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REEBUILD Integrated Techniques for the Seismic Strengthening and Energy Efficiency of Existing Buildings

Methodologies for the assessment of the combined seismic and energy retrofit of existing buildings: a new simplified method and application to case studies

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Integrated Techniques for the
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Methodologies for the assessment of the combined seismic and energy retrofit of existing buildings: a new simplified method and application to case studies

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Foreword

Our buildings are ageing, posing an urgent need for renovation to align with the goals of multidimensional European and international policies. The built-up area in Europe covers 25 billion square meters, 10 billion of which were constructed before 1960 and 20 billion before 1990. It is worth noting that 40% of the European Union (EU) building stock is located in seismic prone regions and was built without modern seismic design considerations. Apart from Member States with moderate and high seismic risk, such as Greece and Italy exhibiting a severe impact (i.e. fatalities, injuries, and economic losses) from earthquakes during the last decades, attention should be drawn to regions with lower risk, e.g. in France and Spain. At the same time, buildings stand out as one of the most energy consuming sectors, therefore having a negative environmental impact. In fact, buildings are responsible for 40% of EU energy consumption and 36 % of the EU total CO_2 emissions, whereas 75 % of the EU existing building stock is considered energy inefficient. The highest amount of energy use in buildings derives from the operational stage of their life time (e.g. heating, cooling), resulting in a significant source of carbon emissions with detrimental effects on climate change.

Notwithstanding this negative impact, the building sector provides a unique opportunity to create, through risk-proofed renovation, a safe, sustainable, and resilient built environment which promotes wellbeing and economic growth, and ensures that EU energy and climate targets are met. In this context, the European Parliament entrusted the European Commission's Joint Research Centre with the two-year pilot project "Integrated techniques for the seismic strengthening and energy efficiency of existing buildings" or REEBUILD.

REEBUILD aims to define technical solutions that can reduce seismic vulnerability and increase energy efficiency of existing buildings, at the same time and in the least invasive way. Thereby, increased earthquake resilience and limited environmental impact of buildings is sought by protecting life, economy and the environment. The project has the following key-objectives:

- Define the tools and guidelines to reduce, all at once, vulnerability and energy inefficiency of buildings.
- Stimulate the use of integrated solutions.
- Create awareness about the topic in the aim of prevention.
- Increase resilience of the built environment to seismic hazard and climate change.

The geographical scope of the project covers EU seismic prone regions. However, all EU citizens are potential beneficiaries of the project since it can easily be extended to all EU regions considering the ageing of existing buildings and other hazards, including extreme climatic events.

In a policy context, REEBUILD provides scientific advice to support the development of an action plan, which shall supplement existing European Union policies and initiatives in the field of buildings' renovation. Crucially, the European Green Deal (COM (2019)640) emphasises the need for a Renovation Wave (COM (2020)662), supported by the New European Bauhaus ([1]) (COM (2021)573) to create sustainable, inclusive and beautiful living spaces. The plans to put the European Green Deal into effect further contribute to the economic recovery following the COVID-19 pandemic. In the Energy Performance of Buildings Directive (Directive 2018/844) and the recent proposal for its revision (Proposal COM (2021)802), besides reducing greenhouse gas emissions, measures related to seismic risk and fire safety are encouraged for planning long-term renovation strategies. The implementation of clean and circular economy principles for the construction sector to achieve a climate-neutral society by 2050 are stressed in the new Circular Economy Action Plan (COM (2020)98) which also addresses the revision of the Construction Products Regulation (Regulation (EU) 305/2011). The new idea for a holistic approach to the renovation of buildings is in line with the Union Civil Protection Mechanism (Decision (EU) 2019/420), with respect to disaster prevention measures and the integration of risk reduction and cohesion policies. Likewise, the Action Plan on the Sendai Framework (Commission SWD 2016/205) encourages investment in disaster risk reduction, integrating "Build Back Better" principles for a more resilient built environment. The European Framework for Action on Cultural Heritage (Commission SWD 2018/491), emphasises the need to safeguard cultural heritage against natural disasters and climate change, and relevant measures are encouraged when planning long-term renovation strategies and national disaster risk reduction strategies. The above policies and initiatives contribute to the implementation of the 2030 Agenda for Sustainable Development ([2]) (UN, Resolution 2015/A/Res/70/1) and the Sustainable Development Goal (SDG) 11 "Make cities and human settlements inclusive, safe, resilient and sustainable".

([1]) New European Bauhaus, https://europa.eu/new-european-bauhaus/index_en

([2]) Sustainable Development Goals (SDG) Policy Mapping tool, https://knowsdgs.jrc.ec.europa.eu/intro-policy-mapping

Integrated retrofitting of existing buildings can be seen as a nexus between policies improving the disaster resilience of the EU, encouraging the energy renovation of buildings, promoting circularity within the building sector, and protecting cultural heritage.

Several activities were foreseen to achieve the REEBUILD objectives. EU buildings requiring upgrading were identified, and existing seismic and energy retrofit technologies were assessed in a life-cycle perspective. Combined retrofit solutions were explored based on available technologies and recent scientific developments in the field. A simplified method for the assessment of the combined upgrading was proposed and applied to case studies of representative building typologies retrofitted with the identified solutions. Seismic risk and energy performance of buildings along with socioeconomic aspects were assessed at regional level throughout Europe. Such regional assessments were used to identify appropriate intervention scenarios based on their regional impact and highlight the regions where interventions are of higher priority. National, regional and local authorities, industrial associations and expert communities were involved in enquiries and discussions of relevant implementing measures (legislation, incentives, guidance and standards), technologies and methodologies for the combined upgrading of existing buildings. Dissemination and outreach is further supported by reports, a web platform and public communication material. REEBUILD activities were organised in five main actions:

1. Overview and classification of technologies for seismic strengthening and energy upgrading of existing buildings
2. Analysis of technologies for combined upgrading of existing buildings
3. Methodologies for assessing the combined effect of upgrading
4. Regional impact assessment and contributions to an action plan
5. Stakeholders' engagement.

This report deals with the main results carried out within Action 3, presenting an overview of the existing assessment methodologies for the combined seismic and energy retrofit of the existing buildings and introducing a simplified combined assessment method based on a multi-performance, life cycle thinking (LCT) approach. An existing standard assessment method and the proposed simplified one are also applied to four case studies representative of European residential and non-residential buildings needing combined seismic and energy retrofit.

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Abstract

The urgent need to accelerate the renovation rate of the European built environment, making it more energy-efficient and less carbon intensive over its entire life cycle, is a key-priority in the European Union (EU) to mark a turning-point towards the climate-neutrality goal by 2050. Furthermore, the existing building stock in the EU seismic prone regions also suffers from seismic vulnerability leading to significant social and economic impacts due to the extensive damage or collapse of buildings, as demonstrated by past and more recent earthquakes (e.g. 1999 Athens, 2009 L'Aquila, 2012 Emilia Romagna, 2016 Central Italy). Hence, the effort to consider an integrated approach for making existing buildings simultaneously safe and sustainable is of paramount importance. In this framework, the pilot project '*Integrated techniques for the seismic strengthening and energy efficiency of existing buildings*' or REEBUILD aims to define retrofit solutions able to achieve the reduction of seismic vulnerability and the increase of energy efficiency of the EU existing building stock, at the same time and in the least invasive way. This holistic approach consequently leads to significant environmental benefits by reducing the carbon dioxide (CO_2) emissions and the waste generated by means of building replacement actions, as well as minimises economic losses and fatalities due to future earthquake disasters, supporting several EU polices related to the sustainable renovation of buildings.

This technical report presents the study carried out within the Action 3 'Methodologies for assessing the combined effect of upgrading' of REEBUILD project, introducing a simplified integrated method for the assessment of the combined seismic and energy retrofit of existing buildings, along with their environmental performance, in a life-cycle perspective by achieving a global assessment result in economic terms. The development of a user-friendly method to assess the potential improvements achieved in a combined renovation project is essential to ease and speed up the knowledge of benefits that different stakeholders e.g. owners, industry, policy makers, etc., can gain by combining seismic safety and energy efficiency retrofit technologies, thus overcoming renovation barriers, such as intervention cost, execution time, inhabitants' relocation, institutional and administrative issues. A review of the existing methodologies for the seismic and energy retrofit assessment of existing buildings is first carried out, serving as a state-of-the-art for proposing the simplified combined assessment method. Specifically, two key-streams of available methods and tools are investigated: (i) sector-specific methods, focusing on methods and tools devoted to the independent assessment of either seismic or environmental/energy performance of buildings, and (ii) multi-performance methods, including sustainability assessment methods and tools, mainly focused on qualitative procedures (i.e. sustainability rating systems based on indicators of different weight), and integrated methodologies developed in the last years to provide a quantitative holistic life cycle-based assessment. Within the latter category of the analysed existing assessment methods, the Sustainable Structural Design (SDD) methodology, developed in the framework of the SAFESUST (SAFEty and SUSTainability) approach results particularly noteworthy. Hence, it is considered as point of reference to introduce a simplified combined assessment method, consisting of four main steps, namely (i) input information, (ii) selection of techniques, (iii) integrated retrofit design and evaluation, and (iv) optimised solutions. Finally, four case studies referring to EU representative residential and non-residential building typologies needing combined seismic and energy retrofit are identified in order to apply both the selected standard (i.e. SSD methodology) and the proposed simplified combined assessment method.

1 Introduction

The exponential population growth and the increase of the global energy consumption with its related carbon dioxide (CO_2) emissions, as well as the intensification of natural disasters with their consequent fatalities, and economic losses, represent unsustainable trends still affecting the Planet. Geophysical disasters were responsible of 1.3 million people death and further 4.4 billion people injured, homeless, displaced or in need of emergency assistance between 1998 and 2017, with earthquakes showing the highest percentage (i.e. 56%) of fatalities (UNISDR, 2018). Although the most consolidated definition of Sustainable Development, as the *'development that meets the needs of the present, without compromising the ability of future generations to meet their own needs'* (Brundtland, 1987), was pointed out more than three decades ago, the figures above underline that sustainability is still a global challenge and a radical change of direction is needed to help lessen the huge burdens produced on the Planet.

The built environment plays a key-role in this context, since it is responsible of various impacts produced on the three dimensions of sustainable development – Environment, Economy, Society – also known as the Triple Bottom Line (TBL) – Planet, Profit, People (Elkington, 1997). The challenge of renew and plan cities and human settlements in a safe, inclusive and resilient way satisfying the sustainable urban development and management is one of the 2015 United Nation Sustainable Development Goals (UN SDGs) (UN, Resolution 2015/A/Res/70/1). In line with the international actions, the achievement of a sustainable building sector is recognised as a fundamental goal also at European level in order to meet the climate-neutrality by 2050, with a particular focus on the existing building stock, since 85-95% of buildings that exist today will still be standing in 2050 (COM (2020)662). Indeed, the European existing building stock, considering both residential and non-residential segments, accounts for 25 billion square meters of built-up area (BPIE, 2011) of which 20 billion erected before 1990, thus representing ageing built environment compliant neither with the recent energy efficiency regulations, nor with modern seismic design code requirements. The achievement of an energy-efficient built environment by boosting renovation solutions for obsolete and ageing buildings is a high-priority issue for Europe, as it represents not only an effective key to meet the EU ambitious energy and climate targets, but it can also generate economic and social benefits, fulfilling the sustainable development principles. However, the annual energy renovation rate of the EU building stock is still very low, being equal to only 1%. Thus, the European Commission has recently emphasised the need for a large-scale upgrading of the EU existing building stock in line with the Renovation Wave strategy (COM (2020)662) within the European Green Deal priority (COM (640)2019). These strategies aim to ensure that the building sector effectively plays its fundamental role in meeting the EU climate and energy ambitious targets of both reducing the greenhouse gas (GHG) emissions by at least 55% below 1990 levels by 2030 and achieving the overarching goal of climate-neutrality by 2050, legally enshrined by the first European Climate Law (Regulation 2021/1119) and to be implemented via the 'Fit for 55' legislative package ([3]) (COM (2021)550). The recent proposal for the revision of the Energy Performance of Building Directive (EPBD) (Proposal COM 2021/802) also supports these objectives, updating the existing regulatory framework to reflect higher ambitions and more pressing needs in climate and social action through the increase of the rate (at least double, as set in the Renovation Wave strategy) of the annual energy renovation of the EU existing building stock by 2030 and the promotion of deep renovations to make buildings more resilient and accessible. Moreover, the revised EPBD will complement the building-related provisions included in other 'Fit for 55' initiatives, such as the request to Member States to renovate at least 3% of the total floor area of all public buildings annually or the introduction of a separate emission trading for building fuels in the proposals to revise the Energy Efficiency Directive (Proposal COM (2021)558) and the EU Emission Trading system (EU ETS) (Proposal COM (2021)551), respectively. However, any action aimed at achieving exclusively the optimisation of energy performance of existing buildings without simultaneously addressing structural safety could be a business dead-end, mainly in seismic prone regions. In the case of an earthquake, the damage due to an inadequate seismic performance of buildings may yield considerably high economic, environmental, and social impacts, as demonstrated in recent earthquakes, also leading to a high likelihood of the loss of energy retrofit interventions, if any. Emblematic examples in this direction refer to the aftermath of the 2012 Emilia earthquake (in Italy) showing various damaged buildings characterised by broken new high-performance windows and solar panels, as well as wrecked thermal insulation elements clustered on top of their ruins (Marini et al., 2014).

This picture significantly alerts towards the need of an integrated seismic and energy retrofit of existing buildings, considering that uncoupled approaches are ineffective in fostering a sustainable transformation of the EU existing building stock (Belleri and Marini, 2016; Passoni et al., 2021). Conversely, retrofit strategies

([3]) Fit for 55 Package, Press release (14 July 2021), https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541 aimed at enhancing simultaneously both the seismic and energy performances of an existing building result into long-term incisive solutions. Indeed, the integrated seismic and energy renovation of buildings currently represents a prevention action that is crucial to increase the sustainability of our towns (La Greca and Margani, 2018). However, different barriers still impede an effective integrated renovation of existing buildings to improve all at once their various potential deficiencies with the final aim to foster safety and resilience of built environment. According to BPIE (2011) and La Greca and Margani (2018), the main obstacles affecting the building renovation concern economic barriers (e.g. high cost of retrofit intervention, insufficient fiscal incentives and/or subsides), technical obstacles (e.g. ineffective conventional retrofit technologies), building functionality barriers (e.g. disruption time, occupants' relocation, etc.). Furthermore, institutional and administrative barriers, mainly regarding potential regulatory and planning issues, as well as information and cultural barriers may slowdown renovation interventions. In addition to the renovation barriers, in the last years another emerging challenge at the forefront of the scientific community to further develop integrated retrofit strategies refers to the implementation of Life Cycle Thinking (LCT) principles at the beginning of the design procedure to conceive a truly sustainable LCT-based solution, instead of using post-design life cycle tools (Passoni et al., 2022).

In the above context, the pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or REEBUILD was launched to put forward a simplified holistic approach to enhance simultaneously the seismic safety and energy efficiency of the existing European building stock and to stimulate the use of integrated solutions in a life cycle perspective. Once the need to foster an integrated seismic and energy retrofit of the EU existing building stock is recognised (Romano et al., 2023), a fundamental step to facilitate the integrated renovation of buildings deals with the development of adequate assessment methodologies. These methodologies aim to assess the enhanced performances of the retrofitted buildings in an effective and streamlined way, providing the corresponding results in a simplified language, such as economic terms, which allows different stakeholders to easily recognise the importance of implementing such a renovation strategy.

This report aims to introduce a simplified integrated method to assess the combined seismic and energy retrofit of the EU building stock in a life cycle perspective, along with its application to representative EU buildings to provide a user-friendly tool aimed at tangibly demonstrating the benefits gained by an integrated seismic and energy renovation. Following this introduction, Section 2 provides an overview of the existing assessment methodologies for the combined seismic and energy retrofit of existing buildings. Two key-streams of assessment methods are analysed: (i) *sector-specific methods*, which include two main categories of assessment methods, namely seismic loss estimation methods, and conventional Life Cycle Assessment (LCA) and Life Cycle Energy Assessment (LCEA) methodologies, and (ii) *multi-performance assessment methods* and tools, which include qualitative (i.e. sustainability rating systems) and quantitative integrated methods. Based on the review above, Section 3 introduces a novel simplified method for the assessment of the combined seismic and energy retrofit of existing buildings based on a LCT approach. The proposed method aims to satisfy specific requirements grouped into three main categories related to (i) general principles of sustainable development, (ii) technological characteristics of both seismic and energy retrofit technologies, and (iii) engineering computation addressing the computational step of the proposed method. The various requirements are first presented for each category. Subsequently, the framework of the proposed simplified combined assessment method is introduced by analysing its four main steps: (i) Input information, (ii) Selection of techniques, (iii) Integrated retrofit design and evaluation, and (iv) Optimised solutions, with a particular focus on the third step representing the computational core of the method and enabling the assessment of the seismic, energy and environmental performances into equivalent costs in a life cycle perspective. Section 4 focuses on the identification of four case studies, indicative of EU representative residential and non-residential buildings needing combined seismic and energy retrofit. An investigation on case-studies categories and location is presented to select four existing buildings to be retrofitted to simultaneously enhance their seismic performance and improve their energy efficiency. Subsequently, a selected standard, i.e. the Sustainable Structural Design (SSD) methodology, and the proposed simplified combined assessment methods are applied to the four case studies in order to assess their seismic, energy, and environmental performances before and after the retrofit. Besides assessing the integrated retrofit benefits, the applications of the two methodologies serve as a comparison key of their feasibility and ease of use. Final remarks and conclusions are summarised in Section 5, also providing potential future developments and further fine-tuning of the proposed simplified combined assessment method.

2 Assessment methodologies for the combined seismic and energy retrofit of existing buildings

2.1 State-of-the-art of existing assessment methodologies for the combined retrofit

Independent retrofit strategies, mainly focused on either seismic or energy retrofit, are still the most common approaches for building renovation, when the demolition and reconstruction alternative can be discarded, thus partly avoiding various detrimental impacts on the TBL of sustainable development, including exploitation of raw materials, demolition and reconstruction waste, high costs, occupants' relocation, among others. These strategies can be referred to as *sector-specific methods*, based on uncoupled assessment methods, aimed at evaluating either the seismic or the environmental/energy performance of an existing building before and after the retrofit intervention. It is evident that an ineffective building renovation is achieved in case of a single-performance retrofit because the investigated building remains either unsafe or energy consuming, depending on the adopted strategy. Unsustainable solutions over time are envisaged in this direction with consequent huge life-cycle environmental, economic, and social burdens.

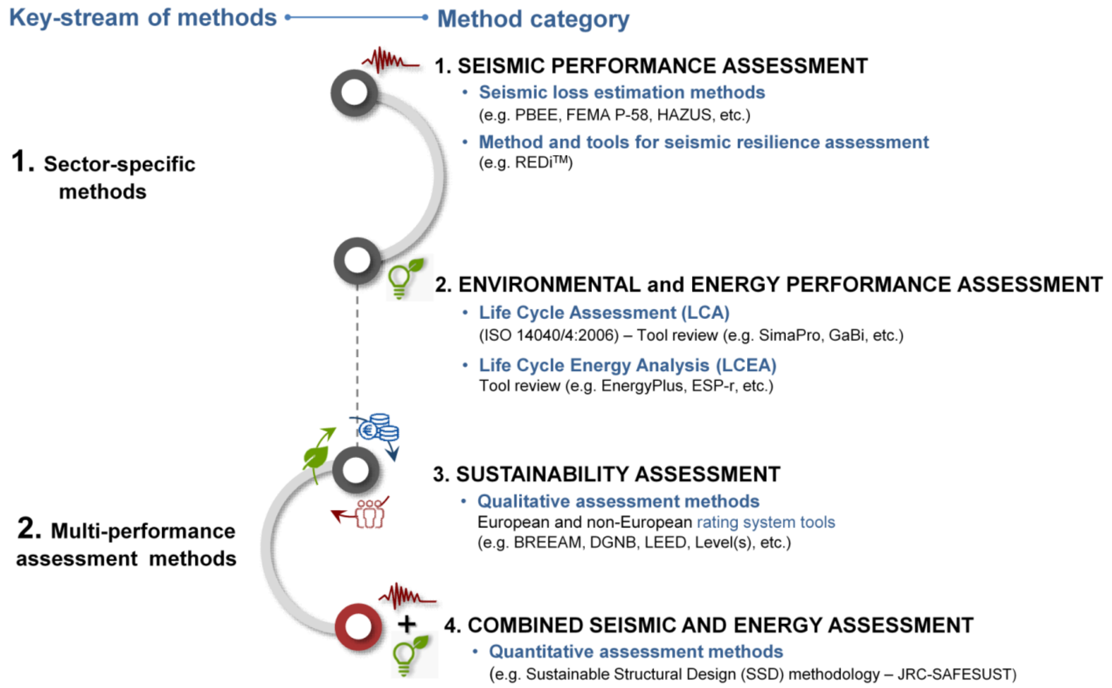
In the perspective of a sustainable and resilient built environment, the importance of considering multi-performance design/assessment methodologies has arisen in the last decades due to the awareness that a radical change of direction was essential by considering a building as a multi-performance whole (COST Action C25, 2011a; b; Landolfo et al., 2011) with different potential deficiencies, as underlined by recent studies aimed at emphasising the need for an integrated retrofit (Belleri and Marini, 2016; Passoni et al., 2021). Specifically, a first tentative to face the issue of the fast increasing market demand for sustainable solutions in the construction sector led to the development of new and more practical approaches based on rating systems, founding their roots in 1990s, to provide potential investors, clients, and other stakeholders with an indication of the sustainability level of a specific building (COST Action C25, 2011a). However, these tools essentially enable a qualitative assessment based on indicators of different weight, generally focusing only on environmental aspects, although an effort to update some tools by including economic and social aspects was made over time. Furthermore, these rating systems rarely encompass indicators related to structural safety. Hence, they result quite limited in terms of multi-performance assessment. Since the last decade the importance of developing quantitative methods aimed at assessing different building performances has led the scientific community to develop integrated life-cycle based approaches, some of which focus on coupling the seismic and energy performance assessment of buildings in a LCT perspective.

In this context, the outline of the available methods and tools can be grouped in two key-streams: (i) sector-specific methods, and (ii) multi-performance assessment methods, which together define the following four main categories of assessment methods:

- **Key-stream 1 - Sector-specific methods**, which include the two following categories of methods:
  1. Methods for seismic performance assessment (Section 2.1.1).
  2. Methods for environmental and energy performance assessment (Section 2.1.2).
- **Key-stream 2 - Multi-performance assessment methods**, which encompass the two following categories of methods:
  3. Methods for sustainability assessment (Section 2.1.3).
  4. Combined methods for seismic and energy performances assessment (Section 2.1.4).

Although the first key-stream of methods addresses separately the seismic and energy performance assessment, it is useful to also review this class of methods since the development of the majority of quantitative combined/integrated methods is based on existing consolidated procedures devoted to assess either the seismic or the energy/environmental performance of buildings. A detailed review and analysis of the various methods and tools included in each of the four categories above (Figure 1) is presented in the following.

Figure 1. Outline of the examined assessment methods



Source: JRC

2.1.1 Methods for seismic performance assessment

The first category of the examined assessment methods refers to seismic performance assessment methods and tools. This category can be further subdivided into two main sub-categories: (i) seismic loss estimation methods, and (ii) methods and tools for seismic vulnerability and resilience assessment. The former sub-category includes a class of quantitative methods and tools, focused on the so-called Performance-Based Earthquake Engineering (PBEE) approach (Gunay and Mosalam, 2013), which broadly consists of four main steps: hazard analysis, structural analysis, damage analysis, and loss analysis. The latter sub-category encompasses resilience-rating systems, which provide the possibility to enlarge the seismic vulnerability assessment of a building to the post-disaster functionality beyond the loss-assessment. According to the proposed classification, specific methods and tools are considered for each of the two aforementioned sub-categories and they are briefly analysed in the following.

