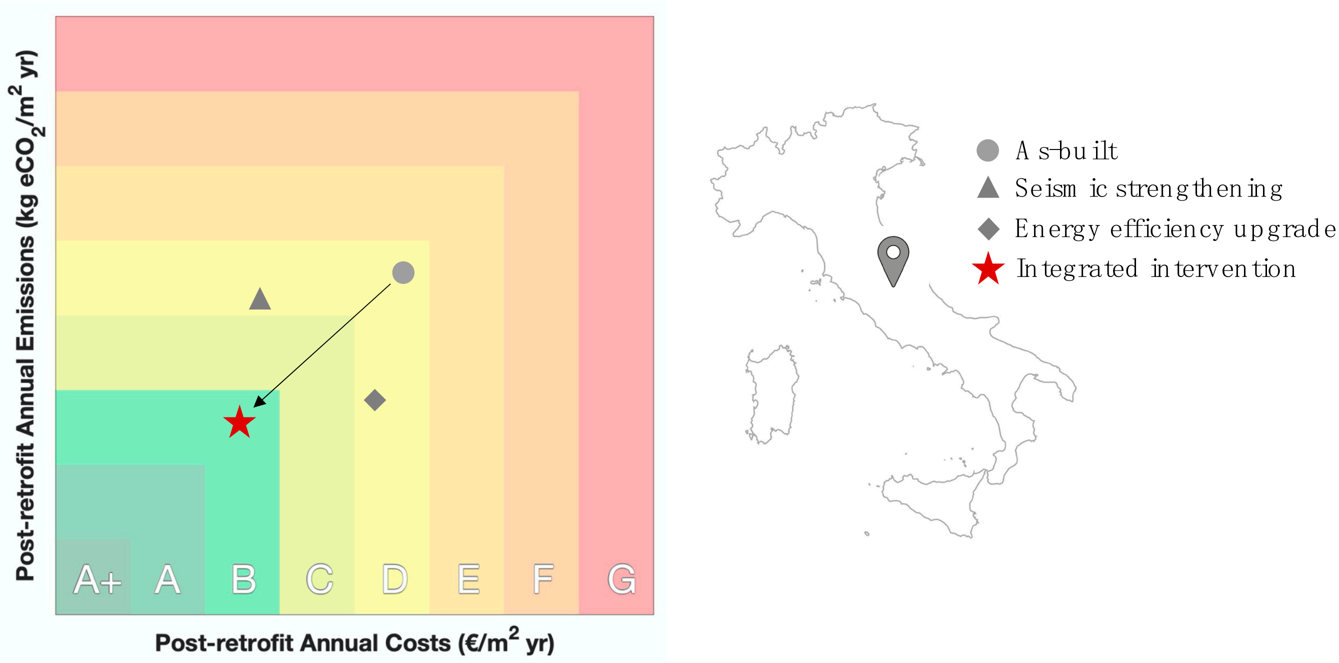

Figure 8. Potential seismic vulnerability—energy efficiency classification scheme for buildings.

It is clear how this proposed integrated economic and environmental building classification system encourages an integrated reduction of costs/impacts of the existing building stock and most notably may facilitate the definition and the accessibility to financial incentives for building retrofitting at a national or international level (and/or possibly also aid the definition of carbon taxes for buildings). However, defining value ranges of costs/impacts for classes is anything but a trivial task. It is expected that such economic and environmental value ranges might vary from one geographic location to another; thus the influence of seismic and climatic conditions at the site of interest will need to be explicitly addressed through extensive calibrating parametric studies involving a portfolio of case-study buildings of different structural/architectural typologies (reinforced concrete, masonry, steel, etc.) and with different destination uses (residential, educational, offices, etc.).

Further development of such a tool may envision the shift to a 3D classification graph, introducing the comfort-level axis to foster the adoption of retrofitting interventions pursuing sustainability, safety, resilience and human comfort.

4. Discussion

This study presents a framework aimed at operationalising the Life Cycle Structural Engineering approach for the sustainable renovation of existing buildings, which integrates and synthesises the recent research contributions in terms of sustainability. The steps of this framework are: (i) multi-performance holistic assessment of the building in the as-built configuration; (ii) identification of retrofitting solutions that satisfy a suite of performance targets (through a pre-screening based on qualitative and quantitative performance criteria), including seismic resistance and energy efficiency, as well as other sustainable requirements; (iii) preliminary design of the retrofitting techniques identified in step (ii), including schematic design and preliminary proportioning of the retrofit components; (iv) selection of the optimal retrofitting strategy for the given building based on meaningful performance metrics; (v) design development of the selected optimal retrofitting solution according to new LCT-based design objectives and targets; (vi) use of tools/classification that facilitates accessibility to potential financial incentives; (vii) advanced design of the retrofitting solution and construction, adopting LCT-inspired technical detailing; and (viii) management of building in-use performance and its end of life. The adoption of such an approach in actual engineering practices will require a robust shift towards an interdisciplinary perspective in building assessment and retrofitting, which would hopefully increase the resilience of the existing built environment against natural hazards and climate change.