2.1.1.1 Seismic loss estimation methods

The seismic performance assessment of an existing building is essentially devoted to twofold objectives, namely (i) the evaluation of potential negative effects of seismic events occurring on a specific structure, and (ii) the identification and application of the relevant strategies for the seismic retrofitting (Flora et al., 2021). In this context, the importance of focusing not only on preventing damages of structural and non-structural components, limiting potential damages, or ensuring life-safety depending on earthquake intensity, as in traditional earthquake design philosophy, but considering a performance-based approach, in which the expected losses (e.g. economic losses due to downtime, repair costs, etc.) become key-parameters to quantify and compare the building performances in its reference life, has been underlined in the last three decades. To this end, a first generation of PBEE design and assessment procedures for buildings was developed in the United States of America (USA) leading to remarkable outcomes, such as Vision 2000 report (SEAOC, 1995), FEMA 273 (1997), followed by other important pioneering PBEE efforts including FEMA 356 (2000). In these documents, the PBEE is framed as a methodology to assure combinations of desired system performance at various intensity levels of seismic hazard. Specifically, in the Vision 2000 report performance is expressed in terms of a series of discrete performance levels identified as Fully Operational, Operational, Life Safety, and Near Collapse, slightly modified into Operational, Immediate Occupancy, Life Safety, and Collapse Prevention by FEMA 356. However, various shortcomings were identified in these procedures, mainly related to engineering demands (Moehle and Deierlein, 2004). Furthermore, the performance levels defined in these first-generation documents were often qualitative, not well defined and, consequently, open to subjectivity

(Ramirez and Miranda, 2009). Hence, the need to develop a next generation of PBEE assessment methodologies arose in the late 1990s. Two types of loss estimation methodologies can be considered in this direction, namely (i) building-specific methods, and (ii) regional methods.

As for the **building-specific seismic loss estimation** methodologies, the PBEE developed by the Pacific Earthquake Engineering Research Center (PEER), i.e. PEER-PBEE, as evolution of the FEMA 273, represents one of the most robust methodologies to assess the seismic performance of a facility in terms of one of the three following main metrics useful for stakeholders' decision-making process: (i) Deaths (loss of life), (ii) Dollars (economic losses), or (iii) Downtime (temporary loss of use of the facility), the so-called 3 D's (Cornell and Krawinkler, 2000, Porter, 2003). However, the process to estimate these losses can become complicated because of the type and amount of required computations. Hence, the challenge of moving forward the frontier of the PEER-PBEE approach by developing methodologies and tools accessible to engineering practice led to the development of simplified PBEE methodologies with the most consolidated, but not limited, example referring to the FEMA P-58 methodology (FEMA, 2018a). Proposals to further simplify the approach, by replacing the fully probabilistic formulation by simple equivalent piecewise summations were also introduced (Contini et al., 2008; Negro and Mola, 2017). Currently, research studies in this direction continue to be very fervid (e.g. Cardone and Perrone, 2016; Flora et al., 2021, among others). In the context of a broader view of existing PEER-PBEE simplified approaches, it is worth mentioning also the Italian guidelines for seismic risk assessment of constructions based on the calculation of the expected annual losses (EALs), first issued in 2017 (Ministerial Decree 28/02/2017) and last modified in 2020 (Ministerial Decree 09/01/2020). These guidelines define the general principles and the technical rules, also validated in Cosenza et al. (2018), to exploit tax deductions, currently up to 110% (Decree law 34/2020; Law 234/2021), for seismic strengthening interventions on private buildings (i.e. the so-called 'Sisma Bonus' mechanism). The latter can also be combined with retrofit interventions to improve the energy efficiency of existing buildings (i.e. the so-called 'Eco Bonus' mechanism) representing a tangible example on the activation of fiscal incentives by national governments to foster the integrated renovation of the building environment at large-scale.

The **regional loss estimation** methodologies attempt to quantify losses for a large number of buildings within a specific geographic area. A brief literature review of the initial studies to develop these approaches is provided in Ramirez and Miranda (2009). Although the first studies in this direction date back to the '70s, significant research results were achieved two decades later with the development of a geographic information system (GIS)-based regional loss estimation methodology implemented in a dedicated tool, i.e. Hazard US (HAZUS). This tool follows an approach similar to the PEER-PBEE methodology, but it includes additional losses connected to damage to lifelines, and considers further risks, such as inundations, fire, etc.

2.1.1.1.1 Building-specific seismic loss estimation methods

Two of the most consolidated building-specific seismic loss estimation methodologies, i.e. PEER-PBEE and FEMA P-58, are briefly presented, as follows:

- The **PBEE methodology**, established by PEER with various developments between 1997 and 2010, is a fully probabilistic framework due to the inherent uncertainty and variability in seismic response, that uses the results from seismic hazard analysis and response simulation to estimate damage and losses incurred during earthquakes. The PEER-PBEE methodology consists of the following four consecutive analysis steps (Cornell and Krawinkler, 2000; Moehle and Deierlein, 2004):

    1. **Hazard analysis** – The first step of this procedure carries out the calculation of the frequency with which the intensity of a ground motion, described by the *Intensity Measure (IM)*, is exceeded. Traditionally, the spectral acceleration has been used as IM for its simplicity and easiness of computational work and the analysis is performed probabilistically through the Probabilistic Seismic Hazard Analysis (PSHA). The output of a PSHA is a seismic hazard curve that shows the relation between an IM and its annual frequency of exceedance (λ(IM)).

    2. **Structural analysis** – Based on the outcome of the first step, i.e. IM, the second step deals with the structural simulation to compute the *Engineering Demand Parameters (EDPs*), which characterise the response of a facility in terms of deformations, accelerations, induced forces, or other appropriate quantities. Focusing on buildings, the EPDs generally refer to inter-storey drift ratios (IDR), floor acceleration spectra, and inelastic component deformation.

    3. **Damage analysis** – The third step relates the outcome of the second step, i.e. EPD, to the *Damage Measures (DMs)*, which indicate the damage to structural and non-structural

components, and contents, to quantify the corresponding repair interventions, disruption of function, and safety hazards.

4. **Loss analysis -** The last step consists of computing the seismic performance metrics in terms of three categories of losses (i.e. direct monetary loss, downtime loss, and life loss), referred to as *Decision Variables (DVs)*, since they are useful to different stakeholders in the decision-making process.

The framework of PEER–BPEE methodology above can be expressed in terms of a complex triple integral based on the total probability theorem (Cornell and Krawinkler, 2000), according to the following Equation (1).

$$\lambda(DV) = \iiint G(DV|DM)dG(DM|EDP)dG(EDP\,|IM)d\lambda(IM) \tag{1}$$

— The FEMA P-58 methodology (FEMA, 2018a, b) was developed since 2001 by the Applied Technology Council (ATC) under its ATC-58 series of projects with an overall program consisted of two main phases. The first phase (ATC-58-1 Project), from 2002 to 2012, focused on the development of a next-generation performance-based assessment methodology to assess the seismic performance of a building expressed as probable consequences in terms of direct economic losses (repair costs), indirect losses (repair times), and human losses (casualties), explicitly considering inherent uncertainties. Furthermore, this phase was also devoted to the practical implementation of the proposed methodology by means of a dedicated tool, referred to as the Performance Assessment Calculation Tool (PACT). The second phase (ATC-58-2 Project), from 2012 to 2018, aimed to provide performance-based seismic design procedures and guidelines to engineers and stakeholders in the perspective of seismic risk reduction (Hamburger, 2014). Alternative approaches to add indirect losses in terms of probable environmental impacts (i.e. CO_2 emissions, energy use, and solid land fill generation) associated with repair of earthquake damage were also developed and implemented into the methodology within this phase. The extensive work carried out in the overall program of the project was released in a package of seven volumes, published in 2018, supporting electronic materials, and calculation tools available at the dedicated FEMA P-58 website.

The FEMA P-58 methodology finds its technical basis in the PEER-PBEE framework. The complexity of the PEER-PBEE framework to achieve a closed form solution of the multi-level integral in the form of Equation (1) measuring the probable value of an earthquake loss is widely recognised. Hence, Yang et al. (2006) developed an application of the PEER-PBEE methodology using a modified Monte Carlo approach to implement the integration by considering inferred statistical distributions of building response obtained from limited suites of analyses. This approach was adopted and expanded by the ATC-58 project team to develop the FEMA P-58 methodology. It expresses performance as statistical distributions of the probable values of earthquake impacts, termed performance functions, addressing repair costs, repair time, casualties, and environmental impacts associated with repair of earthquake damage. The FEMA P-58 methodology enables three different types of performance assessments, namely (i) intensity-based assessment, (ii) scenario-based assessment, and (iii) time-based assessment. The first and the second type evaluate the performance functions of a building assuming that it is subjected to a specified earthquake shaking intensity, and to an earthquake scenario at a specific magnitude and distance from the location of the building site, respectively. The third type assesses the performance function of a building over a specified period of time, considering all potential earthquakes and their probability of occurrence.

The framework of the FEMA P-58 performance assessment methodology consists of five basic steps (FEMA, 2018a), as illustrated in Figure 2. Each step is briefly presented, as follows:

1. **Assemble building performance model** – The building performance model defines an inventory of the building assets at risk of shaking-induced damage and their exposure to seismic hazard by means of three different categories of data related to (i) structural components and assemblies, (ii) non-structural systems, components, and contents, and (iii) occupancy. Structural and non-structural components are classified by fragility groups based on their similar vulnerability to seismic damage and consequences of this damage, and subsequently assigned to performance groups, aggregating fragility group components subjected to the same seismic demands. Occupancy allows the development of a building population model, used to determine casualties; representative models for

eight common occupancies including education, healthcare, hospitality, office, research, residential, retail, and warehouse are provided by the methodology, although specific population models not covered by the representative models above can be created.

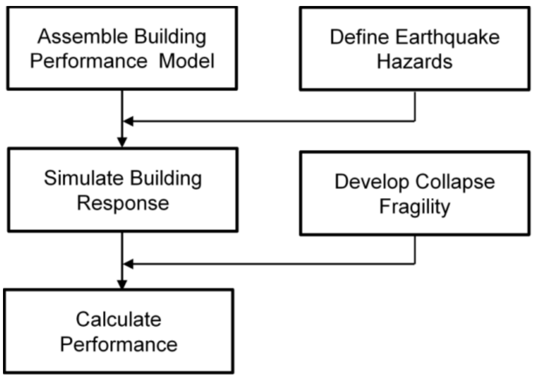
2. **Define earthquake hazards** - Earthquake hazard is a quantification of the intensity of the seismic event effects, such as ground shaking, ground fault rupture, liquefaction, etc.; the methodology addresses the seismic performance of a building related to the ground shaking. Ground shaking hazards can be defined in different ways depending on the type of performance assessment and structural analysis. As for intensity-based assessments, users must select an elastic acceleration response spectrum that represents the intensity of interest. As for scenario-based assessments, users must employ a ground motion prediction model to determine a median acceleration response spectrum for the magnitude-distance pair. As for time-based assessments, ground shaking hazards are characterized by a series of mean seismic hazard curves at different sites.

3. **Building response simulation** – The structural analysis of the examined building is carried out by means of a nonlinear dynamic analysis or a simplified analysis based on equivalent lateral force methods to predict the structural response of the building to earthquake shaking in terms of demand parameters, including storey drift, floor velocity, floor acceleration, and residual drift ratio, that can be associated with structural and non-structural damage. The preferred analysis method consists of the nonlinear dynamic analysis, but the alternative simplified analytical method can be considered for low- and mid-rise structures, fulfilling regularity requirements in plan and elevation, with moderate inelastic demands.

4. **Develop collapse fragility** – The methodology computes casualties related to component damage associated with falling hazard. However, most of the earthquake casualties occur as a consequence of partial or total collapse of a building. Hence, it is essential to define collapse fragility functions, which define the probability of incurring structural collapse of a building as a function of ground motion intensity along with the modes of structural collapse. The collapse fragility functions, in the form of lognormal distributions defined by a median value and dispersion, can be determined by using a combination of structural analyses and engineering judgements.

5. **Performance calculation** – The last step of the methodology is devoted to the calculation of performance loss employing a Monte Carlo procedure to account for many uncertainties inherent in factors affecting the seismic performance. This procedure results into a highly repetitive process in which building performance is calculated for each of a large number of 'realizations'; a single realization represents one possible performance outcome of the earthquake response of a building to an intensity or scenario shaking event.

Figure 2. Steps of the FEMA P-58 performance-based assessment methodology



Source: FEMA P-58-1, 2018a

One of the most significant outcomes achieved within the development of the FEMA P-58 methodology refers to the implementation of the procedure related to the Step 5 into a dedicated tool, i.e. PACT, to perform calculations and manage data in the perspective of a practical simplification of the methodology due to the numerous and data-intensive calculations to be carried out for a complex system as a real building. However, the possibility to use PACT outside the USA represents a huge criticality since the database of fragility curves and consequence functions for different categories of structural and non-structural components refer to the

USA buildings, thus not resulting valid for several building typologies worldwide. Recent research developments in this direction were carried out by Cardone and Perrone (2016) defining new sets of fragility curves and loss functions for typical Italian pre-1970s RC frame buildings in order to enable the application of the FEMA P-58 methodology to non-USA buildings.

2.1.1.1.2 Regional loss estimation methods

One of the most robust regional loss estimation method refers to the **Hazards US (Hazus) Loss Estimation** methodology, which is a nationally standardised risk modelling methodology for estimating potential physical damage, economic and social losses from natural hazards. Its development began in early 1990s by the USA Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (NIBS). The methodology intends to primarily provide state, local, and territorial government officials with a decision supporting software, i.e. the multihazard version of Hazus (Hazus-MH) tool including earthquake, flood, hurricane, and tsunami models, to develop plans and strategies for risk reduction of natural hazards and to prepare for emergency response and recovery. Specifically, FEMA and NIBS initiated HAZUS in 1992 to develop a GIS-based earthquake loss estimation methodology on a regional basis, which was implemented in the 1997 first release of the HAZUS tool for earthquakes (Whitman et al., 1997). Subsequently, the Hazus earthquake loss estimation methodology has been expanded to perform similar loss evaluations also for flood and hurricane (first release of the Hazus-MH version in 2004), and last tsunami. All Hazus models use common inventory data (i.e. built environment and demographics) to avoid eventual discrepancies when switching from one hazard to another. Although Hazus is designed for use in the USA, the tool adaptation has been carried out for use by emergency management organisations in Canada, Singapore, Australia, and Pakistan (Nastev and Todorov, 2013, Islam and Ryan, 2016). A description of the **HAZUS Earthquake Loss Estimation** methodology is briefly introduced. The application of this methodology generates an estimation of the consequences of a scenario or probabilistic earthquake event to a city, county, or region in terms of (i) quantitative assessment of losses in the form of direct costs for repair/replacement of damaged buildings, transportation and utility systems, (ii) functionality loss, and (iii) extent of induced hazards. The following main steps are considered to obtain these results: (i) select the area to be investigated, (ii) specify the earthquake hazard scenario, (iii) integrate local inventory data, (iv) use the formulas embedded in Hazus to compute probability distributions for damage to different classes of buildings, facilities, and infrastructure system components in order to subsequently estimate the loss of function, (v) estimate direct economic loss, casualties and shelter needs, and (vi) estimate fire risks following earthquake impacts. Specific details on each step are provided in the dedicated technical manual (FEMA, 2020).

2.1.1.2 Methods and tools for seismic vulnerability and resilience assessment

The concept of resilience has only recently been applicable to the engineering field (Kammouh et al., 2017) and, specifically, to earthquake engineering introducing the time dimension to cover the post-event recovery phase (Tsionis, 2014). Indeed, according to Bruneau et al. (2003), resilience can be defined as the capacity of a system to reduce the chances of perturbations, to absorb them, or recover quickly after a shock. Thus, seismic resilience assessment could become a significant tool for decision makers to evaluate retrofit alternatives for existing buildings, preferring the one with the lowest recovery period, i.e. downtime (Carofilis Gallo et al., 2022).

The assessment of resilience results particularly difficult due to the absence of a concise and methodical approach (Kammouh et al., 2017). Focusing on seismic resilience, it is commonly quantified through a recovery function that represents how a building restores its original functionality over time. However, there are other methodologies and studies that evaluate resilience from different perspectives and parameters, which can be grouped into three main categories, as recently reviewed by Carofilis Gallo et al. (2022): (i) index-based methods, (ii) methods based on recovery states, (iii) performance-based multi-criteria decision making methods.

In the context of the second group of methods, a number of resilience rating systems have been developed to assess building performance and resilience to an earthquake. Existing resilience rating systems commonly address safety (occupant safety during the event), damage (financial cost to repair the building), and recovery (time required to make necessary repairs to the building). Each rating system varies in the assessment of post-disaster functionality (Boston and Mitrani-Reiser, 2018). One of the most robust tool within this group refers to the **Resilience-based Earthquake Design Initiative (REDi™)** (Almufti and Willford, 2013), which provides to owners and other stakeholders a framework for implementing resilience-based earthquake design according to the PEER-PBEE methodology. REDi framework is a holistic beyond-code design method, which assigns a building a rating class from its three-tiered system (i.e. Platinum, Gold, or Silver) after satisfying mandatory criteria of baseline resilience objectives referring to downtime, direct financial losses and occupant safety.

2.1.2 Methods for environmental and energy performance assessment

The second category of the examined assessment methods deals with environmental and energy performance assessment methods and their specific tools. This category includes methods based on a LCT analysis to quantify the environmental impacts from the raw material extraction, via production and use phases, to the end-of-life of a product/building – from *cradle to grave*, with the possibility to also include the potential recycling of materials and/or reuse of components – from *cradle to cradle*. The main stream of this category refers to the **Life Cycle Assessment (LCA)** methodology. However, depending on the objectives of the evaluation, a LCA sub-stream is also included in this category. Specifically, the importance to assess the energy inputs to a building at each stage of its life cycle led to the definition of a specific approach, indicated as **Life Cycle Energy Assessment (LCEA)** methodology, although the energy performance assessment should be formally part of the LCA (Fay et al., 2000, Ramesh et al., 2010). A LCEA aims to facilitate the decision-making process concerning energy efficiency of buildings, in case of both design of new constructions and retrofit of existing buildings, rather than to replace a broader environmental assessment method, i.e. LCA (Fay et al., 2000). An overview of the LCA framework along with a focus on LCA and LCEA methodologies applied to the construction sector is provided in details in the following.

2.1.2.1 Life Cycle Assessment (LCA) methodology – Evolution and framework

The most accepted approach for the environmental performance assessment of a product or activity is currently the LCA methodology, which allows the quantitative evaluation of the ecological impacts of products and services throughout their entire life cycle according to the *cradle-to–grave* (i.e. from raw material extraction to end-of-life) approach. However, LCA studies can also follow a *cradle-to-gate* (i.e. from raw material extraction to production stage of a product's life cycle) or a *cradle-to-cradle* (i.e. recycle and reuse stages are included beyond the cradle-to–grave phases) approach depending on the investigated life cycle boundaries.

According to Guinée et al. (2011), the LCA evolution into the current science-based methodology can be divided into three main phases based on the following timeline:

- **Conceptualisation phase (1970-1990)** - The first studies on environmental impacts date back to 1960's and 1970s with the aim to assess or compare consumer goods (e.g. beverage containers and detergents). A synthesis of the early history of LCA is provided in Udo de Haes and Heijungs (2007). This initial era of the LCA development was marked by a chaotic methodological basis, different terminology, and conflicting results with the consequent lack of consensus in the use of LCA. A growing interest was obtained only one decade later, in 1980s, when the attention to the sustainable development arose with the Brundtland report (1987), leading to the definition of the sustainable development as the interaction of three main dimensions (i.e. Environment, Economy, and Society). However, the keystone for the LCA development occurred in 1989, when the Society of Environmental Toxicology and Chemistry (SETAC) started playing a leading and coordinating role in bringing LCA stakeholders together to harmonise the LCA framework, terminology and methodology.
- **Standardisation phase (1990-2000)** - The second phase of the LCA development was essentially devoted to the standardisation process of the LCA framework in order to respond to the increasing need to assess the environmental impacts of services and products in different industrial sectors. At the beginning of 1990, the coordination process of the European and North American SETAC branches led to a fundamental outcome, namely a 'Code of Practice' (SETAC, 1993), aimed at providing a recognised guidance for LCA studies. Although this document was not intended to be a standard, it created the basis towards the achievement of proper LCA legislative instruments. Indeed, the International Organization for Standardization (ISO) has been involved in LCA since 1994, releasing a first series of four ISO 14040 standards, which are part of the group of 14000 series on management of environmental systems, in the period 1997-2000. These standards aimed to define a general methodological framework of LCA, which consequently could facilitate the comparison of different LCA studies.
- **Elaboration phase (2000-2020)** – The third phase of the LCA development was devoted to both foster the practical application of LCA and enlarge the LCT approach to the concept of sustainable development. The first decade of the 21st century was characterised by an ever-increasing worldwide focus on LCA. Following the efforts of SETAC and ISO, in 2002, the United Nations Environmental Programme (UNEP) and SETAC launched an international partnership, known as Life Cycle Initiative, to enable worldwide LCA

users to implement the LCT approach into effective practice. A significant effort to encourage LCA applicability was also made out at European level, as demonstrated by numerous EU policies and action plans incorporating the LCA use. A brief review of these policies and action plans is provided in Romano et al. (2014); Sala et al., (2016), among others. In this context, it is worth mentioning the European Commission (EC)'s 2003 Integrated Product Policy Communication (COM (2003)302) leading to the development of the European Platform on Life Cycle Assessment (EPLCA) by the EC's Directorate-General for Environment (DG ENV) and the Joint Research Centre (JRC) in mid-2005, aimed at providing methodological guidance for LCA practice. To promote the tangible application of LCA, in 2006 the ISO standardisation process was also finalised through the publication of a second series of two core ISO 14040 standards, i.e. ISO 14040-44 (ISO, 2006a, b), grouping and substituting the former 1990s series, and currently regulating the LCA methodology. Specifically, ISO 14040 describes the LCA principles and framework, whereas ISO 14044 focuses on the LCA requirements and guidelines. However, a unique method/technique to calculate the environmental impacts when conducting an LCA (Buyle et al., 2013) is not provided in these standards. Thus, the latter leave the LCA practitioners and data developers with a range of important choices individually interpretable, leading to differences in consistency, reliability, and comparability of assessment results. As a consequence, although the LCA methodology is internationally accepted as the most valid and useful tool to assess the life cycle environmental impacts of products or services and its involved processes, its practical application is still in a fragmented state (Dossche et al., 2017), requiring further guidance. At European level, the EPLCA played a key role in this direction, and it still occupies a relevant position. Indeed, the EPLCA implements the International Reference Life Cycle Data system (ILCD) initiative, developed since 2005, to provide guidance for greater consistency and quality assurance in applying LCA. The major contribution to the ILCD is the ILCD Handbook, which consists of a series of technical documents (published in 2010) providing guidelines for good practice in LCA by industry and government, by using ISO 14040-44 as starting point. An overview of the ILCD Handbook guidance documents is provided in the homonymous JRC Reference Report (Wolf et al., 2012). Furthermore, since 2013, the European Commission has launched the Environmental Footprint (EF) methods, namely Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) methods, to enhance the comparability of LCA applied to products and organisations, respectively. Both methodologies, which were first defined by the 2013 EU Commission Recommendation (2013/179/EU) to measure the life cycle environmental performances of products and organisations, completed a so-called 'Pilot phase' between 2013-2018, and are currently in the 'Transition phase', started in 2019. The main efforts related to the progress of the EF methods at this stage refer to the development of PEF Category Rules and OEF Sector Rules, making these methods more stringent in their rules than the common LCA, and allowing the assessments to be more comparable and suitable for benchmarking products/services.

The second decade of the 21th century, beyond continuing to be focused on developments for the practical use of the LCA methodology, highlighted the importance of extending the LCA approach to the concept of sustainable development by defining an assessment framework focused on the broader range of sustainability pillars, namely the economic and the social dimensions, beyond the environmental one. Hence, a Life Cycle Sustainability Assessment (LCSA) framework was proposed to integrate the three dimensions of sustainable development, i.e. Environment, Economy, and Society, by combining stand-alone life cycle assessment methodologies, already in use, namely LCA, Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) (UNEP/SETAC, 2011) to assess the environmental, economic, and social impacts, respectively. This idea was first translated into a conceptual formula (i.e. LCSA = LCA + LCC + S-LCA) by Klöpffer (2008) and Finkbeiner et al. (2010). This formula underlines the importance of considering the results of each methodology in a holistic way rather than summing them up. It is evident that the application of multi-criteria decision making methods is needed to carry out a global sustainability result (Lin et al., 2020).

The framework of the LCA methodology consists of four iterative standardised steps (Figure 3), addressed by ISO 14040-44 standards (ISO, 2006a, b), which have been recently reviewed leading to the amended ISO 14040/AMD 1 (ISO, 2020a) and ISO 14044/AMD 2 (ISO, 2020b) standards. The four steps are briefly described, as follows:

1. **The Goal and Scope definition** - The goal defines the purpose, the intended use, and the audience of the LCA. The scope should ensure that the details of the study are sufficient to address the stated goal. The scope includes the product system and its functions, quantitatively measured through the functional unit, as well as the system boundaries, the materials flow, and the impact categories selected. The scope also defines the required data quality, the technology and the assessment parameters. The goal and scope of a LCA study should be clearly defined to optimise both the assessment process and time requirements.

However, it is worth noting that they may also be subjected to change depending on analysis findings due to the iterative nature of the LCA (Stephan, 2013).

2. **The Life Cycle Inventory analysis (LCI)** - At this stage all the data is collected on inputs (resources) and outputs (emissions, wastes) for each phase of the life cycle of the assessed product or process in relation to the functional unit. Hence, a workflow diagram of the entire life cycle of the product is constructed according to the goal and scope of the study. This step, which results the most labour and time consuming stage of the LCA framework (Finnveden et al., 2009), requires a rigorous approach as basis for evaluating the environmental inflow and outflow associated with the various stages of the product's life cycle.

   The inputs and outputs can be quantified by using three different methods, namely (i) *process analysis*, (ii) *input-output (I-O) analysis*, and (iii) *hybrid analysis*, which generally differ in the level of precision for the inventory analysis. Indeed, the process method is a bottom-up technique relying on manufacturer-, product-, or region-specific data, whereas the I-O method is a top-down approach based on national average data and broad industry sectors (FEMA, 2018b). The hybrid method combines the potentialities of these two traditional approaches. The process analysis method, also known as unit-process method, is the conventional approach for the LCA, which models the inputs from the environment and outputs to the environment (e.g. GHG emissions) for each of the individual processes, resulting particularly detailed and precise. However, weaknesses and limitations associated with this method have historically included truncation error, missing data, or processes extending beyond the analysis boundaries. The I-O method, which relies on a framework established by Leontief (1986) between 1940s and 1970s, found its roots in the economic field to represent the interdependencies between different sectors of a national economy, leading national governments to develop input–output tables since 1950s. Reyling on these tables, this approach started to be used also in the LCA studies to overcome the limitations of the process-based models. Although the I-O-LCA method enables to avoid the truncation error of the process-LCA method, it is not considered an attractive alternative in case of a detailed product-level LCA (Finnveden et al., 2009). Furthermore, this method also suffers from inherent issues, such as errors and uncertainty of economic data, aggregation and grouping of sectors, etc. (Dixit et al., 2010). Hybrid methods, which became widely acknowledged by LCA practitioners only at the end of 1990s (Finnveden et al., 2009), combine aspects of the unit-process and economic I-O methods to capture the strengths of each approach, while limiting their drawbacks. However, it is essential to validate data comparability between the unit-process and I-O portions of the assessment to achieve consistent results.

   The LCI step can be quite challenging due to the lack of data for a specific product under study. Thus, in the last three decades, several international, national or regional, industry, and consultants' LCI databases, which began appearing in early 1990s (Sphera, 2022), have been developed and integrated into LCA software tools to both facilitate the data inventory and avoid a duplication in data compilation (Finnveden et al., 2009, Ortiz et al., 2009). However, no single LCI database available to date can be considered fully complete (Rashid and Yusoff, 2015) due to the wide variability in terms of application, data, geographical location, manufacturing process and scope. Some LCI databases are commercially available by paying for a licence, whilst others are accessible free of charge. Within the former category, one of the most accredited European LCI databases is the Swiss Ecoinvent database, which is considered as the world's leader in LCA databases since it includes tens of thousands of LCI datasets. Moreover, it is updated annually since 2013 to include new and upgrading data, as well as technical improvements. Within the category of free LCI databases, a valid example refers to the US Life cycle inventory database (USLCID), which was developed in 2001 by the National Renewable Energy Laboratory (NREL) of the United States Department of Energy to provide data flows for the USA.

3. **The Life Cycle Impact Assessment (LCIA)** - The outcome of the inventory analysis is used as an input into the framework for life cycle impact assessment (LCIA). This phase aims to quantify the potential environmental impacts and resource inputs using the inventory data, which are translated into indicators to understand burdens on different impact and/or damage categories. Specifically, the LCIA step is a multi-stage process consisting of two main parts (Ortiz et al., 2009, Finnveden et al. 2009).

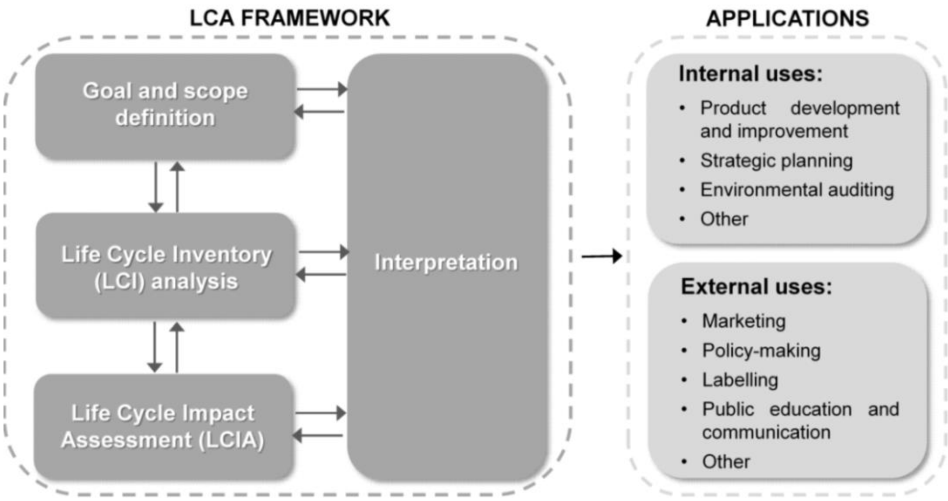
   The first part of the LCIA step includes three mandatory elements, namely (i) *selection of impact categories*, (ii) *classification*, which consists in the assignment of LCI results to the selected impact categories, and (iii) *characterisation*, aimed at modelling category indicators to achieve measurable impact results. Specifically, the selection of impact categories refers to the identification of environmental impacts categories relevant to the LCA study, generally adopting predefined categories (Finnveden et al., 2009). Classification deals with the process of sorting the LCI results in terms of emissions, wastes, and resources to the chosen impact categories, according to the ability of inventory data to contribute to the different environmental burdens. Characterisation consists of quantitatively modelling the impacts within the selected impact categories by using characterisation (conversion) factors to express the impacts into reference units, e.g. Global Warming Potential (GWP) for the climate change category. However, impact results are strongly dependent on the impact assessment method used. Specifically, two main approaches can be used to classify and characterize environmental impacts; problem-oriented (or midpoints) methods and damage-oriented (or endpoints) methods, which can be also combined (Buyle et al., 2013). The problem-oriented method uses values at the beginning or middle of the environmental mechanism and refers to impact categories, such as GWP, acidification potential, ozone depletion potential, etc. The damage-oriented method refers to the end of the environmental mechanism, where the midpoints are grouped into general damage categories such as, damage to human health, ecosystems and resource availability (Buyle et al., 2013), which eventually can be calculated into a single score. Some examples related to the midpoint methods are CML baseline method, IMPACT 2002+ (midpoint), etc., whereas some of the most used endpoint methods are Ecoindicator 99, IMPACT 2002+ (endpoint), ReCiPe (Bueno et al., 2016). Beyond midpoint and endpoint methods, single issue-oriented LCIA methods, allowing users to assess the environmental impacts from a single point of view, can be also chosen. Some examples in this direction include the Cumulative Energy Demand (CED) providing only the amount of energy involved in a system, the Intergovernmental Panel on Climate Change (IPCC) 2021 (i.e. the recent successor of the IPCC 2013) dealing only with the GWP, etc. (Carvalho et al., 2014, Santos et al., 2019).

The second part of the LCIA step refers to the two following optional elements: (i) *normalisation*, and (ii) *weighting*. Normalisation refers to the computation of the relative magnitude of impact scores to some reference values, thus converting differing units into a common and dimensionless format to obtain normalised results. Weighting indicates the relative significance of impact scores - normalised results are multiplied by a set of weighting factors (in percentage) - according to the goal of the study. It is worth mentioning that both normalisation and weighting are mandatory within the PEF and OEF methods.

4. **Interpretation** - This step is the last one of the LCA procedure where results of LCI and LCIA are interpreted in accordance with the defined goal of the study. Specifically, these results should lead to conclusions of the assessment, explain limitations, and provide recommendations.

LCA studies may support decisions for a wide range of applications, which are mainly devoted to either internal uses (e.g. development and improvement of a product, strategic planning, environmental auditing and waste minimisation), or external uses (e.g. marketing, policy making, labelling), as depicted in Figure 3.

Figure 3. Framework of LCA methodology and its main direct applications



Source: based on ISO 14040, 2006a.

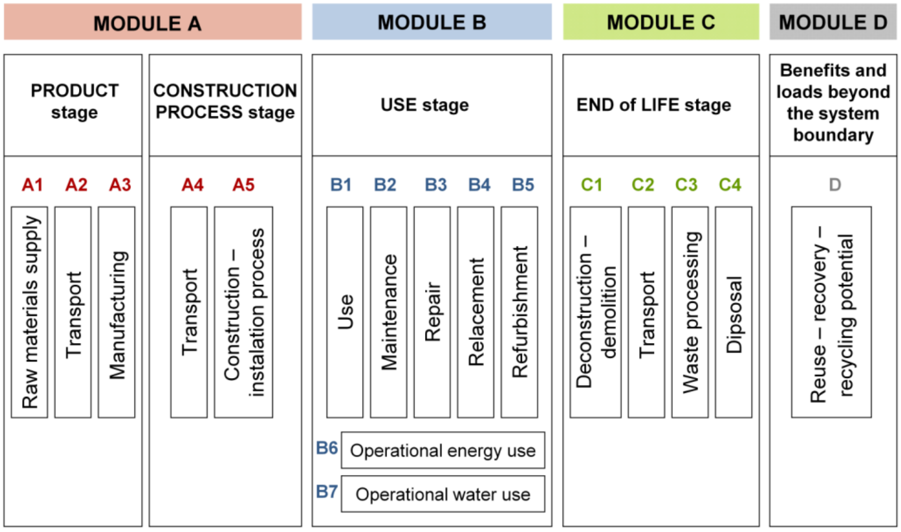
Three different types of LCA can be carried out based on the specific objectives of the study (Stephan, 2013). The first type is the conventional LCA, commonly indicated as a baseline LCA, which is used to assess individual processes or products in order to improve their environmental performance by reducing the related life cycle impacts. A conventional LCA is typically performed into two main field of applications. On one hand, manufacturing companies of various industrial sectors internally perform LCA studies to optimise the production chain of their products. On the other hand, conventional LCA is externally used to produce voluntary, third-party verified labels, namely Environmental Product Declarations (EPDs), according to ISO 14025 (ISO, 2006c) in order to communicate transparent and comparable information about the life cycle environmental impacts of a product to a wider audience. The second type of LCA is the comparative LCA used to compare the environmental impacts of two or more products or processes fulfilling the same function in order to identify the best life cycle green solution. This type of LCA can be used within a decision-making process to justify the product and/or processes choices, thus exhibiting an external use. Finally, the third type of LCA is defined as a streamlined LCA, which is a simplified version of the conventional LCA by considering only some environmental impacts and stages of the life cycle of a product or process. In such a case, it is essential to specify the reason of a narrower LCA in the 'goal and scope definition' step of the analysis. One of the most popular streamlined LCA is the Life Cycle Energy Analysis (LCEA), which quantifies solely the energy inputs of a product.

2.1.2.2 Life Cycle Assessment in the construction sector: overview

The LCA methodology is widely used in a multitude of industrial sectors to investigate the interaction of their own products with the environment (Toniolo et al., 2021). This increasing interest is essentially due to the scientific consensus in the recognised LCA capability to assess the environmental impacts of products and processes with the aim of overcoming the current concerns of resources depletion, unsustainable production of waste, and high consumption of energy. Industrial sectors, extensively exploiting LCA applications, are food and agriculture industry (Roy et al., 2009; Del Borghi et al., 2020), chemical industry (Santos et al., 2019), textile industry, and information and communications technology (ICT) industry (Arushanyan et al., 2014), to name a few. LCA is also widely applied for waste management systems, mainly to support decision-making process (Nyland et al., 2003, Laurent et al., 2014).

The huge pressure exerted on environment by the construction sector, resulting into the highest energy consumer in Europe – about 40%, and the main contributor to GHG emissions – 36% of the EU total CO_2 emissions (COM (2020)662), has made this sector one of the most fertile grounds for LCA studies. The LCA methodology has been used in the construction industry since 1990 by including both the infrastructure sector, with initial studies referring to the environmental impact assessment of bridges (Horvath and Hendrickson, 1998) and highways (Park et al., 2003), and the building sector (Ortiz et al., 2009). However, LCA studies on buildings resulted rather limited during the 1990s, although the initial attention to the LCT approach within the building segment dates back to the beginning of 1980s thanks to a study by Bekker (1982) on the consumption of limited resources and environmental losses in the field of construction. The impetus to the direct application of LCA to the building sector significantly increased in the first decade of the 21th century, as reviewed by Ortiz et al. (2009), Singh et al. (2011), Buyle et al. (2013), and it is still fervid. In fact, in the last two decades important developments in terms of guidance and standardisation process of LCA are related to the construction sector. Specifically, in 2003 SETAC published a state-of-the-art report on Life-Cycle Assessment in building and construction to underline the differences of the LCA application to building material/components and whole buildings, and the need of harmonization. To this end, a significant step forward has been carried out through the development of specific standards in the field of sustainable constructions at both international (ISO) and European (EN) level by the Technical Committees (TC) ISO/TC59/SC17,'Building construction – Sustainability in building construction', established in 2003, and CEN/TC 350, 'Sustainability of construction works', founded in 2005, respectively. These standards address the quality and performance of construction works at three levels: (i) methodological/framework; (ii) building; and (iii) product, in order to satisfy the environmental, social and economic dimensions, according to a life cycle based approach. Although this standardisation process refers to the three dimensions of sustainable development, standards regulating the assessment of the economic and social performances have been developed solely at building level within the European context. Conversely, the environmental performance assessment results into the most advanced aspect with standards developed at building and product levels within both international and European contexts, as briefly reviewed in Romano et al. (2020). At building level, both ISO 21931-1, recently revised (ISO, 2022) and EN 15978 (CEN, 2011) standards provide the calculation method for the environmental performance assessment in terms of impacts and resources consumption based on LCA in order to define a common evaluation language for building designers. At product level, both ISO 21930 (ISO, 2017a) and EN 15804+A2/AC (CEN, 2021) standards provide core product category rules (PCR) for developing Type III environmental declarations of construction products – a particular type of LCA referred as Environmental Product Declarations (EPDs). They allow manufacture market to facilitate environmental information flow regarding business-to-business construction products and to avoid barriers to trade. One of the main achievements within the European standards developed by CEN/TC 350 refers to the standardisation of the life cycle of a building into the following four main modules: (i) the production and construction stages (Module A), (ii) the use stage (Module B), (iii) the end-of-life stage (Module C), and (iv) the benefits and loads beyond the system boundary (Module D). Each module includes specific stages, as depicted in Figure 4.

Figure 4. Standardisation of building life cycle in a modular concept



Source: based on EN 15978 (CEN,2011)

The application of the LCA methodology within the construction sector can be carried out at three different levels increasing with the complexity of the system to be investigated, namely (i) construction product, (ii) building component, and (iii) building as a whole (Buyle et al., 2013). Specifically, the LCA of construction products led to the definition of EPDs containing information associated with the acquisition of raw materials, energy use, content of materials and chemical substances, emissions into the air, land and water and waste generation (Ortiz et al., 2009). Buildings, instead, are special products compared to industrial products and/or industrial processes, thus the LCA becomes a challenging task for their assessment. Main issues refer to the long lifespan, the assessment of local impacts depending on building site, the LCA data collection, potential impacts on occupants' well-being, and occupants' behaviour during the use phase of the building (Cabeza et al., 2014, Chau et al., 2015), among others. Anand and Amor (2017) reviewed challenges, knowledge gaps and future areas of research for each of the four stages of the LCA methodology applied to buildings. Finally, it is worth noting that the LCA applicability to a fourth level related to broader and more complex systems referring to urban scale, namely neighborhood or district, has been investigated in the last decade (Mastrucci et al., 2015, Mailhac et al., 2016, Palumbo et al., 2019).

2.1.2.3 Life Cycle Assessment in the construction sector: tools

Several LCA tools have been developed to estimate the life cycle environmental impacts of products or processes within various industrial sectors. As for the construction sector, the increasing need of the environmental performance assessment of construction materials and/or buildings in the last two decades led to the development of LCA tools in different countries (Cabeza et al., 2014). These tools can be global, national and, in some cases, local (Haapio and Viitaniemi, 2008), thus implementing different LCI databases, which can lead to a high variability of the assessment results at building level, as demonstrated by Takano et al. (2014), among others, and reviewed by Säynäjoki et al. (2017). Generally, the most analysed environmental impact metrics for buildings and/or their materials/components refer to GHG emissions and energy consumption indicators (Rashid and Yusoff, 2015; Anand and Amor, 2017), although they may not be the most impact intensive indicators in all building analyses as demonstrated by Mastrucci et al. (2015). However, the availability of a specific impact category in a LCA software depends on the impact assessment methodology available to the tool. Thus, the choice of a LCA tool becomes one of the key-issue for a reliable assessment, also affecting the uniformity and consistency of results in building sector, as reviewed by Säynäjoki et al. (2017).

The LCA tools can be classified according to two main categories: (i) generic LCA tools, devoted to product assessment and/or comparison, and (ii) building-specific LCA tools, aimed at the whole building design decision process (Ortiz et al., 2009, Anand and Amor, 2017).

The **first category** of LCA tools refers to general LCA tools applicable to the construction sector to carry out the environmental impact assessment of building materials and/or components. A list of generic LCA tools is provided by the EPLCA. General comparative studies of different LCA database-software combinations have been carried out over time, as reported in Emami et al. (2019), also providing a brief review of LCA tool comparative studies related to the construction sector. Two of the most used LCA tools within the first category are GaBi and SimaPro, briefly described, as follows:

- **GaBi** (Ganzheitliche Bilanzierung) is a process-based product modelling and assessment software, developed at the University of Stuttgart (Germany), formerly produced and distributed worldwide by the German company PE International, now Sphera (an international market leader in strategic consultancy and software solutions in the field of sustainability). The tool, that first appeared on the market in 1992, is currently considered as a next generation product sustainability solution to support several business applications. Indeed, GaBi combines one of the world's leading LCA modelling and reporting software, content databases with intuitive data collection, allowing for ISO 14040-44-compliant LCAs, carbon and water footprint assessment, EPDs, PEF studies, product eco-design. The software also provides the possibility to carry out LCC analyses to design and optimise products and processes for cost reduction, as well as to add social impact information to a model, becoming a holistic life cycle analysis tool. Over the last 30 years, GaBi developers have collaborated with companies, associations, and public bodies to provide the software with the largest internally consistent and transparent LCI databases available on the market, i.e. GaBi databases, covering different industrial sectors. Furthermore, a professional database maintenance and governance ensure a unique annual update of GaBi databases aimed at keeping their quality continuously high to allow multiple stakeholder groups (e.g. industry, academia, policy and regulation, research, etc.) to achieve accurate results (Sphera, 2022). GaBi includes its own building and construction sector LCI database, among others, as well as it integrates the USLCID and Ecoinvent datasets, which also incorporate LCI data on building sector, thus making this tool particularly suitable for reliable LCA studies within the construction segment. Furthermore, the EF database has been integrated into the tool to support the implementation of PEF and OEF studies. The software also provides several options of impact assessment methods.
  For sake of clarity, PE International also offers a building-specific software product, called *GaBi Build-It* and currently available only in German, that uses data specific to European construction.

- **SimaPro** (System for Integrated Environmental Assessment of Products) was developed in 1990's by the PRè Sustainability company (based in the Netherlands) as its flagship product. This tool has been recognised as the world's leading LCA software solution trusted by both industry and academia in more than 80 countries for the last 30 years. Indeed, similarly to GaBi software, this process-based LCA tool can be used for a large extent of applications referred to sustainability reports, carbon and water footprint assessment, product design, EPDs generation, and determination of key performing indicators. SimaPro provides complete transparency processes during all the life cycle stages of a product assessment and it is fully integrated with both the latest science-based LCI databases, such as Ecoinvent, European and Danish Input/Output database, and consistent LCIA methods, such as ReCiPe 2016 Midpoint and Endpoint, CML-IA, CED, IPCC 2021, etc.. This aspect has led SimaPro to be also accepted as one of the most flexible supporting tool for the environmental assessment of products and processes in the construction sector. Specifically, the world's leader Ecoinvent database incorporated in the tool covers a diverse range of sectors at global and regional level, encompassing building and construction segment. As for the LCIA methods, SimaPro provides the possibility to assess the GHG emissions- and energy consumption-related impacts by means of two single issues impact methods, namely the IPCC 2021 and CED, respectively. It is worth noting that various updates and new additions of both databases and impact assessment methods have been implemented in the tool over time according to the evolution of its releases, with the latest one being currently SimaPro 9.4 (PRè Sustainability, 2022). An important achievement in this direction in relation to the construction sector regards the inclusion of a new LCIA method, namely the EN 15804 + A2 method for producing EPDs of construction products (PRè Sustainability, 2020), according to the homonymous European standard (CEN, 2021), implemented since the previous tool releases (i.e. 2020 SimaPro 9.1).

Beyond Gabi and Simapro, which provide a wide range of methodologies from energy assessment and water footprints to diverse impact category assessments, a large number of LCA tools belongs to the first category, such as OpenLCA, TEAM™, UmbertoLCA+, etc. **OpenLCA** is an open-source and free tool for sustainability and

LCA, offering the largest collection of free and commercial datasets and databases worldwide for LCA software (e.g., Ecoinvent, GaBi database, etc.), which can be accessed through the openLCA Nexus. This LCA tool also integrates the LCC and the assessment of social aspects in the life cycle model. TEAM™ (Tool for Environmental Analysis and Management), developed in France by the Ecobilian Group, is a professional process-based LCA-tool aimed at evaluating the life cycle, environmental and cost profiles of products and technologies, also enabling products comparison and information resources related to building sector (Haapio and Viitaniemi, 2008). **Umberto LCA+**, developed in Germany and distributed by ifu Hamburg that is member of the iPoint Group since 2017, is one of the leading LCA software solutions to analyse the environmental impact and carbon footprint of products according to ISO 14040-44 standards (ISO, 2006a, b) in a fully transparent and reliable way thanks to the integration with the most common LCA databases (e.g. Ecoinvent) and LCIA methods.