The main novelties of the LCSE approach are:

- The introduction of LCT and sustainability principles in the design process of retrofitting strategies, with a view to foster the adoption of solutions that satisfy specific requirements;
- The definition of an LC-based procedure for the choice of optimal retrofitting solutions and of a classification tool that will allow the introduction of new financial incentives for building renovation;
- The implementation of a comprehensive framework that would aid the process of building retrofitting under several viewpoints, including structural safety, energy efficiency, comfort and architecture.

Future research needs to be aimed at the development of principles and tools that can assist in rendering the framework fully operational, including:

- The characterisation of relevant performance targets of different nature (e.g., structural safety, energy efficiency, comfort and architecture) that are all oriented to sustainability under economic, environmental and social perspectives;
- The classification of retrofitting techniques on the basis of qualitative and quantitative criteria representative of such performance targets, with a view to develop an inventory of solutions that will be made available to practitioners, ensuring the adoption of the best strategies for any building;
- The definition of a new tool for the pre-screening of alternative solutions on the basis of technical feasibility, depending on building features and restrictions, DM requirements and LCT principles;
- The definition of economic and environmental value ranges for the proposed classification tool, which entails an extensive parametric study on different building typologies located in different geographic sites;
- The implementation of new business models for financing retrofitting actions on buildings, including incentives and tax deductions for stakeholders, based on the new classification system.

5. Conclusions

The Next Generation EU recovery plan of EUR 750 billion represents an unprecedented resource to boost the modernisation of the existing building stock (to meet the target of the renovation rate of 4.4% [57], 35 million building units renovated by 2030). This envisaged so-called Renovation Wave [58] will boost the activities and hence financially aid small and medium enterprises (SMEs) that have been strongly affected by the economic crisis following the COVID-19 pandemic, and it is also expected to give rise to an additional 160,000 green jobs in the EU construction sector.

The transition towards a more sustainable society envisioned by current policies requires a comprehensive renovation of existing buildings under varied perspectives, including structural safety, energy efficiency, comfort and architecture. However, today, uncoupled interventions are still financed with public incentives. It is thus within the above context that this study presents a redefinition of the Life Cycle Structural Engineering approach for sustainable construction and a comprehensive review of available methods and tools for the application of the LCSE approach, which are focused on the inclusion of sustainable and LCT principles in the retrofitting design process, the integration of seismic loss estimation and environmental impact assessment and the implementation of integrated retrofitting strategies. Such a review highlighted potentials and weaknesses of current approaches, and the major research needs to make the LCSE approach operable in actual engineering practices. However, the greatest ambition of the proposed methodology is to foster a paradigm-shift for building engineers towards an interdisciplinary perspective in building assessment and retrofitting, including aspects related to structural engineering, energy efficiency, life cycle analysis, architecture, environmental impact, sustainability and financing tools, amongst others. The LCSE approach aims indeed at introducing LCT and sustainability principles from the very beginning of the design process, providing LC-based procedures for the identification of optimal retrofitting solutions and implementing a new classification tool for existing buildings.

According to this new approach, a sustainable retrofitting strategy is conceived from the beginning to minimise the economic, environmental and social impacts along the whole building life cycle while also maximising performances. To this aim, the principles of LCT and the circular economy, the need to overcome the main barriers to renovation and the specific needs of decision makers are addressed before the final design of possible retrofitting alternatives. In addition, such a methodology will also contribute to the increase of the resilience of the existing built environment against both natural hazards and climate change.

The above said, it is acknowledged and recognised that the operational development of the proposed framework is still needed, with a view to: (i) define LCT principles and provide an inventory of retrofitting solutions and technological details that comply with relevant performance targets including seismic resistance and energy efficiency, as well as other LCT-based sustainable requirements (e.g., eco-efficiency, durability, adaptability to future needs, indoor air quality, etc.); (ii) introduce a new simplified tool for the pre-screening of alternative solutions adaptable to buildings having different needs and requirements; and (iii) introduce a classification tool based on economic and environmental value ranges that will facilitate the accessibility to potential financial incentives for building retrofitting (and also possibly aid the definition of carbon taxes for buildings).

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