The **second category** of LCA tools includes software packages developed to analyse the environmental performance of a building as a whole throughout its entire life cycle. This category includes various tools developed as stand-alone programs, such as ATHENA, BeCost, etc., or as plugs-in in the perspective of the growing integration of Building Information Modeling (BIM) and LCA (Soust-Verdaguer et al., 2017; Bueno and Fabricio, 2018), such as One-click LCA, among others, extensively used at European level. **ATHENA** consists of two main tools, available for free: (i) Impact Estimator for Buildings, and (ii) EcoCalculator for Assemblies, developed by the Athena Sustainable Materials Institute (ASMI) in Canada to provide usable tools for North American designers. These tools are correlated, but different. Specifically, the Impact Estimator for Buildings tool, which was originally developed during 1990's and first released as a commercial product in 2002, is a stand-alone software applicable to new and existing buildings to model their assemblies and subsequently carry out the life cycle environmental impacts of the related materials, also providing the possibility to assess the operating energy of the examined building. The EcoCalculator for Assemblies tool, first released in 2007, enables a rapid and rough estimation of building design environmental footprint based on pre-defined assembly and envelope configurations, by using results derived from the Impact Estimator tool. **BeCost**, is a user-friendly web-based tool developed by the VTT Technical Research Centre in Finland to carry out the LCA of building structures and whole buildings, relying on environmental profiles, costs and maintenance costs of building materials produced in Finland. **One-Click LCA** is a cloud software, developed and marketed by the Finnish Bionova Ltd (this business name changed into One-Click LCA Ltd in July 2021) to carry out construction life-cycle metrics by automating the calculations directly from common design tools (e.g. Revit) to get environmental impacts results of a building in a simplified and rapid way. The tool enables also the calculation of LCC and Carbon Footprint, as well as it can be used for and complies with sustainability certification schemes, such as Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB).

2.1.2.4 Life Cycle Energy Assessment (LCEA) methodology

Buildings consume energy directly or indirectly in all phases of their life cycle. Direct energy is used for construction, operation, renovation, and demolition of a building, whereas indirect energy is consumed by a building for the production of material used in its construction and technical installations (Sartori and Hestnes, 2007). Specifically, the energy consumed directly and indirectly through various products and processes used in design, initial construction, life cycle maintenance/renovation, and final demolition of a building is indicated as embodied energy (E_E). Energy required during the operational stage of a building to maintain its indoor comfort conditions through different processes, such as heating and cooling, hot water use, and powering appliances, is defined as operational energy (E_O). The traditional assumption related to the life cycle energy distribution in buildings considers the E_O as the major share, accounting for 80-90 % of the total life cycle energy use, whereas the E_E constitutes only a little segment equal to 10-20 % (Adalberth et al., 1997a, Ramesh et al., 2010), thus the latter is typically considered in second instance or neglected into the energy assessment. However, in the last decades these figures have been re-evaluated by acknowledging the importance of the E_E relative proportion into the estimation of total life cycle energy use of buildings (Stephan, 2013; Crawford, 2014). A recent emblematic study in this direction underlined that different factors, such as climate characteristics of building location, time value of carbon, fuel sources used, can generate more critical E_E results. Indeed, the embodied energy of conventional residential buildings placed in worldwide regions with mild climatic conditions can represent up to 25 % of the total life cycle energy (Karimpour et al., 2014). Moreover, the E_E value could increase to 40-60 % of the total life cycle energy in the case of low-energy housing even in harvest climatic regions, such as Sweden (Thormark, 2002; 2006). In the case of nearly zero energy buildings, the share of the embodied energy can reach a percentage equal up to 74-100 % of the total life cycle energy consumption (Chastas et al., 2016). Indeed, the growing demand for the reduction of the operational energy of buildings to tackle the climate change mitigation can lead to an increase in the total building life cycle energy use due to increasing the embodied energy from the building components, as analysed by various studies for both new (Huberman and Pearlmutter, 2008; Stephan et al., 2013; Crawford, 2014) and retrofitted buildings (Beccali et al., 2013; Vilches et al., 2017; Shadram et al., 2020). Consequently, the interest in understanding the possibility to reduce embodied impacts of buildings, both in terms of energy and GHG emissions, is exponentially arising with research efforts towards the definition of effective design strategies, as analysed in Malmqvist et al. (2018). Hence, it is essential to consider the significance of both embodied and operational energy of buildings throughout their life cycle to properly assess their energy efficiency by means of a specific methodology, namely the LCEA.

The LCEA is a simplified version of the LCA methodology focused on the energy inputs to a building during its entire life cycle (Adalberth, 1997b; Fay et al., 2000; Ramesh et al., 2010), thus considering energy as the sole measure of potential environmental impacts. Indeed, the LCEA employment results into a simplification of the four stages of the LCA framework. Specifically, the goal and scope definition, the LCI analysis, and the interpretation stages remain unchanged, although the LCI is streamlined by considering a single input. The original LCIA stage instead is extensively simplified since a unique impact category, i.e. energy use, is considered. Thus, the impact assessment does not require the mandatory elements of classification and characterisation (Stephan, 2013). It is essential to consider the LCEA results in terms of 'primary energy', intended as the energy in its raw form required from natural resources (e.g. coal) to generate the energy used by a consumer (e.g. electricity), known as 'delivered energy', since this output can also give a useful indication of the GHG emissions attributable to buildings, thus indicating their impact on the environment (Fay et al., 2000). Indeed, broader environmental analyses carried out through LCA studies demonstrated that a high share of environmental impacts correlate closely with primary energy demand of buildings in their life cycle (Ramesh et al., 2010).

The system boundaries for performing a LCEA analysis include the energy use of the following three phases of the building life cycle: (i) production phase, including building materials manufacture and transport, construction, and maintenance/renovation of the building, (ii) use phase, and (iii) demolition phase, thus leading to the estimation of three main energy contributors, as follows:

— **Embodied energy** – The embodied energy of a building consists of two major components: (i) initial embodied energy, indicating the energy consumed for the production and transport of materials used in the initial construction of a building and the related onsite installation process, and (ii) recurring embodied energy, referring to the production of materials used in maintenance, repairs or renovations during the service life of a building.

  In line with the conventional LCA methodology, three different methods developed within the LCI step can be used to estimate the embodied energy of a building, namely process-based analysis, I-O analysis, and hybrid analysis (Bullard et al., 1978; Fay et al., 2000), as briefly introduced in Section 2.1.2.1. A comprehensive literature review on these calculation methods is reported in Dixit et al. (2010) and Chau et al. (2015).

  The simplest computational approach adopts a process-based analysis, which is a bottom-up technique relying on E_E databases for construction materials, drawings and specifications from an investigated building. Specifically, the quantity and type of building materials, as well as the values of embodied energy intensity factors are needed to quantify the initial embodied energy of building materials ($E_{E,I,m}$), according to the following Equation (2).

$$E_{E,I,m} = \sum_{i=1}^{n} m_i \, M_i \tag{2}$$

  Where

  m_i is the mass of the *i*-th type of building material (expressed in Kg).

  M_i is the embodied energy intensity factor related to the extraction and manufacturing of the *i*-th type of building material (expressed in MJ/Kg).

  Consequently, the initial embodied energy of a building ($E_{E,I}$) is expressed according to the following Equation (3).

$$E_{E,I} = E_{E,I,m} + E_T + E_C \quad (3)$$

Where

$E_{E,I,m}$ is the initial embodied energy of building materials.

E_T is the energy consumed for the transportation of building materials to the construction site.

E_C is the energy used on site for building construction.

However, this bottom-up method truncates the system boundaries at a certain stage of the supply chain with the consequent incapability of accounting for inputs at higher stages or in related supply chains. Hence, the measurement suffers from incompleteness leading to an underestimation of the embodied energy contribution. This issue can be improved by using the second approach focusing on an I-O analysis, which estimates the materials, energy use, and emissions for a given economic sector based on national statistics. However, this method suffers from an aggregation error, as it assigns the same energy intensity to all products within a sector (Stephan et al., 2013). A valid alterative is the hybrid analysis, which combines the benefits of the two traditional methods above by minimising their inherent limitations and errors, although this type of analysis needs to be compared and validated. It is evident that all methods in their practical implementation present some limitations in terms of completeness and reliability, thus no available method is fully efficient and globally accepted to date (Dixit et al., 2010, 2019), leaving the computation of embodied energy a complex area of research, mainly concerning the recurrent embodied energy (Dixit et al., 2019).

— **Operational energy** – The operational energy indicates the energy in terms of thermal (i.e. heating and cooling) and non-thermal (i.e. ventilation, hot water production, lighting and other electrical appliances) loads expended in a building to carry out all activities related to its use, over the building life span. The operational energy can be quantified by using three major approaches, namely (i) energy bills method, (ii) national statistics-based method, and (iii) Building Energy Simulation (BES) methods, as reviewed in Chau et al. (2015) and Omrany et al. (2020; 2021).

The first approach refers to the actual energy consumption records obtained from utility bills (Crawford, 2014; Atmaca and Atmaca, 2015) or energy audit exercises (Escrivá-Escrivá et al., 2011; Ascione et al., 2013), thus the feasibility of this method strongly depends on data availability. The employment of the 'energy bills' method allows researchers to indirectly consider the effects of occupants' behaviours on the energy use on a yearly basis. This aspect represents an important advantage, since a different behaviour of users can result into two/three times variability of operational energy consumption for the same building (Steemers and Yun, 2009; Gram-Hassen, 2010). Despite this potentiality, the method only provides an aggregation value of the energy consumption without its corresponding breakdown by use, thus preventing potential energy use hotspots from ad-hoc interventions for an effective energy reduction within the decision-making process. This drawback may be overcome through the application of monitoring systems consisting of specific sensors and actuators (Cellura et al., 2014; Englund et al., 2020) or simply energy meters (Devi and Palaniappan, 2014), which provide an accurate record of actual data related to both energy consumption and different types of energy use on an daily, monthly, or yearly basis. However, the use of monitoring systems still faces some challenges for its complete optimisation, also in the perspective of the increasing development of smart homes/intelligent buildings. The main issues refer to data interoperability, high initial cost, and difficulty in managing and storing huge amounts of metering data (Ghaffarianhoseini et al., 2017).

The second approach allows the estimation of operational energy consumption by means of energy use databases, commonly provided by governmental bodies based on national/regional statistics. However, the derived results refer to average values of energy consumption, mainly in terms of electricity and natural gas, for a specific building typology (e.g. residential buildings, offices, etc.), depending of its location. The use of average data can illustrate the divergence between the actual and the estimated energy consumption. Moreover, the employment of this method could also suffer from the age of data (Omrany et al., 2021).

The last approach focuses on BES methods, which enable users to compute the operational energy for space heating/cooling by means of dynamic methods to achieve accurate results, which manual methods (e.g. the degree-day or bin methods) difficultly can provide by assuming a steady-state characteristic of building thermal system (Zhai and Chen, 2003, Wang and Zhai, 2016). In the last two decades the BES methods, typically applied through specific tools, result into the most applied approach to compute the operational energy in LCEA studies on conventional and energy-efficient residential buildings, as reviewed in Omrany et al. (2021). However, BES-based results are very sensitive to modelling assumptions, mainly related to inputs inherently variable and stochastic in nature, thus generating uncertainties that lead to discrepancy between predicted and measured energy, commonly denominated as 'performance gap'. The latter depends mostly on an inadequate characterisation of two main classes of input parameters related to (i) occupants' behaviour, and (ii) weather data, often assumed imprecisely or oversimplified (Erba et al., 2017, Englund et al., 2020). However, incorrect modelling of building components and their properties, as well as limitations in the simulation algorithms implemented into the BES software used by an analyst are also limiting factors to achieve accurate results (Erba et al., 2017; Casini, 2021). Over the last two decades, research studies dealing with the energy performance gap of buildings substantially increased. A quite recent review on this critical issue by focusing on its magnitude, causes, and solutions is provided in Shi et al. (2019). Some potential solutions to the performance gap refer to the combination of models with measurement or monitoring calibration (Coakley et al., 2014), model validation with a particular attention to occupancy behaviour (Englund et al., 2020), implementation of hygrothermal simulation for historical buildings (Andreotti et al., 2020), or machine learning (Cho et al., 2019), among others.

Regardless the computational approach, the operational energy (E_O) over the life span of a building is expressed in the following Equation (4).

$$E_O = E_{O,a} \cdot L_b \tag{4}$$

Where

$E_{O,a}$ is the annual operational energy estimated according to one of the three aforementioned approaches.

L_b is the life span (in years) of the building.

— **Demolition energy** – The demolition/end-of-life energy is the sum of energy consumed by the actual demolition process and energy required for transportation of waste, which typically accounts for a negligible share of total life cycle energy consumption (Chau et al., 2015). It can be expressed according to Equation (5), as also reported in Lamperti Tornaghi et al. (2018).

$$E_D = E_{DIS} + E_T \tag{5}$$

Where:

E_{DIS} is the energy used during the demolition/dismantling process.

E_T is the energy consumed for the transportation of materials to landfill/recycling sites

Once the three aforementioned energy contributions associated with the manufacture, use, and demolition phases of a building life are estimated, it is possible to calculate the total energy consumption of the investigated building over its entire life cycle (E_{LC}), according to the following Equation (6).

$$E_{LC} = E_E + E_O + E_D \tag{6}$$

The LCEA is a valid methodology for the assessment of the life cycle energy of buildings, which can be implemented for both design and retrofit of buildings to improve their energy efficiency by focusing not only on thermal requirements for operational energy consumption, but also on embodied energy. Indeed, the E_E significance confirmed the importance to include its estimation into energy efficiency regulations by means of an LCEA, as advocated in the Australian context by Crawford et al. (2016). Nevertheless, a critical review by Omrany et al. (2020) highlighted that the current trend of the LCEA application in residential buildings still suffers from significant inaccuracy of results, mainly due to two aspects: (i) incomplete definition of system boundaries and (ii) lack of consensus related to the existing approaches for calculating embodied and operational energy. Hence, the call for a framework for standardisation of system boundaries in embodied energy measurement is urgently needed, as also underlined nearly one decade ago by Dixit et al. (2012), to facilitate the result comparability and consequently the decision-making process.

2.1.2.5 Building Energy Simulation tools

The BES methods were found to be the most applied approach to compute the operational energy in LCEA studies on conventional and energy-efficient residential buildings in the last two decades (Omrany et al., 2021). The determination of the life cycle energy demand of buildings is a complex task requiring different data sets and matrix calculations. Thus, the development of BES tools increased to facilitate and automate demanding calculation processes or model highly complex systems (Stephan, 2013) to study energy performance of buildings and their heating, ventilation, and air conditioning (HVAC) systems, as well as thermal comfort for their occupants during the building life cycle.

A huge variety of BES programs, equal to more than four hundred tools, has been developed, enhanced and is in use throughout the energy community in the last six decades. Detailed building energy simulation program dates back to the 1970s when the oil embargo first raised energy awareness. Indeed, tools with capability of treatment of multiple thermal zones and HVAC systems under different operating conditions all emerged after this period, followed by a second generation of BES tools in mid-1990s due to the increasing capability of computers and improved programming languages (Wang and Zhai, 2016). A comprehensive list of the available international BES tools to date is provided in the Building Energy Software Tool Directory (BEST-D), managed by the United States International Building Performance Simulation Association (IBPSA-USA) since late 2014, by taking over the former task of the United States Department of Energy (US DOE). Some of these tools are commercial, while others are open-source. An interesting comparison among some BES tools is provided by Crawley et al. (2008), whereas a more recent state-of-the-art review of BES tools can be found in Stavrakakis et al. (2021).

Although the BES tools differ in many aspects, including their thermodynamic models, purpose of use, interoperability with other software applications, they can provide detailed energy information for a whole building and its HVAC system (Zhai and Chen, 2003), relying on detailed simulation techniques to consider the dynamic process of heat flow through the building envelope. The most conventional approach used for transient heat transfer calculation in the majority of BES tools is the conduction transfer function method aimed to predict the hourly cooling load of different types of wall, roof and fenestration. Other methods can be also considered, such as the thermal response factor method, the radiant time series method, lumped parameter models, as reviewed in Wang and Zhai (2016). However, the BES method assumes a well-mixed indoor environment for energy and load calculation which can lead to unsatisfactory results. Hence, the importance of considering an air-flow model to be combined with an energy simulation model emerged and it is still a key-research topic (Zhai and Chen, 2003; Wang and Zhai, 2016; Tian et al. 2018, among others). The most common air-flow models are zonal models, multi-zonal approach, whereas the computational fluid dynamic (CFD) is the most sophisticated one. However, the latter suffers from a high computational cost, which represents the major barrier to couple CFD with BES, although their combination can be a valid tool to seek a holistic solution for the design and operation of low-energy buildings (Tian et al., 2018).

The architecture of BES tools typically consists of two main programs (Maile et al., 2007): (i) the engine software representing the computing core to enable detailed thermal simulations by means of mathematical and thermodynamic algorithms, and (ii) the Graphical User Interface (GUI) serving as an input-output device to facilitate the tool use and the results reading by non-expert users of programming language. However, some BES tools are not developed with their own specific GUI. A brief analysis of some of the most used dynamic BES tools (e.g. EnergyPlus, ESP-r, and TRNSYS) is provided herein, as follows:

— **EnergyPlus** is a US DOE's whole-building energy simulation engine, considered as a second generation energy simulation code by exploiting the features and capabilities of two energy simulations engines, i.e. DOE-2 and Building Loads Analysis and System Thermodynamics (BLAST). It is an open-source software, originally released two decades ago (Crawley et al., 2001) and continually updated with major updates twice annually. However, EnergyPlus features high modelling complexity and needs deep simulation expertise, especially for building geometry and energy systems, thus being particularly complex when used as a stand-alone tool. One of the main drawbacks of EnergyPlus is the absence of a GUI able to provide the user with all the software functionalities. However, DesignBuildier is currently recognised as the most comprehensive GUI for EnergyPlus.

— **ESP-r**, which is the acronym of Environmental System Performance-research, is a transient energy simulation software developed by the Energy Systems Research Unit (ESRU) of the University of Strathclyde, Glasgow in the United Kingdom (UK) with its first prototype released over four decades ago (Clarke, 1977). This open-source software enables the integrated modelling for the simulation of the thermal, visual and acoustic performances of buildings (Coakley et al., 2014). A model built in ESP-r includes a set of thermal zones to which a description of the geometry, characteristics, and use of the building is associated. Each thermal zone refers to the characteristics of the heating, cooling, ventilation, and artificial lighting and the respective operational schedules.

— **TRNSYS** is a TRaNsient SYStem simulation software, originally developed at the Solar Energy Laboratory of the University of Wisconsin-Madison and the Solar Energy Application Laboratory of the University of Colorado to model and validate active solar systems (Van der Veken et al., 2004). This software became commercially available in 1975 and it continues to be developed by the international collaboration of various institutions, namely the two aforementioned laboratories in United States, the Centre Scientifique et Technique du Bâtiment in France, and Transsolar GmBH Energietechnik in Germany. TRNSYS is currently used to perform detailed analyses of any energy system with a time-dependent behaviour, including multi-zone buildings. Specifically, the main applications regard the energy simulation of solar processes, building analysis, thermal energy, renewable energy systems, cogenerations, fuel cells.

2.1.3 Methods and tools for sustainability assessment

The third category of the examined assessment methods refer to sustainable building rating systems based on indicators of different weight to provide a final evaluation score of their sustainability. These methods and tools essentially provide a qualitative assessment of buildings to award sustainability certificates, although they generally focus only on the environmental aspects. The 1990 marked the beginning era of the development and use of rating systems towards sustainable constructions with the introduction of the Building Research Establishment Environmental Assessment Method (BREEAM) in the UK (Ding, 2008; Reed et al, 2009; Retzlaff, 2009; among others), which still remains one the most widely used sustainability rating scheme. Following the launch of BREEAM, many other assessment rating schemes have been developed around the world (Ding, 2008; Haapio and Viitaniemi, 2008) with a growth rate increasing exponentially in few years, mainly during the period 1995-2010 (Bernardi et al., 2017), with a final extent of approximately 600 tools (Reed et al., 2009; Sánchez Cordero et al., 2020; Del Rosario et al., 2021). However, only some of them were recognised as consistent protocols. It is worth noting that these rating systems are usually denoted as Green Building Rating Systems, since the first generation of these protocols was mainly developed to urgently respond to the market needs to assess the environmental performance of whole buildings, neglecting the other two dimensions of sustainable development, i.e. society and economy (Retzlaff, 2009). However, attention should be drawn on the overall concept of sustainability, redefining the scope of building assessment systems, which should focus on the addition of social and economic issues, beyond the environmental ones (Retzlaff, 2009; Ferreira et al., 2014). Examples of this second generation of rating systems refer to the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) system, developed in Germany or the Sustainable Building Tool (SBTool), developed as an international framework.

In general, the framework of the sustainable building rating systems consists of four main components (Bernardi et al., 2017): (i) *Categories*, forming a specific set of items, in terms of criteria and indicators, related to the environmental, economic, social performances considered during the assessment, (ii) *Scoring system*, indicating the performance assessment system that cumulates the number of possible points or credits that can be earned by achieving a given level of performance in several analysed aspects; (iii) *Weighting system*, representing the relevance assigned to each specific category within the overall scoring system, (iv) *Output*, aimed at showing, in a direct and comprehensive manner, the final results of the performances obtained during the scoring phase. However, specific own categories, different calculation methods, credits, and weights characterise each rating system, thus negatively impacting on the comparability of the final score of the assessment, which exhibits a high level of variation depending on the tool (Reed et al., 2009; Ferreira et al., 2014; Dossche et al., 2017; Mattoni et al., 2018). Furthermore, the majority of rating systems are based on local versions, thus being specific of the regional characteristics of the area where the tool was developed. Indeed, only few rating systems provide international versions enabling their application by other countries or regions apart from the origin country, such as BREEAM, Leadership in Energy and Environmental Design (LEED), DGNB, and Haute Qualité Environnementale (HQE).

The recognised heterogeneity of the available rating systems led the scientific community to extensively focus on comparative analyses of various tools, mainly referring to the environmental methods . One the first research study in this direction was provided by Crawley and Aho (1999), followed by the milestone in categorising tools by Haapio and Viitaniemi (2008).

An overview of the most used European and non-European rating systems is provided in the following. Each rating system is described according to three macro-aspects to facilitate their comparability: (i) general information, indicating the *year* and *country* of launch, as well as the *certification body*, (ii) building type application, aimed at indicating whether the method/tool is able to assess *new* or *existing building*, and (iii) assessment method framework. Furthermore, in the light of the review of combined seismic and energy method and tools, each investigated rating system is evaluated by considering if it integrates the following essential indicators*: Energy use, Climate change* in terms of associate CO_2 emissions, and *Natural disaster/seismicity,* as indicated in summary tables at the end of specific sections (i.e. Section 2.1.3.1 – Table 1 and Section 2.1.3.2 - Table 2 for European and non-European rating systems, respectively).

2.1.3.1 European sustainability rating systems

Some of the most widespread and consolidated European rating systems are briefly described with the main information and data collected from technical manuals and official websites (when available), as well as from scientific literature (Bernardi et al., 2017; Mattoni et al., 2018; Sánchez Cordero et al., 2020, among others), as follows:

— **Building Research Establishment Environmental Assessment Method (BREEAM)**

General information - The BREEAM tool was conceived in 1988 by the Building Research Establishment (BRE) in the UK, and subsequently launched on the market in 1990, becoming the world's leading science-based suite of validation and certification systems for a sustainable built environment. Indeed, BREEAM is currently used in more than 80 countries worldwide, after the first release of its international version in 2008.

Application - The BREEAM tool provides a suite of schemes to enable consistent and comparable assessment and verification across the entire built environment life cycle, focusing on both buildings and communities. Specifically, BREEAM New Construction and BREEAM In-use address newly developed and operational commercial and residential assets, respectively. BREEAM Refurbishment & Fit-Out assesses the refurbishment of the external envelope, structure, core services, local services, and interior design of existing buildings. BREEAM Communities concerns the assessment of sustainable design in the master planning of new communities and regeneration projects.

Assessment method framework - The building-level BREEAM tools consider 9 main *categories*: (i) management, (ii) health and wellbeing, (iii) energy, (iv) transport, (v) water, (vi) materials, (vii) waste, (viii) land use and ecology, and (ix) pollution. Each category is divided into a range of assessment *issues* with their own criteria and indicators, awarding different credits, which are subsequently weighted and aggregated to provide the overall score for grading the building/project based on a specific rating scale. Specifically, the BREEAM scheme related to new buildings provides five levels of certification: (i) Outstanding (≥ 85 %), (ii) Excellent (≥ 70 %), (iii) Very Good (≥ 55 %), (iv) Good (≥ 45 %), (v) Pass (≥ 30 %). A sixth level of certification is considered within the BREEAM scheme related to existing buildings and it refers to the following entry-level of certification, i.e. Classified (> 10 %). Furthermore, different threshold scores are considered for the Good (≥ 40 %) and Pass (≥ 25 %) levels.

— **Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) system**

General information - The DGNB system was developed by the Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council), a non-profit organisation founded in 2007, with the collaboration of the Federal Ministry of Transport, Building and Urban Affairs. The tool was launched in the market in 2009 to promote the sustainability in building sector in Germany and to provide an effective procedure for sustainability certification of German buildings. Since its first release, the tool has been continuously developed, and it is currently considered the most advanced sustainability rating system in the world, becoming the market leader in Germany. The DGNB system has also acquired international success, being recognised as the Global Benchmark for Sustainability, since it can be easily adapted to climatic, structural, legal, and cultural variations in other countries. Indeed, DGNB system is currently used in 30 countries worldwide due to its flexibility to create tailored solutions for diverse countries. In this context, a new international version of the DGNB system has been recently released for the assessment of new buildings to further facilitate its worldwide applications (DGNB, 2020) by using international standards (i.e. ISO standards) for the evaluation.

Application - The DGNB system is available in different variants for buildings (residential and non-residential), districts, and interiors, according to a life cycle-based approach, which takes into account the various phases of the life cycle of a building, from planning and construction, via operation and renovation, to end-of-life. Hence, the DGNB system allows users to assess new buildings/districts (planning and construction phases), buildings in-use (operation phase), and existing or renovated buildings (renovation phase). An additional DGBN system to assess the deconstruction of buildings has been recently introduced, but it is still in its pilot phase.

Assessment method framework - Conversely from the majority of sustainability rating systems, the DGNB system includes assessment categories related to the three dimensions of sustainable development – focused on environmental, economic, and social aspects, to which technical aspects are also added. Furthermore, the sustainability assessment categories account for the same importance within the scoring system, thus underlining the relevance of a holistic understanding of a sustainable built environment. Specifically, the assessment framework of the tool consists of six categories, named *topics*: (i) Environmental quality (ENV), (ii) Economical quality (ECO), (iii) Socio-cultural and functional quality (SOC), (iv) Technical quality (TEC), (v) Process quality (PRO), and (vi) Site quality (SITE). Each topic is divided into *criteria group*, which are further sub-divided in specific *criteria* with their own *indicators.* Specifically, the DGNB system foresees 37 criteria for the assessment of new buildings. The criteria are reduced to 22 for the assessment of existing buildings, although in this case the criteria are only available in German. As for the assessment of building in use, an extent of 9 criteria related to only the ENV, ECO, and SOC topics is provided. Regardless the DGNB system application, each criterion can achieve a specific maximum of points based on the corresponding indicators weighted differently depending on their use, the documented or calculated quality. According to the 2020 international version of the DGNB system for new buildings (DGNB, 2020), the ENV, ECO, and SOC topics are weighted equally in the assessment (i.e. 22.5 %), while TEC and PRO topics have lower weights (i.e. 15 % and 12.5 %, respectively). The site quality, which accounts for an even lower weight (i.e. 5 %), is rated independently, thus not affecting the final score to grade a potential assessed building. The DGNB system can provide three levels of certification depending on percentage thresholds of both the total performance index (calculated using all the six topics), and the minimum performance index (MPI) in each of the relevant topic (with exception of the Site quality): (i) Platinum (≥ 80 %, with MPI ≥ 65 %), (ii) Gold (≥ 65 %, with MPI ≥ 50 %), and (iii) Silver (≥ 50 %, with MPI ≥ 35 %). A fourth level of certification, corresponding to Bronze (≥ 35 %) and based exclusively on the total performance index, can be obtained only for the assessment of existing buildings or building in-use.

— **Haute Qualité Environnementale (HQE) approach**

General information - The HQE approach was developed in 1994 in France by the HQE Association. The tool was launched to the market as a voluntary method with the aim of guaranteeing the high environmental quality of buildings. It is structured to have various partners acting as official HQE trademark certification bodies. Specifically three bodies (i.e. Certivèa, Cerqual, and Cèquami) are in charge of delivering national evaluations, depending on the building use type, whereas one body (i.e. Cerway) supports the evaluation across the world since 2013 (Sánchez Cordero et al., 2020), acting in more than 25 countries in different continents (including Europe, Asia, South America) to date.

Application - The HQE approach can be applied to both new and existing buildings.

Assessment method framework - The HQE approach includes assessment categories related to the environmental performance of buildings/districts, along with some aspects related to the social performance, mainly referring to the well-being of people. Specifically, the assessment framework consists of four categories, named *themes*: (i) energy and savings, (ii) environment, (iii) health and safety, and (iv) comfort. Each theme is divided in *targets* (14 targets in total), which are further divided in *sub-targets* with their own *indicators*. The themes and the targets are the same for both residential and non-residential buildings, although targets are arranged differently between the two building use types. The HQE approach provides five levels of certification based on the following scale: (i) Pass (1 star), (ii) Good (2 stars), (iii) Very Good (3 stars), (iv) Excellent (4 stars), and (v) Exceptional (5 stars).

— **Protocollo dell'Istituto per l'innovazione e Trasparenza degli Appalti e la Compatibilità Ambientale (ITACA) – ITACA Protocol**

Background information - In 1996, the Green Building Challenge initiative, later named the Sustainable Building Challenge, set the basis for an international collaborative effort involving representatives from over 20 countries to develop an international building environmental assessment tool. This research process coordinated by the non-profit association International Initiative for a Sustainable Built Environment (iiSBE) led to the development of the Sustainable Building Method (SBMethod). The SBMethod is a generic framework with a twofold objective: (i) to rate the sustainability performance of buildings and projects and (ii) to offer an easy customisation with respect to individual national contexts. Originating from the SBMethod, iiSBE first developed the Sustainable Building Tool (SBTool), formerly known as the Green Building Tool (GBTool), also extending the tool sets over time through the release of the Sustainable Neighbourhood Tool and the Sustainable District Tool. SBTool is a generic framework to assess the sustainable performance (including social and economic aspects beyond the sustainable ones) of site and new or renovation building projects at different phases of the life cycle, i.e. pre-design, design, construction, operations, taking into account region-specific and site-specific context factors., The assessment framework of the SBTool consists of the following seven categories of assessment, named *issues*: (i) A. Site Development and Infrastructure, (ii) B. Energy and Resource Consumption, (iii) C. Environmental Loadings, (iv) D. Indoor Environmental Quality, (v) E. Service Quality, (vi) F. Social, Cultural and Perceptual Aspects, (vii) G. Cost and Economic Aspects. Each issue area is divided in specific sub-sets, named *categories*, which are further sub-divided in *criteria* and their corresponding indicators. The number of criteria (i.e. scope of the system) that can be activated ranges from a maximum version, consisting of more than 100 criteria, to a mid-size or a minimum version. Importantly, SBTool is also intended as a toolkit to assist local organisations to develop their local SBTool rating systems. To this end, SBTool has been adapted to different national contexts, leading to the development of the following sustainability rating systems in various European countries: SBTool PT in Portugal, SBTool CZ in Czech Republic, VERDE in Spain, TQB in Austria, and ITACA Protocol in Italy. Based on the background synopsis on SBTool, details on its Italian version adaptation leading to the release of the ITACA protocol are provided herein.

General information – The ITACA Protocol, derived from the customisation of the international SBTool to the Italian context, is a voluntary rating system that was first developed in 2002 by the Istituto per l'innovazione e Trasparenza degli Appalti e la Compatibilità Ambientale (ITACA) ([4]), i.e. a non-profit association within the political body Conference of the Italian Regions and autonomous Provinces, with the technical support of the iiSBE Italia and the Construction Technologies Institute of the National Research Council of Italy (ITC-CNR). The first release of this national labelling system for assessing the environmental sustainability of residential buildings was officially adopted in 2004. Furthermore, many Italian regions (e.g. Calabria, Campania, Lazio, Marche, Piedmont, etc.) have customised the national system version, adapting it to local features (Mattoni et al., 2018). In 2015, in the context of the collaboration between ITACA and the Italian national standard body (UNI), the ITACA Protocol was identified as the operational tool to be adopted within the UNI reference practice document UNI/PdR 13 for the environmental sustainability assessment of construction works. The document above was last updated in 2019 and consists of three parts devoted to (i) general framework and methodological principles (UNI/PdR 13.0:2019), criteria for the assessment of the environmental sustainability of (ii) residential (UNI/PdR 13.1:2019) and (iii) non-residential (UNI/PdR 13.2:2019) buildings.

Application – The ITACA Protocol can be applied to buildings of different intended uses, including residential and non-residential ones, in their various life cycle stages, i.e. building design, construction, refurbishment, and operation phases.

Assessment method framework – The assessment framework of the ITACA Protocol is based on the master list of issue areas, categories, and criteria implemented in SBTool by including only the first five issues (i.e. the ones regarding the environmental aspects) out of the seven ones considered in SBTool. Specific indicators (quantitave or qualitative) for each criterion are computed and correlated to a benchmark performance scale to determine the point of each criterion, based on a performance assessment scale consisting of 7 performance levels, from the value −1 (performance lower than the standard) to 5 (advanced performance). These normalised values enable the aggregation at category level and then at issue area level to carry out the final aggregation defining the final score of the performance assessment of the examined building.

A synthesis of the information above, along with indications on the essential indicators implemented in each examined European sustainability rating system is provided in Table 1.

([4]) ITACA, Institute for Innovation and Transparency of Procurements and Environmental Compatibility (in Italian)

Table 1. European sustainability rating system.

Rating system	General information			Type of building		Indicators		
	Year of launch	Country of launch	Issuer	New	Existing	Energy use	Climate change	Natural disaster/ Seismicity
BREEAM	1990	UK*	BRE	✓	✓	●	●	/
DGNB system	2009	Germany*	DGNB	✓	✓	●	●	●
HQE	1997	France*	HQE Association	✓	✓	●	●	/
ITACA Protocol	2004	Italy	iiSBE Italia and ITC-CNR	✓		●	●	/

* International use, apart from its origin country/region.

2.1.3.2 Non-European sustainability rating systems

Some of the most widespread and consolidated non-European sustainability rating systems are briefly described with the main data collected from technical manuals and official websites, as well as from scientific literature, as follows:

— **Building Environmental Assessment Method (BEAM Plus)**

General information - **BEAM Plus** is a voluntary scheme for the assessment of the environmental performance of buildings. The tool was first launched in Hong Kong in 1996 with the name of Hong Kong-Building Environmental Assessment Method (HK-BEAM) by the Real Estate Developers Association of Hong Kong (Hui et al., 2017) and developed by the non-profit public body BEAM Society, become BEAM Society Limited (BSL) since 2010. The first version of the HK-BEAM tool, largely based on BREEAM scheme, aimed to reduce the environmental impacts of new and existing office buildings to subsequently extend the scheme to high-rise residential buildings (Yau et al., 2014). A brief history of the tool evolution until releasing the first version of the revised assessment system under the name of BEAM Plus in 2009 is provided by Hui et al. (2017). Since 2010, the tool started to gain popularity with a consequent increasing number of buildings certified by the Hong Kong Green Building Council (HKGBC) with this scheme, also due to the 2011 requirement issued by the Hong Kong Government's Building Department to foster a sustainable built environment. Currently, BEAM Plus has extended reach to geographical areas outside Hong Kong, including Macau, Shenzhen, Guangzhou, Shanghai and Beijing.

Application - The BEAM Plus system includes a family of assessment tools focused on the entire built environment, from a single building to the neighbourhood planning, across the whole life cycle of buildings and projects. Specifically, four BEAM Plus tools are available depending on the project needs: (i) New Buildings, (ii) Existing Buildings, (iii) Interiors, and (iv) Neighbourhood. Recently, a beta version tool to assess existing school buildings is in its pilot phase. The BEAM Plus New Buildings (BEAM Plus NB) and BEAM Plus Existing Buildings (BEAM Plus EB) tools (currently, available in their Version 2.0) cover all types of new and existing buildings, respectively, including both residential and non-residential buildings (e.g. commercial, educational, government, industrial, office hotels, etc.). The BEAM Plus NB tool (BSL, 2021a) focuses on planning, design, and construction of new buildings, but it can also be applied when planning major renovations, alterations and additions of existing buildings. The BEAM Plus EB tool (BSL, 2021b) evaluates the operation and maintenance performance of existing buildings. Furthermore, the BEAM Plus Interiors, first launched in 2013, addresses the needs of the most common non-domestic interior fit-out projects. Finally, the BEAM Plus Neighbourhood tool, first released in 2016, addresses sustainability issues at the early stage or master planning stage of a project.

Assessment method framework - The assessment framework of the BEAM Plus tools relies on various categories, indicated as *assessment aspects*. Each category consists of various *core objectives*, further subdivided into specific *prerequisites* and *criteria*, which allow the attainment of different normal and bonus credits. Specifically, buildings and projects have to first fulfil various prerequisites, thus providing an assessment baseline, in order to proceed with the remaining assessment to allocate the criteria credits and award the BEAM Plus certification. In case the project fails to demonstrate compliance to any of the applicable pre-requisites, it will be graded as 'Pre-requisite(s) Not Achieved'. Similar categories are considered for the whole BEAM Plus tool family, although the nature and the number of credits, as well as the weight of each category differ by tool. Focusing on building-level BEAM plus tools, the assessment framework of the BEAM Plus NB tool consists of seven assessment aspects: (i) Integrated Design and Construction Management (IDCM), (ii) Sustainable Sites (SS), (iii) Materials and Waste (MWA), (iv) Energy use (EU), (v) Water use (WU), (vi) Health and Wellbeing (HWB), and (vii) Innovations and Additions (IA). A total of 121 normal credits can be achieved for the assessment of new buildings in 69 criteria, after satisfying a total number of 8 prerequisites. Seven analogous assessment aspects are also considered for the BEAM Plus EB tool. However, the IDCM, HWB, and SS categories are substituted by the Management (MAN), Site Aspects (SA), and Indoor Environmental Quality (IEQ) categories, respectively. Furthermore, the BEAM Plus EB tool enables two major assessment approaches since 2016, namely (i) comprehensive or (ii) selective scheme. The former regards the assessment of all aspects according to a one-step or a step-wise approach, whereas the latter is based on an individual aspect assessment approach. As for the BEAM Plus EB comprehensive scheme, a total of 8 prerequisites and 67 criteria are considered for a total allocation of 150 attainable normal credits. It is worth noting that the IA category includes only bonus credits for both new and existing buildings assessment tools, thus the corresponding criteria and credits were not included into the total counting above. A maximum possible score of credits under each category equal to 100 % can be reached by transforming the corresponding achieved credits in percentage to subsequently compute the weighted score. As for the BEAM Plus NB tool, the EU category accounts for the highest percentage weight (29 %), followed by the HWB (22 %), IDCM (18 %), SS (15 %), MW (9 %) and WU (7 %) categories. As for BEAM Plus EB tool, the MAN and EU categories account for the same weight (24 %), followed by the MWA, WU, and IEQ categories (14 %) and, finally, by the SA category (10 %). The overall rating by aggregating the weighted score of all the assessment categories enables to award the assessed building/project. Specifically, the BEAM Plus assessment scheme for both new and existing buildings provides four levels of certification depending on score thresholds, namely (i) Platinum (≥ 75), (ii) Gold (≥ 65), (iii) Silver (≥ 55), and (iv) Bronze (≥ 40). However, the building certification is achieved if minimum percentages for each category are obtained.

— Comprehensive Assessment System for Built Environment Efficiency (CASBEE)

General information - CASBEE is a sustainability rating system of buildings and built environment developed in Japan in 2001 by the Japan Sustainable Building Consortium (JSBC), which is a nongovernmental organization comprising the Japanese government, academic partners, and industry, under the auspices of the Housing Bureau. The tool was launched on the international market in 2005, becoming mandatory in various Japanese municipalities since 2011, until reaching a number of 24 municipalities in 2014 (JSBC, 2014).

Application - The tool has been designed to both enhance the quality of people's lives and to reduce the life cycle resource use and environmental loads associated with the built environment, from a single home to a whole city. Indeed, CASBEE consists of assessment tools tailored to different scales, namely housing scale, building scale, urban scale (urban blocks and town development), and city scale, collectively known as the CASBEE family. It is worth noting that the tool developed for the assessment at building scale (CASBEE for Building), which is applicable to all residential (except detached houses) and non-residential building types, relies on four basic versions of CASBEE, which correspond to the individual stages of a building life cycle (i.e. Pre-design, New Construction, Existing buildings, and Renovation).

Assessment method framework - The assessment method implemented in CASBEE is based on the evolution of the concept of eco-efficiency to integrate two main assessment categories taking into account the inside and outside of the building site: (i) built environment Quality (Q), and (ii) built environment Load (L). The two categories represent two metrics evaluating the 'improvement of living amenity for the building users' and the 'negative aspects of environmental impact beyond the site boundary', respectively. The ratio between Q and L provides the Built Environment Efficiency (BEE) indicator, which represents the core concept of CASBEE. The BEE indicator can be presented numerically, according to Equation (7). Specifically, the Q category is divided into three main sub-categories: *Indoor environment* (Q1), *Quality of service* (Q2), and *Outdoor environment* (Q3). Similarly, L is divided into *Energy* (L1), *Resources and Materials* (L2), and *Off-site Environment* (L3), generally indicated as load reduction (LR). The values for Q and L, ranging from 0 to 100, are achieved by converting the total score for the Q sub-categories (SQ) and the total score for the LR sub-categories (SLR), which are assessed according to a five-scoring level system (from 1 to 5), into the Q and L scales of 0 to 100, according to the following Equation (7).

$$BEE = \frac{Q}{L} = \frac{25\,(SQ - 1\,)}{25\,(5 - SLR)} \tag{7}$$

The BEE indicator can be also represented graphically, since it is expressed as the gradient of a straight line passing for the origin of a graph that has L on the x-axis and Q on the y-axis in a Cartesian plane. The higher the Q value and the lower the L value, more the building is sustainable.

Finally, the CASBEE assessment is ranked in five grades corresponding to decreasing BEE value: (i) Superior – S (BEE ≥ 3 and Q ≥ 50), (ii) Very Good – A (1.5 ≤ BEE < 3 and Q < 50), (iii) Good - B+ (1 ≤ BEE < 1.5), (iv) Slightly Poor - B- (0.5 ≤ BEE < 1), and (v) Poor - C (BEE < 0.5), also expressed as a number of stars (from 5 to 1) to facilitate the final assessment interpretation.

— **Green Star**

General information - Green Star is a national and voluntary environmental rating system for buildings and communities launched in 2003 by the Green Building Council of Australia (GBCA).

Application - Green Star consists of a suite of four rating tools to carry out certifications at different scales of the built environment: (i) building design and construction, (ii) operation, (iii) interiors, and (iv) communities. Sustainability of projects can be assessed at all stages of the built environment life cycle.

Assessment method framework - The system assesses a broad range of sustainable issues to improve the environmental efficiency of buildings, also considering occupants' health and productivity, and cost savings.

— **Leadership in Energy and Environmental Design (LEED)**

General information - The first version of the LEED rating system was launched as a voluntary, market-based assessment method in the USA in 1998 by the US Green Building Council (USGBC), a non-governmental organization that includes representatives from industry, academia, and government. The framework of LEED is periodically updated to better reflect developing strategies, leading to the release of its last version, i.e. LEED v4.1 in 2018, which is still in use.

Application - The LEED system intends to evaluate the environmental performance of whole buildings, both new and existing, over their life cycle (design, construction, maintenance and operation) providing a globally recognised certification. Different schemes are designed for rating various types of projects including new construction (e.g. school, retail, hospitality, healthcare, data centres), existing buildings, residential buildings, as well as interior design and even city and communities. Furthermore, the possibility to carry out a LEED recertification is also available to all occupied and in-use projects that have previously achieved certification under LEED to monitor their performance long after their construction and occupation.

Assessment method framework - The various schemes have different has the same list of performance requirements set out in seven categories, namely (i) Integrative process, (ii) Location and transportation, (iii) Sustainable sites, (iv) Water efficiency, (v) Energy and atmosphere (vi) Materials and resources, (vii) Indoor environmental quality, (viii) Innovation in design, and (ix) Regional priority. The first fundamental element to proceed with a LEED assessment of a building refers to minimum, mandatory requirements, named 'prerequisites', which an examined project needs to meet in order to achieve LEED certification. Once the prerequisites are met, the project can earn 'points' by adhering to non-compulsory 'credits' that address different areas such as carbon, energy, water waste, transportation, materials, health and indoor environmental quality. The number of prerequisites, credits, and available points change considerably according to the specific area of interest and the building type. The scoring system foresees a maximum score equal to 100 points, plus up to 10 additional bonus points for complying with two special categories, i.e. 'Innovation in design' and 'Regional priority'. Out of the total of 100 points, a minimum of 40 points should be obtained after the assessment to pass the basic evaluation. Specifically, LEED has four levels of certification depending on defined point thresholds: (i) Platinum (> 80 points), (ii) Gold (60-79 points), (iii) Silver (50-59 points), and (iv) Certified (40-49 points).

A synthesis of the information above, along with indications on the essential indicators implemented in each examined non-European sustainability rating system is provided in Table 2.

Table 2. Non–European sustainability rating systems

Rating system	General information			Type of building		Indicators		
	Year of launch	Country of launch	Issuer	New	Existing	Energy use	Climate change	Natural disaster/ Seismicity
BEAM plus	1996	Hong Kong	HKGBC	✓	✓	●	●	/
CASBEE	2001	Japan	JSCB	✓	✓	●	●	●
Green Star	2003	Australia	GBCA	✓	✓	●	●	/
LEED	1998	USA	USGBC	✓	✓	●	●	/

2.1.3.3 Hybrid sustainability assessment methods

The picture on the most used sustainability rating systems at both international and national level underlines the need to create a holistic transparent and regionally adaptable tool that can be used by policy makers and stakeholders in any country within the EU (Sánchez Cordero et al., 2020) to overcome the difficulty of managing the extensive heterogeneity of the existing certification schemes. A significant attempt in this direction within the European context started in 2015 when the Joint Research Centre (JRC - Seville) of the European Commission initiate to develop a new tool, named **Level(s)**, which is a voluntary reporting framework to improve the sustainability of buildings, based on a common system of indicators. Furthermore, since 2019 the EU-funded LIFE Level(s) project has been supporting the alignment of assessment and certification schemes and public procurement criteria with Level(s) (European Commission, 2021) in partnership with some of the most recognisable Green Building Councils across Europe in order to foster the ambitious challenge of creating a common language for the sustainability assessment of buildings.

In order to provide an overview of the tool consistent with the previous analyses related to the European and non-European sustainability rating systems, the description of Level(s) also refers to the three following macro-aspects: (i) general information, (ii) building type application, and (iii) assessment method framework.

General information: The project for the development of Level(s) accounts for three main phases. The project started in 2015 leading the JRC to launch the beta version of the tool in 2017 (Dodd et al., 2017a; b) (Phase 1 – 2015-2017), followed by a two-years testing period, during which 136 buildings including residential and office buildings were tested in all Europe (European Commission, 2019) (Phase 2 – 2018-2020), which led to the release of the first official version of the tool (i.e. version 1.1) in 2020 (Dodd et al., 2021) (Phase 3 – 2020-2021). The comprehensive package of publications including specific reports and documents related to each of the three development phases above can be retrieved at Product Policy Bureau – Level(s) common framework.

Application: Level(s) can be used to report on and improve the performance of new buildings and major renovation projects.

Assessment method framework: Level(s) features similar aspects to the most common sustainability rating systems by using core sustainability indicators to measure carbon, materials, water, health, comfort and climate change impacts throughout a building's entire life cycle. Specifically, six assessment categories, named *macro-objectives*, are considered along with 16 indicators. One of the novel aspect of Level(s) framework refers to its capacity to provide both qualitative and simplified quantitative assessments, depending on the stage of the building's life-cycle a stakeholder wants to assess, thus it can be considered as a hybrid tool integrating peculiarities of rating systems and quantitative methods.

2.1.4 Combined methods for seismic and energy assessment

The fourth category of the examined assessment methods focuses on the scientific research efforts carried out in the last decade to provide quantitative assessment methods for a sustainable integrated retrofit of buildings. Indeed, the need of a radical change of direction by considering a building as a multi-performance whole with different potential deficiencies to be simultaneously improved is underlined by recent studies, aimed at emphasising an integrated retrofit (Belleri and Marini, 2016; Passoni et al., 2021) based on a fully quantitative approach. Furthermore, the importance of considering a LCT-oriented method is at the forefront of scientific awareness, since buildings produce environmental, economic, and social impacts during all the stages of their life cycle (Passoni et al., 2022).

The first step to overcome the use of single performance assessment methods led to the development of a group of assessment methods, broadly indicated as *partly coupled assessment methods*, aimed at combining only a couple of different building performance. Some applications in this direction are related to the integration of environmental requirements and safety targets (Menna et al., 2013; Wei et al., 2016a; Lamperti Tornaghi et al., 2018), the combination of economic and social impacts as consequences of various seismic retrofit options (Calvi, 2013), or the assessment of seismic risk on the economic management of energy retrofit processes (Mauro et al., 2017).

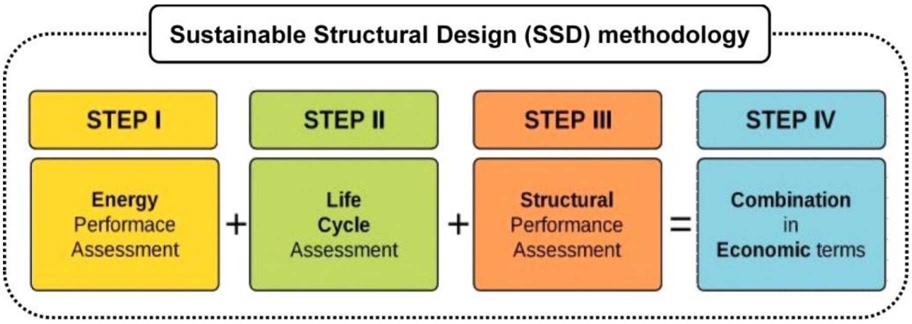
A recent comprehensive review of this class of methods towards the development of holistic methods is provided in Passoni et al. (2021). Holistic methods have the potential to address the retrofit process by using different data such as energy, structural, functional needs, among others, as overall input parameters based on a LCT perspective (Passoni et al., 2021). However, holistic design/assessment quantitative tools are still at an initial stage of development due to the complexity of integrating so many different input data (Romano et al., 2020). According to the scope of this report, attention is drawn on the overview of the existing methodologies devoted to the combined seismic and energy retrofit assessment; a recent detailed review of which can be also found in Menna et al. (2022).

Calvi et al. (2016) extended the procedure developed in Calvi et al. (2013) and introduced the Green and Resilient Indicator based on two parameters, namely the energy and the seismic expected annual losses to compare different retrofit strategies through a cost-benefit analysis. Based on this generic framework, integrated approaches devoted to RC (Mauro et al., 2017) and masonry (Sassu et al., 2017) buildings were also introduced by using an economic parameter as common denominator for the combined seismic and energy assessment of retrofit interventions. One of most promising methodologies in this direction refer to the SSD methodology (Lamperti Tornaghi et al., 2018), which also includes environmental performance assessment of new/retrofitted buildings, as briefly described in the following.

2.1.4.1 The Sustainable Structural Design (SSD) methodology

The Sustainable Structural Design methodology was developed within the SAFEty and SUSTainability (SAFESUST) research activity, proposed at the Joint Research Centre (JRC - Ispra) of the European Commission, and aimed at defining a holistic approach to optimise at the same time safety and sustainability of structures (Caverzan et al., 2018) in both their design and retrofit process. The SSD methodology addresses at the same time the energy, environmental, and structural safety performances of a new or an existing building during its life cycle, resulting into a final unique parameter in economic terms to facilitate the selection of the most appropriate design/retrofit solution. The framework of the SSD methodology consists of four main steps (Figure 5). First, the three following assessment steps are performed: (i) *STEP I - Energy Performance Assessment*, (ii) *STEP II - Life Cycle Assessment*, and (iii) *STEP III - Structural Performance Assessment*. Subsequently, the outcomes of the three previous steps are converted in cost and combined into a global assessment parameter in monetary units, defining the final step of the methodology, i.e. *STEP IV – Combination in economic terms*.

Figure 5. Framework of the SSD methodology



Source: ©Lamperti Tornaghi e al., 2018 (CC BY 4.0)

A detailed description of each step of the SSD methodology is provided in Lamperti Tornaghi et al. (2018), whereas a synopsis is reported , as follows:

— **STEP I – Energy Performance Assessment** – The first step deals with the assessment of the operational energy consumed by a new or an existing building during the use phase of its life cycle, thus corresponding to the energy needed for space heating, space cooling, lighting, use of appliances, etc. Although this evaluation could be part of a conventional LCA or a LCEA, as extensively described in Section 2.1.2, it is performed independently in the SSD methodology since the cost of energy (needed to compute the final result of the SSD methodology) might already include some forms of carbon tax, which represents the environmental impact corresponding to the production and use of the energy from whatever source. Furthermore, the energy performance assessment is routinely performed by professionals, mechanical, electric, and plumbing (MEP) engineers, who mobilise specific competences resulting different from the LCA ones.

  The operational energy is computed according to one of three following main approaches: (i) energy bills method, (ii) national statistics-based method, and (iii) BES methods (details are provided in Section 2.1.2.4). Regardless the used method, its output is the annual operational energy consumption per square meter of building surface, typically in terms of electricity ($E_{O,a}^{Electricity}$, expressed in KWh/m^{2}year) and natural gas ($E_{O,a}^{Gas}$, expressed in KWh/m^{2}year or m^3/m^{2}year). These results enable the subsequent computation of the STEP I outcomes represented by the total operational energy in terms of electricity ($Q_E^{Electricity}$, expressed in KWh) and natural gas (Q_E^{Gas}, expressed in KWh or m^3) consumptions over the life span of the examined building (L_b) (e.g. 50 years for ordinary structures), according to the Equations (8) and (9), respectively.

$$Q_E^{Electricity} = E_{O,a}^{Electricity} \cdot A_b \cdot L_b \tag{8}$$

$$Q_E^{Gas} = E_{O,a}^{Gas} \cdot A_b \cdot L_b \tag{9}$$

  Where:

  A_b is the total surface of the examined building (expressed in m^2).

— **STEP II – Life Cycle Assessment** – The second step refers to the assessment of the environmental impacts of a new or existing building according to a cradle-to-grave approach, carried out by means of the four-step LCA methodology according to the standard ISO 14040-44:2006 (details are provided in Sections 2.1.2.1 and 2.1.2.2).

  The functional unit and system boundaries shall be defined according to the object of the analysis, e.g., two refurbishment alternatives or the refurbishment vs demolition & reconstruction. The assessment of the ecological impacts mainly refer to the GWP impact category in order to evaluate the GHG emissions in terms of CO_2-equivalent emissions due to the structural and non-structural components of the examined building.

— **STEP III – Structural Performance Assessment** – The third step focuses on the assessment of the structural performance of a new or an existing building and it is based on the consolidated PEER-PBEE methodology addressing the importance of integrating the seismic loss-assessment within structural design (details are provided in Section 2.1.1.1). However, this methodology results particularly difficult for ordinary projects due to complex probabilistic relations, high number of parameters, and inherent uncertainties in the assessment (Lamperti Tornaghi et al., 2018), therefore a simplified Performance-Based Assessment (sPBA) methodology has been introduced (Negro and Mola, 2017), based on the direct application of the total probability theorem. The framework of the sPBA methodology consists of four interconnected steps, briefly described, as follows:

  - *Step 1 - Limit States Definition* – The first step concerns the definition of different limit states based on building damageability, typically referring to as (i) low-damage limit state, (ii) heavy-damage limit state, (iii) severe structural damage limit state, and (iv) near collapse limit state.

The Engineering Demand Parameter (EDP) that measures the structural damage is the Inter-storey Drift Ratio (IDR).

- *Step 2 - Structural Analysis* - The second step focuses on the computation of the PGA values to attain the IDR values obtained in Step 1. Specifically, incremental dynamic analyses (IDA) or non-static linear analyses (i.e. pushover analyses) are carried out to this purpose.
- *Step 3 - Hazard analysis* - The third step deals with the computation of the probability of exceedance of the PGA values, calculated in Step 2. Modern seismic design codes provide the relation between the PGA and the return period (T_R). As an indicative example, the Italian seismic code, i.e. NTC 2008 (Ministerial Decree 14/01/2008); NTC 2018 (Ministerial Decree 17/01/2018), provides a set of PGA values for nine return periods, along with an interpolation formula for computing the seismic hazard parameters (*p*) needed to define the design seismic action for any site of the national territory and any T_R value into the range 30-2475 years (NTC, 2008 - Annex A and B). In the context of the Step 3 of the sPBA methodology, the interpolation formula is properly adapted by specifying one of the generic parameter seismic hazard (p) as the PGA ($p = a_g = PGA$), according to Equation (10).

$$\log(a_g) = \log(a_{g1}) + \log\left(\frac{a_{g2}}{a_{g1}}\right) \cdot \log\left(\frac{T_R}{T_{R1}}\right) \cdot \left[log\left(\frac{T_{R2}}{T_{R1}}\right)\right]^{-1} \tag{10}$$

Where:

a_g is the PGA computed for each limit state.

T_R is the return period to be computed for each limit state, based on the PGA values.

Based on the PGA values from the previous step, the corresponding T_R can be determined for each limit state, according to Equation (10), to subsequently compute the probability of exceedance of the PGA values in N years (R_N), according to Equation (11).

$$R_N = 1 - \left(1 - \frac{1}{T_R}\right)^N \tag{11}$$

Where:

N is set to the expected lifespan (expressed in years) of the structure.

- *Step 4 - Cost analysis* - The last step of the sPBA methodology refers to the assessment of the expected losses for each limit state (L_i) based on the corresponding costs for the repair interventions (C_i) to structural and non-structural components of a building due to seismic damages. Hence, the total expected loss (*L*) is computed by the direct application of the total probability theorem, according to Equation (12).

$$L = \sum_i C_i \ (R_{Ni} - R_{Ni+1}) \tag{12}$$

— **STEP IV – Global Assessment Parameter** - The outputs of the three previous steps of the SSD methodology are expressed in terms of different units of measurement, namely operational energy consumption due to electricity (expressed in kWh) and heating (expressed in kWh or m^3 – natural gas) for the Energy Performance Assessment (STEP I), mass of CO_2-equivalent emissions (expressed as tCO_2eq) for the Life Cycle Assessment (STEP II), and expected seismic loss (expressed as €) for the Structural Performance Assessment (STEP III). It is easily inferred that the three outcomes cannot be combined, thus results of the energy and environmental performance assessment need to be converted into monetary terms in order to subsequently proceed with summing up the energy, environmental, and structural costs into a single global assessment parameter (R_{SSD}) in economic terms.

The **operational energy consumptions** in terms of electricity ($Q_E^{Electricity}$, expressed in kWh) and natural gas (Q_E^{Gas}, expressed in kWh), obtained from STEP I, are transformed into costs by means of the electricity ($P_E^{Electricity}$, expressed in €/KWh) and natural gas (P_E^{Gas}, expressed in €/KWh) unitary prices, provided by Eurostat according to various criteria (e.g., level of taxes, consumption bands, etc.) differentiating between electricity and natural gas databases. The electricity and natural gas unitary prices are available in Eurostat as bi-annual data for each EU Member State, as well as in terms of the EU-27 average price, for both household and non-household consumer categories. Specifically, electricity and natural gas price statistics over the period 1985 - 2021 can be retrieved from Eurostat – Energy Statistics.

Once the unitary prices have been selected, the corresponding total energy costs in terms of electricity and natural gas are computed according to Equation (13) and (14). Subsequently, the total cost for the operational energy consumption (R_E) can be obtained according to Equation (15).

$$R_E^{Electricty} = Q_E^{Electricty} \cdot P^{Electricty} \tag{13}$$

$$R_E^{Gas} = Q_E^{Gas} \cdot P^{Gas} \tag{14}$$

$$R_E = R_E^{Electricty} + R_E^{Gas} \tag{15}$$

The **environmental impacts** in terms of CO_2-equivalent emissions (Q_{CO2}, expressed in tCO_2eq), obtained from STEP III, are converted into cost by means of the unitary carbon price (P_{CO2}, expressed in €/tCO_2eq). Once the carbon price is selected, the corresponding environmental costs are computed according to Equation (16).

$$R_{CO2} = Q_{CO2} \cdot P_{CO2} \tag{16}$$

An excursus concerning the most significant developments to date within the carbon market needs to be introduced to identify the carbon price serving for the computation of the environmental impacts in monetary units. The importance to urgently mitigate and adapt against the effects of climate change and the degradation of natural defenses was initially recognised at international level with the Kyoto Protocol (UN, 1997). The 2015 Paris UN Climate Change Conference (COP21) (UN, 2016) represented another fundamental step in this direction. Indeed, this international plan has marked an historic turning point in global action on climate change, establishing for the first time a legally binding and climate agreement, which sets the world on a zero carbon, resilient and fair future. To this end, different types of policies and measures defining the carbon price have been adopted in the last two decades to internalise the external cost of climate change (Romano et al., 2014; The World Bank, 2021) in order to mitigate GHG emissions through price signals. The main direct mechanisms of carbon pricing refer to carbon taxes and emission trading systems (ETS) in the form of cap-and-trade or baseline-and-credit systems. Another explicit instrument is the internal carbon pricing, voluntarily used by corporations, organizations, and governments to internally guide their decision-making process in relation to climate change impacts, risks, and opportunities. However, indirect instruments can be also considered to derive an implicit carbon price, such as through fossil fuel taxes, the removal of fossil fuel subsidies, and regulations that may incorporate a 'social cost of carbon' (The World Bank, 2021).

At European level, the cap-and-trade **European Union Emission Trading System** (EU-ETS) represents the EU's cornerstone strategy to tackle climate change, first established in 2005 to anticipate the 2008-2012 Kyoto Protocol target, and currently at its fourth trading period (2021-2030). Consequently, the EU-ETS has been selected as the most effective instrument to identify the unitary carbon price (expressed as

€/tCO_2eq) for the SSD methodology. An overview of the EU-ETS and its corresponding carbon market is provided to underline the importance of considering an adequate carbon price to reduce emissions in an effective and cost-efficient way (CPCL, 2017), as also emphasised by President von der Leyen in the State of the Union address 2020 ([5]) to the Parliament. The EU ETS is the oldest cap-and-trade system setting the carbon price in the EU and it is currently recognised as the world's largest domestic carbon market. The EU ETS Directive, revised in 2018 (Directive 2018/410), regulates the EU ETS, which allows EU Member States to respect their obligations of reducing GHG emissions in a cost-effective way. It is worth noting that national binding annual GHG emission targets for sectors not included in the EU ETS, such as transport, buildings, agriculture, and waste, are regulated by the Effort Sharing legislation for the periods 2013-2020, i.e. Effort Sharing Decision (Decision 406/2009/EC), and 2021-2030, i.e. Effort Sharing Regulation (ESR) (Regulation (EU) 2018/842). However, contrary to the EU ETS, sectors covered by the ESR are not subject to an EU-wide carbon price signal. Hence, the recent proposal of revising the EU ETS (Proposal COM (2021)551), as part of the 'Fit for 55' legislative package (COM (2021)550), includes the introduction of a new separate, but adjacent, emissions trading system to address emissions from fuels used in road transport and buildings in a cost-efficient way. Indeed, the new system would complement the ESR in meeting the national emission reductions in a cost-efficient way by additional economic incentives (through carbon pricing). Based on the main features of a cap-and-trade system, the EU ETS sets an upper limit, i.e. the cap, on the total amount of GHG emissions that businesses covered by the system (i.e. power, industry, and aviation) can emit each year. Furthermore, a fixed number of emission permits (equivalent to the cap), called EU emission allowances (EUAs), are issued. EUAs are allocated for free or auctioned out according to specific criteria. The issued EUAs can be traded as needed: the businesses covered in the EU ETS can sell excess allowances or buy additional allowances depending on their success in reducing or not their own emissions within the cap, respectively. One EUA represents the right to emit one tonne of CO_2-equivalent, thus becoming the currency of the emission trading. Both auctioning to issue the initial amount of EUAs to the involved companies (primary market) and trade between the businesses (secondary market) help to set the carbon price, determined by EUAs supply and demand. The EU-ETS is implemented in trading phases, namely Phase 1 (2005-2007), Phase 2 (2008-2012), Phase 3 (2013-2020), and Phase 4 (2021-2030), evolving over the years, and gradually becoming more restrictive to meet the ambitious EU decarbonisation targets. Details on the development of the various phases, focusing on different aspects (e.g. ETS size, allocation, etc.), can be found in IACP (2021). However, it is worth mentioning the significant changes of the Phase 3 devoted to set a single EU-wide cap on emissions and use auctioning as the default method for allocating EUAs. Furthermore, within Phase 3 the amount of EUAs equivalent to the cap was reduced compared to the two previous phases by considering a linear reduction factor equal to -1.74 % per year, further increased to -2.2 % per year as of Phase 4 (COM (2020)740).

Large fluctuations of the carbon price occurred within the various trading periods with a downward trend until 2017 (Figure 6). Phase 1 established the initial carbon price reaching a value of 30 €/tCO_2eq in 2006, which drastically fell to 7 €/tCO_2eq in the Phase 2 due to the 2008-2009 financial crisis. The latter led to a large surplus of EUAs, which were transferred from Phase 2 to 3, thus also bringing a very low EUA price equal to an average of 7 €/tCO_2eq within the third trading period until 2017. A price surge was finally achieved in 2018 with the highest registered EUA price stood at about 25 €/tCO_2eq in September 2018 (COM (2020)740). This radically different trend finds its main reasons in the EU market design reforms, such as the entry in force of the revised EU ETS directive (Directive 2018/410), the EU-ETS revision for the Phase 4, and the EU decision on a Market Stability Reserve (MSR) (Decision 2015/1814). The latter, becoming operational since January 2019, addresses market imbalances by temporarily adjusting allowance supply to consequentially avoid future shocks, which can severely reduce the carbon price as occurred in the previous trading phases. The carbon price signal remained strong, levelling at an average of almost 25 €/tCO_2eq until the end of 2020. The phase 4 initiated with an increasing trend of prices passing from more than 30 €/tCO_2eq at the beginning of 2021 to about 60 €/tCO_2eq after six months (COM (2021)962), further increasing to date. The acceleration of the price increase in the last two years could depend on different factors, such as growing credibility in the EU–ETS scheme, MSR activity, higher gas prices, whereas a speculative activity in the market appear unlikely (Ampudia et al., 2017). High prices are fundamentally a sign that the market is pricing in the cost of transition to a greener economy and they are needed to provide the right incentives to meet the stringent EU climate-neutrality goal by 2050 (CPCL, 2017).

([5]) State of the Union 2020, https://state-of-the-union.ec.europa.eu/state-union-2020_en

Figure 6. EUA price trend within the trading phases 2 and 3 of the EU ETS

Note: The EUA price rise observed from 2017 is attributed by the Carbon Tracker report "Carbon Countdown: Prices and Politics in the EU-ETS", to the market's anticipation of the start-up from January 2019 of the Market Stability Reserve (MSR), agreed in 2017.

Source: ECA, based on data from Sandbag.

Source: European Court of Auditors (ECA), 2021 (CC BY 4.0)

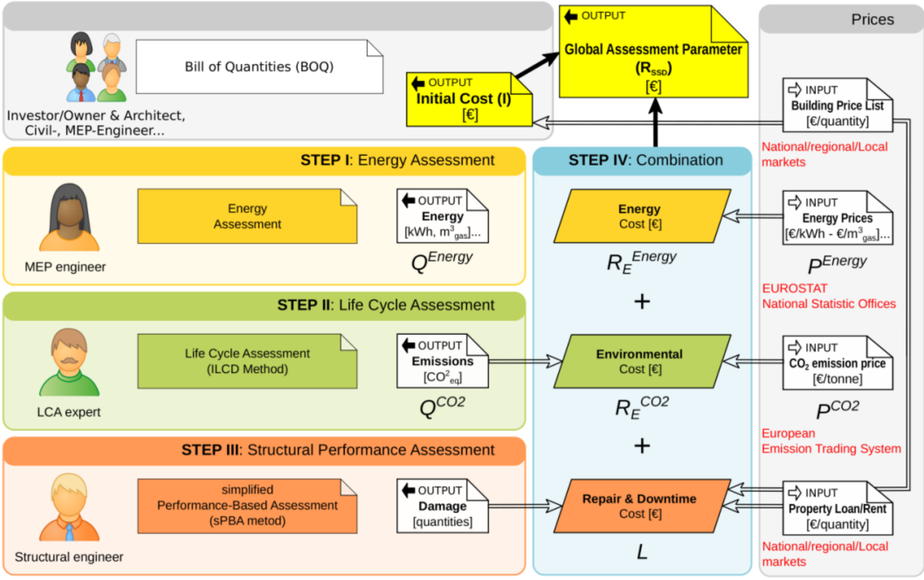
Various accredited exchange markets related to different international organisations provide historical and current data on the carbon price for the EU ETS, such as the World Bank by means of the Carbon Pricing Dashboard platform, and the International Carbon Action Partnership (ICAP) through the Allowance Price Explorer (APE) tool. At European level, the European Energy Exchange (EEX), in Leipzig (Germany), awarded the leading role as the EU common platform for EUAs auctioning, providing both daily EUA auction clearing prices (primary market) and EUA spot (daily expiry), future, and future-style options prices (secondary market). Hence, in the context of the SSD methodology, the EEX is selected to identify the unitary carbon price needed to convert the amount of tonnes of CO_2-equivalent emissions into equivalent costs. Specifically, the EEX spot price of one EUA resulted equal to 76.50 €/tCO_2eq at the end of March 2022 (specific date of observation: 24th March 2022).

Once the energy (R_E) and environmental (R_{CO2}) costs are obtained, they can be combined with the structural cost (L) to compute the R_{SSD}, according to Equation (17).

$$R_{SSD} = R_E + R_{CO2} + L \tag{17}$$

A significant advantage of the SSD methodology is the capacity to offer a common language (in monetary units) to all the design process operators, such as owners, stakeholders, engineers, etc. (Figure 7). Indeed, a key-aspect of this methodology is sharing and coordinating the best design/retrofit practices already available and used by different experts in the building sector, as well as owners and investors. Hence, decision makers can compare and evaluate all parameters, which are independently regulated by their respective markets.

Figure 7. Different operators involved in each step of the SSD framework



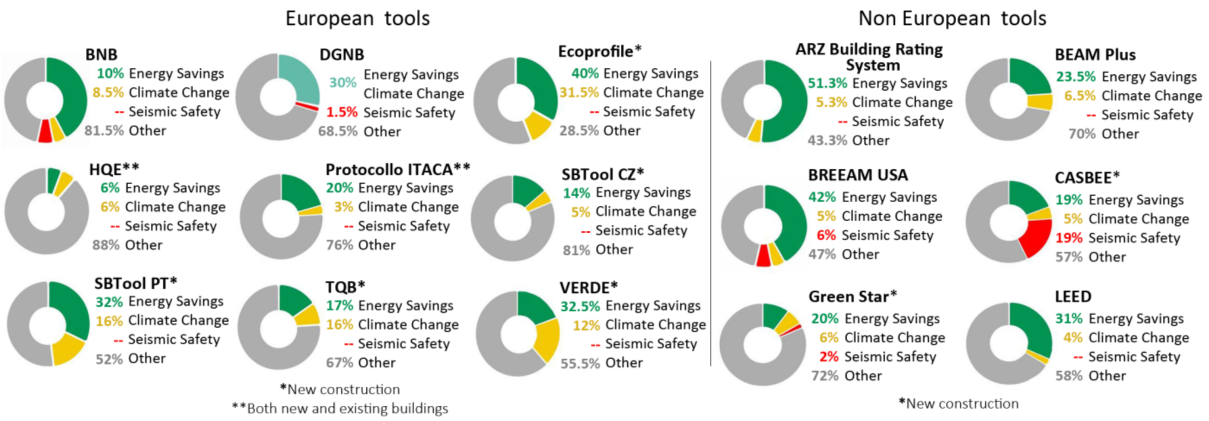
Source: ©Lamperti Tornaghi e al., 2018 (CC BY 4.0)

2.1.5 Remarks on the review of existing assessment methodologies for the combined upgrading

The review of the existing assessment methods and tools for a combined seismic and energy retrofit focused on the second key-stream of methods, i.e. multi-performance assessment methods, leads to the following observations.

Sustainability rating systems, which are mostly developed for new building assessment, define sustainability in different ways, although they are mainly focused on the environmental dimension, and assign diverse weight factors or scores to each category, leading to a huge variability of results amongst the different tools. According to the review, it is pointed out that the investigated tools include energy efficiency and CO_2 emission indicators as highly relevant, but a seismic safety indicator is implemented only in a couple of them with a low weight, such as DGNB at European level or CASBEE at non-European level (Figure 8).

Figure 8. European and non-European sustainability rating systems analysed by selected essential indicators (seismic safety in red, energy savings in green, climate change in yellow, other in grey) and their relevance based on related indicator weight - in percentages)



Source: Data - BNB (BMVBS, 2011), DGNB system (DGNB, 2020), Ecoprofile (Pettersen, 2000), HQE (Cerway, 2014), Protocollo ITACA (iiSBE Italia, 2011), SBTool CZ (iiSBE Czech – CSBS, 2011), SBTool PT (Mateus and Bragança, 2011), TQB (ASBC, 2010), VERDE (GBCe, 2019), ARZ Building Rating system (LGBC, 2019), BEAM Plus (HKGBC, 2016), BREEAM USA (BRE, 2017), CASBEE (JSBC, 2014), Green Star (GBCA, 2017), LEED (USGBC, 2019).

Based on this analysis, although a significant research effort has been carried out with the development of Level(s) as a hybrid tool to overcome the heterogeneity of the existing sustainability rating systems, fully quantitative integrated methods need to be considered for a proper combined seismic and energy retrofit assessment of existing buildings. The SSD methodology was identified as a noteworthy procedure in this direction, also including environmental performance evaluation. Thus, it was considered as a point of reference to define a simplified method for the combined retrofit assessment, as introduced in detail in the following section.

3 A novel and simplified method for the combined assessment of seismic and energy retrofit of existing buildings

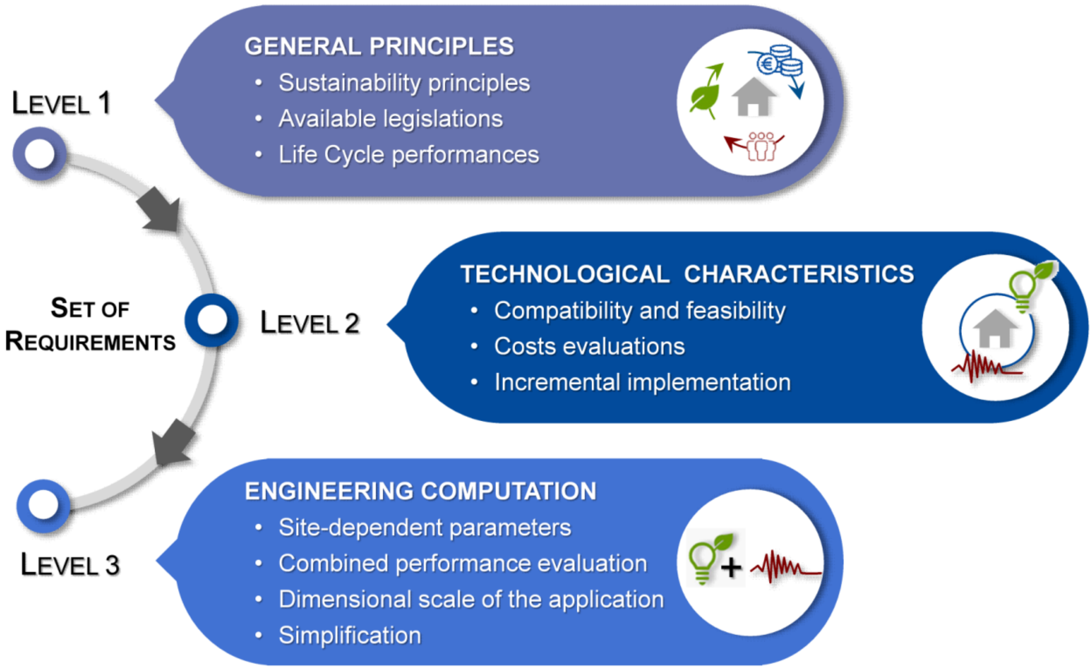
The development of assessment methods for the combined seismic and energy retrofit of existing buildings is a priority issue. The need of an integrated retrofit has been recognised by the scientific community in the last years, first leading to the development of partly coupled assessment methods towards the introduction of holistic assessment methods based on a LCT approach (Section 2.1.4). Further research efforts are needed to provide user-friendly tools, which enable to achieve effective results while streamlining complex approaches.

In this context, a novel and simplified method for the combined seismic and energy retrofit design and/or assessment of existing buildings in a life cycle perspective, hereinafter referred to as the simplified combined assessment method, is introduced by considering the SSD methodology as its reference point. A set of specific requirements (Section 3.1) are first described in the following to subsequently focus on the framework (Section 3.2) of the proposed method.

3.1 Suitable requirements for a simplified combined assessment method

The selection of adequate requirements and principles is the first step for defining the simplified combined assessment method. The proposed set of requirements encompasses different action levels, which can be grouped into three main categories: (i) *Level 1: General principles*, (ii) *Level 2: Technological characteristics*, and (iii) *Level 3: Engineering computation*. Each level accounts for its specific requirements, as depicted in Figure 9. The Level 1 requirements aim to include environmental, economic, and social performance targets derived from the general principles of sustainable development, as well as EU/national legislation on energy management and structural safety to be evaluated on a life cycle perspective. It is worth reminding that the sustainable development is defined as the interaction of three main different pillars - Environment, Economy and Society, also commonly known as the TBL approach – Planet, Profit, and People (Elkington, 1997). The Level 2 requirements intend to ensure the complete integration and feasibility of the combined energy and seismic retrofit technologies. Both retrofit measures also need to be preliminary investigated in terms of cost and time in order to consider potential constraints of the existing building users and/or stakeholders to be overcome through the potential application of an incremental retrofit strategy. Finally, the Level 3 requirements have the objective to compute the heterogeneous results carried out by the site-dependent energy and structural analyses and/or convert them into a single equivalent indicator, thus leading to simplified outcomes of the proposed assessment method. A detailed description of the selected requirements for each level is provided in the following sub-paragraphs.

Figure 9. Overview of the simplified method requirements by action level



Source: JRC

3.1.1 General principles

The first category of requirements - *Level 1: General Principles* - includes three main requirements related to both the TBL approach principles of sustainable development and the concept of Life Cycle Thinking in construction sector, as follows:

1. **Sustainability principles** - General requirements of the simplified combined assessment method should take into account both the sustainability goals in construction sector and the recent EU policies related to the Renovation Wave of existing buildings (COM (2020)622), also supported by the New European Bauhaus movement (COM (2021)573), in the framework of the European Green Deal (COM (2019)640) priority. Specifically, the UN Sustainable Development Goals (SDGs) of the 2030 Agenda for the Sustainable Development (UN, Resolution 2015/A/Res/70/1) and the ambitious targets of the EU long-term Strategy 2050 should be efficiently satisfied. As for the UN SDGs, attention needs to be mainly paid on the Goal 11 for achieving "cities and human settlements inclusive, safe, resilient and sustainable". Emphasis is also placed on the ambitious energy and GHG emission targets for achieving a decarbonised and climate neutral Europe by 2050, enshrined at legal level according to the recent first European Climate Law (Regulation (EU) 2021/1119). A mid-term target for the reduction of GHG emissions by at least 55 % below 1990 levels has also been set to achieve the EU 2050 climate overarching goal, effectively. Hence, according to the recent proposal for the recast of the Energy Efficiency Directive (Proposal COM (2021)558), as part of the 'Fit for 55' legislative package (COM (2021)550), the improvement in energy efficiency by reducing energy consumption by at least 32.5 % (compared to 2007 reference scenario) by 2030 (Directive 2018/2002) should be strengthened. The proposal foresees to increase the energy efficiency targets to achieve a reduction of 36 % and 39% for final and primary energy consumption, respectively. The building sector plays an essential role in this direction considering that it is recognised as responsible for 40% of EU energy consumption and 36 % of the EU total CO_2 emissions. Thus, a large-scale upgrading of the EU existing building stock has been boosted according to the Renovation Wave strategy (COM (2020)662) in order to contribute to strengthen the 2030 targets, and accelerate the transition to a decarbonised, circular, and energy-efficient building sector by 2050.

   It is evident that these general prerequisites for the simplified combined assessment method should satisfy the TBL strategy in the construction sector by considering sustainable retrofit solutions able to ensure environmental/energy efficiency, cost-effectiveness, and safety in a holistic way. Thus, the need of developing new integrated design frameworks to combine the environmental, economic, and social effects of retrofit of existing buildings, without neglecting their structural performance in both ordinary and exceptional scenarios (e.g. in case of an earthquake), has become a priority issue in the scientific research community in the last years. Some research studies dealing with the development of general and integrated frameworks for the global design/retrofit of buildings including safety, cost-effectiveness, and environmental efficiency were proposed in the last decade (e.g. Calvi et al., 2016; Gencturk e al., 2016; Wei et al., 2016b; among others). Furthermore, a recent critical review of the state-of-the-art of the existing methods for an integrated sustainable renovation of buildings is reported in Passoni et al. (2021).

2. **Available legislation** - The requirements of the simplified combined assessment method should comply with the EU legislative context in terms of energy and seismic retrofit. The Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED), both amended in 2018 (Directive 2018/844) are the main regulatory drivers for energy upgrading. A proposal for the EPBD revision (Proposal COM (2021)802) has been recently presented to upgrade the existing regulatory framework to reflect higher ambitions and more pressing needs in climate and social action. The Decision on a Union Civil Protection Mechanism (Decision (EU) 2019/420) could guide in mitigating natural and man-made disaster effects, whereas national and regional legislation should be considered for seismic retrofit design in line with the European structural design codes, i.e. Eurocodes [6].

   According to the key-purpose of the simplified combined assessment method, the set of available legislation and regulations of the EU countries, which are sensitive of seismic risk and climate-related energy issues, are intended in terms of performance targets to be satisfied for the seismic and energy retrofit. As for the seismic retrofit, the corresponding performance targets can be related to either the overall structural safety or the containment of the earthquake damage to structural and non-structural components. As for the energy retrofit strategy, several performance targets may be considered but the reduction of the yearly energy consumption per square meter of the building is the most representative

(6) Eurocodes, https://eurocodes.jrc.ec.europa.eu/en-eurocodes/about-en-eurocodes

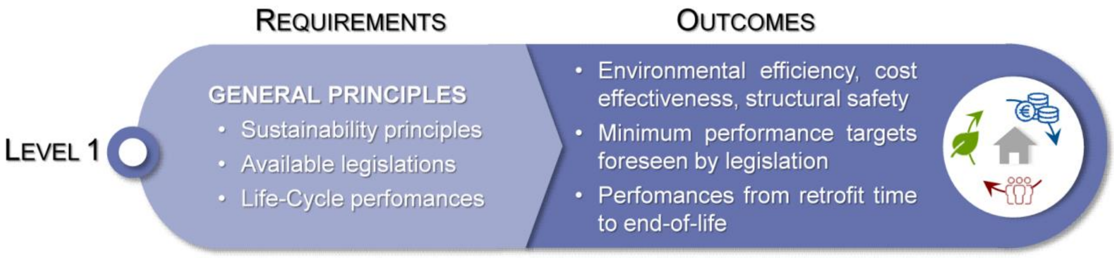
one to indicate the effectiveness of an energy upgrading intervention. Indeed, this parameter allows professionals and/or stakeholders involved in the retrofit intervention to also quantify the environmental emissions of a selected energy source indirectly. Similarly, case-by-case CO_2 emission threshold values should be also considered as national/EU performance targets, varying for each EU Member State.

3. **Life-cycle performances** – An effective sustainable building renovation should simultaneously consider the environmental, economic, and social performance along with the structural one, which assumes a pivotal role for ensuring safety and an adequate seismic behaviour in case of an earthquake. These performances should be assessed over the 'upgraded' service life of the investigated existing building in order to obtain more reliable results in reducing negative impacts by means of a life cycle analysis-based approach.

   The simplified combined assessment method should consider the environmental/energy efficiency, cost-effectiveness, and safety of a renovated building for its entire extended life cycle – from retrofit design stage to the end–of-life of the building. Hence, the combined energy and seismic retrofit based on a LCT approach will minimise the environmental and economic impacts and, simultaneously, it will maximise the energy performance and structural safety of the investigated building from cradle-to-grave. To this end, it is essential to limit the potential seismic-induced losses in case of earthquakes occurring during the 'upgraded' lifetime of the retrofitted building. Thus, the seismic performance of the building should be already evaluated in the retrofit design stage in order to not underestimate the overall environmental, economic, and social performances, as well as to avoid the potential loss of the energy retrofit measure. Indeed, the probability of occurrence of seismic events influences the environmental life cycle results (Menna et al., 2013). Similarly, the assessment of environmental and economic impacts derived only by the energy consumption, neglecting potential seismic-induced losses underestimates the overall environmental, economic, and social performances. Hence, the simplified method should focus on the evaluation of the environmental, economic, and structural performance of the retrofitted building for the various stages of its extended life cycle in order to lessen the corresponding negative impacts. Specifically, in the pre-use stage, which mainly corresponds to both the retrofit design and construction phases, the use of sustainable and eco-efficient materials for the combined retrofit technologies should be envisaged to limit impacts related to raw materials embodied energy/emission. Moreover, transportation, and construction energy burdens should be reduced extensively. During the use phase, it is fundamental to minimise energy consumption and CO_2 emission-related impacts, along with costs while guaranteeing safety and resilience both in ordinary and exceptional conditions (e.g. earthquake). Thus, an adequate structural performance should be ensured in case of a seismic event in order to prevent the building collapse and limit the potential seismic-induced damages leading to economic and human losses, as well as indirect environmental burdens. Finally, the combined retrofit solution should ensure a sustainable waste management at the end-of-life stage of the retrofitted building. The use of retrofit technologies consisting of easily disassembling structural and non-structural components in line with the Design for Deconstruction (DfD) concept (Portioli and Hechler, 2011; Hechler et al., 2011; Kanters, 2018) facilitates the re-use of components and the material recycling, thus reducing the demolition waste, the down-cycling, and the landfill disposal.

The three potential outcomes to satisfy the corresponding requirements related to the 'General Principles' level are defined in Figure 10.

Figure 10. Level 1 requirements and their corresponding potential outcomes



Source: JRC

3.1.2 Technological characteristics

The second category of requirements – *Level 2: Technological characteristics* - identifies the following three specific requirements, which are essentially devoted to guarantee an effective technological integration of the energy and seismic retrofit technologies:

1. **Compatibility and feasibility** – This requirement aims to maximise the efficiency of combined seismic and energy retrofit technologies, avoiding a potential physical-functional incompatibility before the retrofit design phase. Thus, a 'pre-screening' stage of the available integrated energy-seismic retrofit measures is essential to ensure technological effectiveness, feasibility, economic viability, and fulfilment of stakeholder's constraints.

   This aspect becomes an essential prerequisite for a successful combined retrofit intervention. Thus, the simplified assessment method should ensure that both seismic and energy retrofit technologies will be carefully analysed primarily in terms of compatibility based on their own mechanical and physical characteristics. Additional assessment criteria should be also considered, such as application of seismic and energy retrofit technologies at a consistent dimensional scale and extent of the building to be renovated, compatible duration of the installation time to respect potential constraints related to building activities, compliance with legislative performance targets, and possibility of installing the combined retrofit technologies in an incremental way over time depending on the available initial economic resources.

2. **Cost evaluation** - A cost-optimal combined retrofit assessment needs to be carried out through a life-cycle costing analysis. It allows stakeholders to know the real economic investment of the retrofit by assessing not only the initial costs of the energy and seismic retrofit interventions, but also the expected repair costs for structural and non-structural components in case of damages due to earthquakes (i.e. economic losses) and the annual costs for energy consumption, as well as the end-of-life costs.

   The life-cycle cost assessment should be included into the simplified combined assessment method in order to demonstrate the economic efficiency of the combined retrofit intervention making the renovation strategy viable. Specifically, the evaluation of the initial cost of a retrofit intervention should be first carried out. In the case of separated seismic or energy retrofit, the initial costs of the corresponding retrofit technologies can represent a simple selection tool for the retrofit solution itself. In the case of combined energy and seismic retrofit, the initial cost evaluation of different possible interventions could become more complex. Hence, it could be useful to directly relate this cost to the seismic and energy performance, as recently proposed in a study by Giresini et al. (2020) aimed at assessing the initial cost of various combined retrofit solutions applied to a single building component (e.g. masonry wall, façade system) by considering both structural and thermal performances through iso-cost curves. Beyond the initial costs, it is essential to assess the long-term operational energy consumptions costs, the potential damage-related costs due to earthquakes, and the environmental costs by calculating the mean annual energy cost, the seismic expected annual economic losses, and the CO_2 emissions transformed into monetary units leading to equivalent environmental annual losses, respectively. Finally, the end-of-life costs for dismantling and/or dismissing the retrofit technologies, as well as costs for the waste management of the retrofit materials and components need to be assessed, also encompassing the potential recycle/reuse benefits. The use of a life cycle economic metric within the simplified assessment method allows the integrated retrofit solutions to be related to the payback time of the investments in order to assess their economic efficiency. The payback time can be defined as the time (in years) needed to equal the initial investment for the separated/combined retrofit. Thus, the lower is the payback time, the higher is the economic efficiency of the intervention. It is worth noting that a recent study (Pohoryles et al., 2020) has demonstrated that a combined seismic and energy retrofit intervention, performed at once, leads to a significant reduction of the payback period in high seismic hazard zones, if compared with the corresponding separated retrofit interventions.

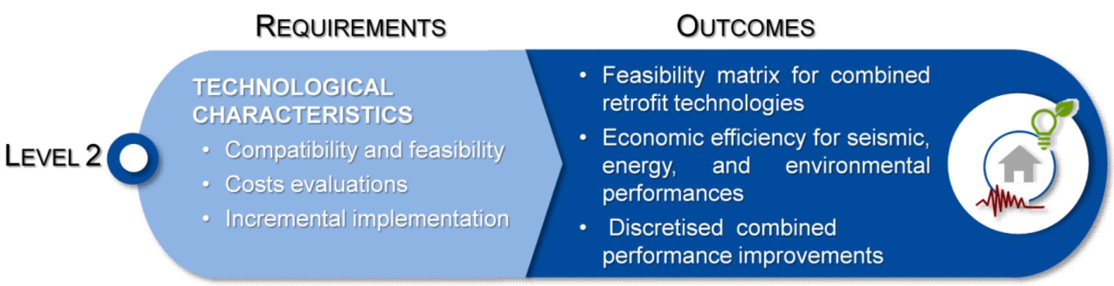
3. **Incremental implementation** – This requirement refers to the possibility of spreading the retrofit intervention and costs depending on time and investment constraints by adopting an incremental retrofit strategy. The possibility to proceed with an incremental retrofit was introduced in USA for seismic interventions to the existing building stock and it is referred to as Incremental Seismic Rehabilitation (ISR). The ISR, addressed by FEMA P-420 (FEMA, 2009), foresees a series of discrete actions to be implemented within the planned maintenance interventions of the structure over an extended lifetime. Each rehabilitation step ensures an incremental performance improvement, expressing a percentage of the overall structural performance enhancement achieved by a single-stage rehabilitation, with a low initial cost and minimum functional disruption of the building. Furthermore, the incremental retrofit

intervention should be prioritised based on structure, use, and integration issues. Focusing on structural priority, a minimum level of safety can be set as initial priority of the incremental intervention process in case of highly vulnerable buildings and/or areas with a high level of seismic hazard. The corresponding minimum intervention removes the main critical aspects of the existing structure, thus avoiding the building collapse and human losses after a potential earthquake (Labò et al., 2018). It is worth noting that the application of this strategy leads to the reduction over time of the expected repair costs associated to the seismic events occurrence (Loa et al., 2017).

In the framework of the simplified combined assessment method, the possibility to consider an incremental retrofit strategy aims to achieve incremental performance targets by implementing the combined retrofit intervention over time. Moreover, the seismic and energy retrofit intervention could be scheduled at the same time of the building maintenance intervention in order to further reduce the final costs and the users' disruption. This solution could become essential in some cases, e.g. in relation to school and/or office buildings for which the continuity of the building functionality needs to be guaranteed.

The three potential outcomes to satisfy the corresponding requirements related to the 'Technological Characteristics' level are defined in Figure 11.

Figure 11. Level 2 requirements and their corresponding potential outcomes



Source: JRC

3.1.3 Engineering computation

The latter category - *Level 3: Engineering computation* - refers to four requirements in order to address the computation stage of the novel/simplified combined assessment method and its related outcomes, as follows:

1. **Site-dependent parameters** - The geographic position of a building influences its structural and energy performances due to their strict dependence to the seismic risk level and the climatic conditions of a specific area, respectively. Thus, the building site characterisation in terms of seismic hazard zone and climatic zone is a fundamental pre-requisite for the effectiveness of the method implementation. Indeed, these two features affect the 'intensity' of the integrated retrofit in achieving the pre-defined sustainability performance targets (i.e. adequate structural and energy performances, respectively).

   It is clear that a requirement accounting for the seismic hazard and the climatic zone of a specific building location should be satisfied by means of the combination of two main site-dependent parameters to be evaluated as input data before the retrofit design. Thus, the two following parameters are considered, respectively: (i) the expected peak ground acceleration (PGA) with a 10 % exceedance probability in 50 years (return period of 475 years), and (ii) the Heating Degree Days (HDD) index. The latter is defined as a weather-based index designed to quantify the energy demand needed to heat a building. According to the ASHRAE method (2013), the HDD index can be computed as the cumulated positive differences between a set-point comfort temperature, namely base temperature (T_b), and the daily mean outdoor temperature (T_d) over a conventional heating year (where d_i and d_f indicate the initial and the final day of the heating year, respectively), according to Equation (18).

$$HDD = \sum_{d=di}^{df} (T_b - T_d)^+ \tag{18}$$

2. **Combined performance evaluation** – Multi-performance retrofit design/assessment methods typically carry out various performance outcomes expressed in different units of measure. Thus, a suitable 'conversion' method is required in order to combine them into an equivalent index/parameter, representative of the integrated retrofit. The equivalent parameter will be essential to evaluate the effectiveness of combined retrofit solutions.

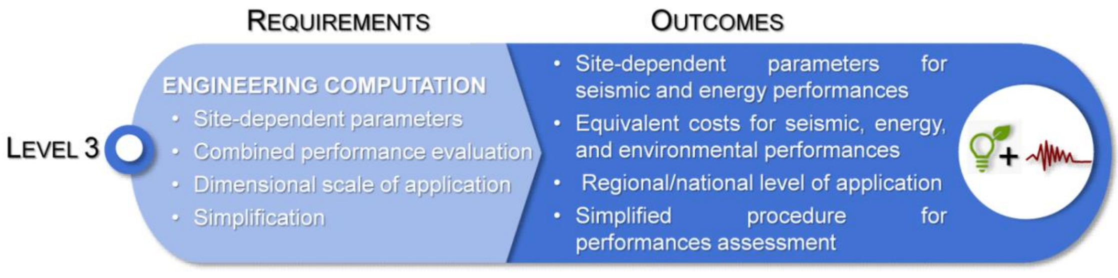
   The simplified assessment method should consider a proper way to combine the performance results into a single global parameter. An effective approach consists in converting the different measure units of the outputs related to seismic, energy, and environmental performance analyses into monetary terms to sum those up and obtain a sole assessment parameter in terms of a final equivalent cost (Lamperti Tornaghi et al., 2018). This conversion will allow stakeholders to easily compare alternative retrofit scenarios in order to select the most suitable one.

3. **Dimensional scale of the application** – The simplified method should ensure its application at urban, regional, and national level in order to support the territorial administrations in addressing EU policy goals related to renovation of buildings from small to big areas, e.g. from districts and cities to regions and whole countries. Thus, the classification of the building stock into group types by similar structural and non-structural characteristics is needed and a consequent global assessment parameter should be defined for each building type in order to identify the geographical areas most needing intervention. A possible classification leads to the identification of representative building classes (RBCs) based on the following categories: (i) structural typology, classified in reinforced concrete, masonry, other, (ii), age of construction, and (iii) geometric details, including number of stories, interstorey height, gross floor area, window-to-wall ratio. The combined assessment results achieved for the RBCs lead to the definition of urban, regional, and national selection criteria for the application of integrated retrofit technologies to the existing buildings in relation to seismic-energy performance targets.

4. **Simplification** – This requirement aims to develop simplified energy and structural indicators based on output data of retrofit options. The application of simplified assessment procedures is needed to achieve clear and easily comprehensible results, although they take into account different building performances in terms of seismic losses, energy consumptions, and environmental impacts. Indeed, available seismic and energy assessment procedures are typically complicated in practical applications to ordinary projects due to complex probabilistic relations and high number of parameters to be determined. It is worth noting that the results of a simplified assessment method assume a strategic value since they could be also implemented in dedicated optimisation tools (e.g. linear programming, convex optimization) in order to obtain a single global parameter associated to the most cost-effective and sustainable combined retrofit solution.

The four potential outcomes to satisfy the corresponding requirements related to the 'Engineering Computation' level are defined in Figure 12.

Figure 12. Level 3 requirements and their corresponding potential outcomes



Source: JRC

3.2 The framework of the proposed simplified combined assessment method

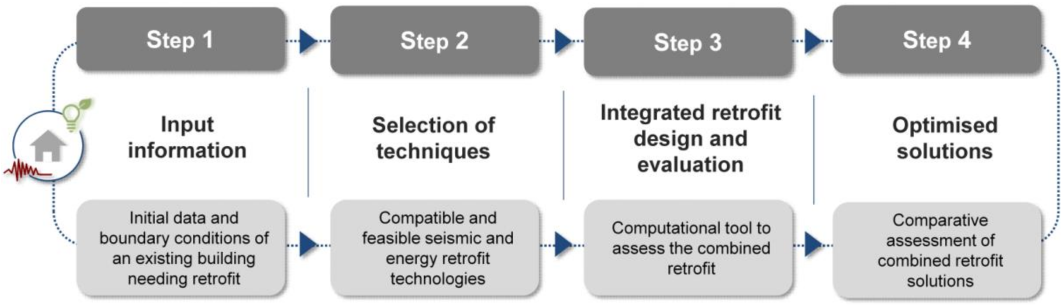
The proposed simplified method for assessing the combined seismic and energy retrofit of existing buildings in a life-cycle perspective is introduced and it can be classified as a holistic method. It is aimed at satisfying the sustainable development principles by considering the peculiarities of both the available seismic and energy retrofit technologies in order to foster the combined renovation of existing buildings through the selection of the most effective solution in terms of safety, energy, environmental, and economic performances throughout the residual life cycle of the examined building.

The framework of the proposed method consists of four interconnected steps (Figure 13), as follows:

- **Step 1: Input information**, devoted to collect the initial data and boundary conditions of the existing building to be retrofitted.
- **Step 2: Selection of techniques**, aimed at analysing the physical and mechanical characteristics of the seismic and energy retrofit technologies, separated or combined.
- **Step 3: Integrated Retrofit Design and Evaluation**, representing the computational tool to assess the life cycle seismic, energy, and environmental performances of the combined retrofit by achieving global results in economic terms.
- **Step 4: Optimised solutions**, dealing with a comparative assessment of different combined retrofit solutions through the simplified economic results carried out in the previous step to identify the most effective one.

Each step is described in detail along with the specific input-output data process in the following.

Figure 13. Framework of the proposed simplified assessment method



Source: JRC

3.2.1 Step 1 – Input information

The first step of the proposed simplified combined assessment method - hereinafter indicated as Step 1 - aims to collect performance data and boundary conditions of an existing building or sets of buildings needing a retrofit intervention. It is worth noting that a pre-step devoted to assess the residual lifetime of the investigated building needs to be carried out before proceeding with the analysis of the initial building data. Indeed, the existing building could have already or nearly exhausted its lifetime, as well as it could be partially or extensively degraded or damaged. In such a case, the priority-issue before designing any retrofit intervention becomes the technical and sustainable decision whether proceeding with renovation or demolition, the latter as ultimate intervention choice, if unavoidable (Sfakianaki and Moutsatsou, 2015). Once the renovation strategy is selected as suitable option, the investigation of building information initiates by leading to the definition of three main classes of technical input data to be processed into the subsequent Step 2 of the framework of the proposed simplified assessment method.

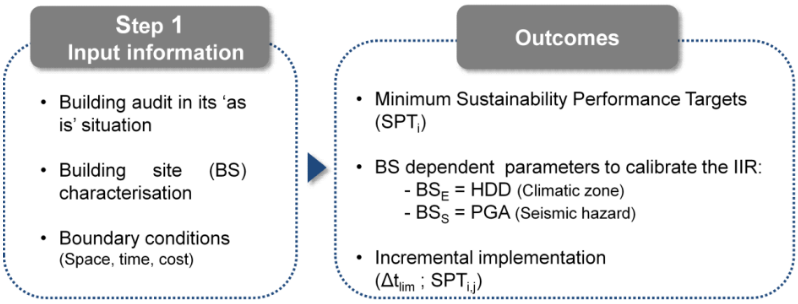
The first class of input data refers to the performance analysis of the 'as is' condition of the un-retrofitted existing building by assessing its lacks or needs in different intervention areas related to structural safety, energy efficiency, and environmental performance in order to define the minimum Sustainability Performance Targets (SPT_i, with i indicating the different targets) for the renovation process. The SPTs can be delineated according to the minimum performance targets foreseen in the current EU/national legislation related to seismic protection, energy efficiency management, and environmental impacts reduction in line with the Level 1 requirements.

The second class of input data investigates the building site (BS) characterisation according to one of the Level 3 requirements, namely site-dependent parameters. Thus, two key-input parameters, which describe the climatic zone (BS_E) and the seismic hazard level (BS_S) of the examined building location, are evaluated before the retrofit design. The two parameters are the Heating Degree Days index (BS_E = HDD) and the expected peak ground acceleration (BS_S = PGA) with a 10 % exceedance probability in 50 years, respectively. Their combination allows the 'calibration' of the Intensity of the Integrated Retrofit (IIR) to be designed subsequently. Indeed, the seismic risk related to the existing building location has a strong influence on the effectiveness of the energy retrofit investment, and vice versa, within an integrated retrofit intervention (Mauro et al., 2017).

Finally, potential constraints associated to the boundary conditions of an existing building in terms of space, time, and/or cost need to be considered as additional input data in line with one of the Level 2 requirements, namely incremental implementation. Particular attention has to be deserved to the duration of the integrated retrofit intervention mainly related to public buildings, such as school or office buildings,, which commonly have to respect a maximum time period for their service interruption (Δt_{lim}). Similarly, the inability or the expensive cost of relocating inhabitants of residential buildings could represent a retrofit barrier. Thus, the implementation of an incremental retrofit strategy, as addressed in FEMA P-420 guidelines (FEMA, 2009), should be considered on the basis of both the available time and budget for a specific building retrofit. This solution provides the enhancement of the existing building energy and structural/seismic performances by means of single incremental interventions satisfying predefined incremental SPTs, (i.e. $SPT_{i,j}$ with j indicating the j-th intervention over time), thus overcoming the detrimental risk of a delayed or missing performance improvement (Labò et al., 2018).

The outcomes of the Step 1 of the proposed simplified assessment method are summarised in Figure 14.

Figure 14. Outcomes of the Step 1 of the proposed simplified combined assessment method



Source: JRC

3.2.2 Step 2 – Selection of retrofit technologies

The second step of the proposed simplified combined assessment method - hereinafter indicated as Step 2 - identifies the set of potential compatible and feasible energy and seismic retrofit technologies by using the outcomes of the Step 1, i.e. SPT_i, BS_E, BS_S, IIR, Δt_{lim}, and $SPT_{i,j}$. This 'pre-screening' phase in line with one of the Level 2 requirements, namely compatibility and feasibility, is necessary before considering the integrated design/assessment of a retrofit intervention to be carried out within the subsequent Step 3 of the framework of the proposed simplified assessment method.

Energy Retrofit Technologies (ERTs) and Seismic Retrofit Technologies (SRTs) are separately evaluated in terms of physical and mechanical characteristics and selected by means of specific classification parameters. The preliminary classification parameter refers to as *Performance Parameter* (PP) and it is related to the SPTs defined in the previous step. The single i-th energy (ERT_i) and seismic (SRT_i) retrofit technologies are distinguished in terms of the Energy (PP_E) and Seismic (PP_S) Performance Parameter categories, respectively, in order to determinate the technological requirements/limitations of the building components they affect. Specifically, the PP_E represents the typical input data to perform building energy analyses, thus it is related to the following energy retrofit performance objectives: (i) reduction of thermal energy demand for space heating (TED_h) and/or cooling (TED_C) with interventions mainly to building components, such as roof, floor, wall and finishing, (ii) reduction of thermal energy demand for the production of domestic hot water (TED_w) by using renewable energy-related systems, (iii) reduction of electric energy demand (EED) for direct electric uses, e.g. lighting and corresponding equipment, (iv) reduction of primary energy consumption (PEC) by replacing the existing energy supply systems, and (v) change of energy consumption patterns. These actions indicate that the ERTs to be applied to an existing building to improve its energy performance can involve either the building envelope or the energy-consumption systems. Similarly, the PP_S is related to the structural/seismic retrofit performance objectives, such as global structural capacity improvement, strength enhancement, ductility enhancement, deformation reduction. Thus, the SRTs to be applied to an existing building to improve its structural/seismic performance can act as either local or global interventions involving the single structural element or the entire structural system, respectively. The PP_E and the PP_S selection leads to the identification of another classification parameter related to the interaction between the retrofit technologies and the existing building. This parameter is represented by the *Affected Building Component* in terms of structural (S_i) or non-structural (NS_i) component for the ERT_i and by the *Affected Structural Element* in terms of vertical (SE_V_i), horizontal (SE_H_i), and/or joint (SE_J_i) structural element for the SRT_i . The other classification parameters for the ERT_i and SRT_i encompass *Building Typology* to indicate the suitability of the retrofit technologies for reinforced concrete, masonry and/or other structures, *Building Site characteristics* to be differentiated in HDD and PGA for ERT_i and SRT_i, respectively, *Initial Cost*, *Potential Environmental Impact* based on life cycle criteria, *Disruption Time*, *Interaction with other renovation works,* and *Thermal interactions* to identify the thermal properties of the retrofit technology materials and systems employed.

The potential ERT_i and SRT_i, distinctly analysed by means of the aforementioned classification parameters, are subsequently combined in a proper **matrix of interference** (Figure 15), which highlights the classification parameters (i.e. green cells) to be carefully assessed to verify the physical-functional compatibility of the preliminary set of selected retrofit technologies. This analysis is fundamental to guarantee the effectiveness of implementing the separated retrofit technologies in an integrated way in the subsequent retrofit design and assessment stage, i.e. Step 3, of the proposed simplified combined assessment method.

Figure 15. Sketch of the retrofit interference matrix

		Energy Retrofit Technology (ERT)								
		Energy Performance parameter (PP_E)	Building Component affected (S/NS_i)	Building Typology	Building Site characteristics (BS_E)	Initial Cost (IC_E)	Potential Environmental Impact (EI_E)	Disruption Time (DT_E)	Interaction with other works (Yes/No)	Thermal interaction (Yes/No)
Seismic Retrofit Technology (SRT)	Structural Performance parameter (PP_S)									
	Structural Element affected (SE_V_i-H_i-J_i)		Check							
	Building Typology			Check						
	Building Site characteristics (BS_S)									
	Initial Cost (IC_S)					Check				
	Potential Environmental Impact (EI_S)						Check			
	Disruption Time (DT_S)							Check		
	Interaction with other works (Yes/No)								Check	
	Thermal interaction (Yes/No)									Check

Source: JRC

3.2.2.1 A simplified approach for the classification of integrated retrofit solutions

The technological compatibility between the ERT_i, and SRT_i is an essential pre-requisite to identify potential combined retrofit solutions, as exposed in the previous paragraph. However, an optimal integrated seismic and energy retrofit intervention can be achieved if both the ERT_i and SRT_i respect additional constraints related to the following aspects (Menna et al., 2021):

— **Performance requirements** - Compliance with seismic and energy performance targets (PTs) defined in dedicated legislative frameworks (at national or European level).

— **Extent of the building** - Application at a consistent dimensional scale and extent of the existing building (e.g. single structural element, entire structural system, building component, building envelope, etc.).

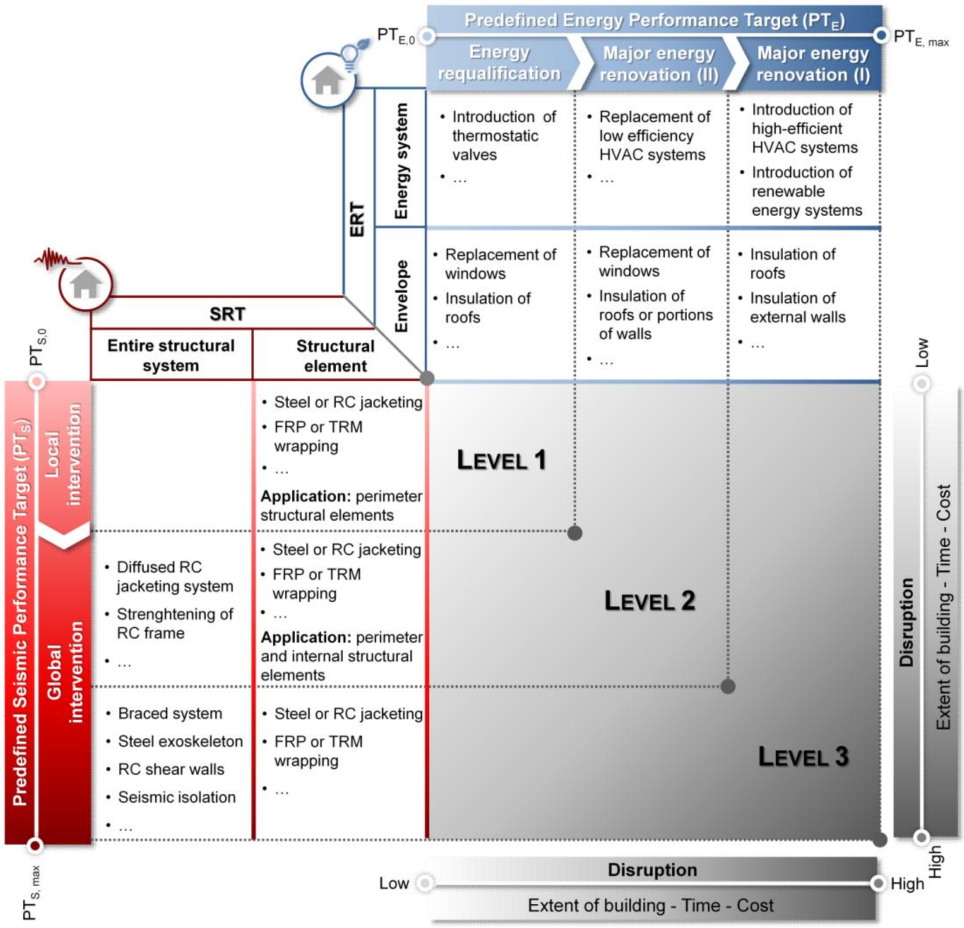
— **Time** - Compatible time duration for the implementation of the retrofit technologies in relation to potential limitations due to building functionality, such as school or office activities for which a long interruption could not be feasible.

— **Cost** - Potential implementation of an incremental retrofit strategy, depending on the available initial budget for the combined retrofit interventions.

These constraints become selection criteria leading to the definition of a potential simplified approach for the classification of available SRTs and ERTs aimed at facilitating the selection of compatible combined retrofit solutions based on increasing levels of predefined seismic and energy performance targets (PTs), as well as of disruption in terms of extent of the building, time, and cost (Menna et al., 2021).

The conceptual framework of the proposed classification tool creating a chequerboard pattern with vertical and horizontal directions referring to seismic and energy aspects, respectively, is depicted in Figure 16.

Figure 16. Conceptual framework of seismic and energy retrofit technologies classification to select compatible integrated retrofit solutions related to RC buildings.



Source: based on Menna et al., 2021

Specifically, the predefined seismic (PT_S) and energy (PT_E) performance targets range between the initial values ($PT_{S,0}$ and $PT_{E,0,}$ respectively) before the retrofit intervention and the maximum values ($PT_{S,max}$ and $PT_{E,max,}$ respectively) achievable by means of the retrofit. The PTs can be discretised according to incremental reference values defined by national legislations (e.g. in the case of Italian regulations, predefined values of safety index in terms of PGA capacity-demand ratio, i.e. PGA_C/PGA_D, at the life safety limit state for PT_S, and predefined values of Primary Energy Consumption (PEC) for PT_E, thus yielding an increasing involvement of the building extent for the retrofit interventions. Hence, the increasing values of the PTs to be achieved correspond to retrofit interventions exhibiting an invasiveness that depends on the adopted retrofit strategies ranging from local to global level as for seismic strengthening, and from energy requalification to two levels of major energy renovation as for energy efficiency improvement. Specifically, seismic retrofit interventions are applied to single structural elements, such as columns, beams, joints (i.e. local intervention) or/and entire structural system (i.e. global intervention), whereas energy retrofit interventions are related to building envelope, including both transparent and opaque components, or/and energy consumption systems, e.g. HVAC, lighting systems, at different scales. The intersection among the seismic and energy retrofit strategies defines optimum integrated solutions of seismic and energy retrofit technologies, accounting for similar compatibility in terms of extent of the building, time, and cost, leading to three incremental levels of integrated retrofit – from Level 1 to 3, which reflect both the increasing performance targets – from minimum to maximum, and the level of disruption – from low to high.

The proposed framework was validated for RC buildings by Menna et al. (2021). Few examples of potential seismic and energy retrofit technologies for RC buildings corresponding to the various retrofit strategies are also listed in Figure 16.

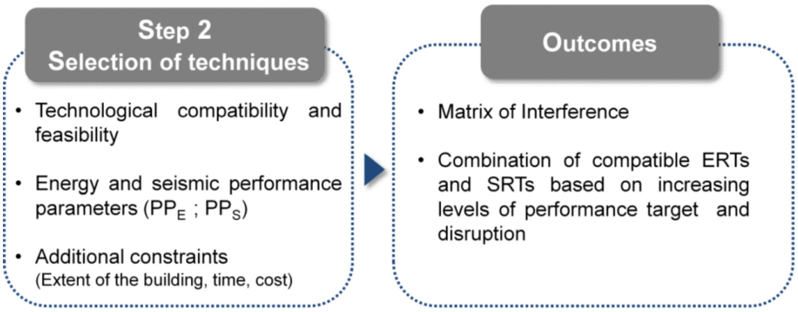
The Level 1 integrated retrofit addresses very low-invasive energy retrofit interventions related to both the energy consumption systems (e.g. introduction of thermostatic valves) and the transparent components of the building envelope (e.g. replacement of windows) leading to a minimum reduction of PEC compliant with the energy requalification strategy. Local strengthening technologies (e.g. steel or RC jacketing, fiber reinforced polymer wrapping, etc.) should be foreseen in order to ensure seismic retrofit interventions compatible with the energy ones above in terms of similar low-impact related to extent of the building, time, and cost. Hence, the application of these local retrofit technologies should be limited as much as possible to structural elements at the exterior of the building, i.e. perimeter beam-to-column joints or perimeter beams and columns with exterior interventions (Frascadore et al., 2015; De Risi, et al., 2020) to guarantee a low level of disruption. Although the proposed seismic retrofit solutions have demonstrated to increase the seismic performance of existing buildings (Frascadore et al., 2015; Di Ludovico et al., 2017) by satisfying the minimum requirements of seismic safety, they do not provide any significant increase in the lateral stiffness of an existing building. Thus, the implementation of energy retrofit technologies to the opaque components of the building envelope, such as thermal insulation to external walls, to further improve the energy performance of an existing building is not recommended in this case.

The Level 2 integrated retrofit refers to more invasive retrofit interventions compared to the previous level due to the need to meet higher seismic and energy performance targets. Specifically, the potential energy retrofit technologies include the replacement of low efficiency HVAC systems, beyond interventions to the building envelope related to either transparent components (e.g. replacement of windows) or opaque components (e.g. insulation of roofs or portions of external walls by means, for instance, of insufflation of insulation materials in the air cavities of the walls). The potential compatible seismic retrofit technologies refer to more invasive local strengthening interventions applied to structural elements at both the exterior and interior of the building to also reduce the expected damages to non-structural components (e.g. addition of a diffused RC jacketing to increase the lateral stiffness of the building, strengthening of beam-to-column joints in RC frames by means of uniaxial steel-reinforced polymer wrapping to resist to the infill action, etc.). In addition to the structural interventions, strengthening of non-structural components is also considered. Focusing on infilled RC framed existing buildings, a couple of examples in this direction refer to the strengthening of infills to contrast their out-of-plane collapse, further increasing the global seismic capacity of the retrofitted buildings (Frascadore et al., 2015) or seismic downgrading of infills by including deformable polyurethane material (Bolis et al., 2020). It is clear that the Level 2 solution leads to a moderate level of disruption, since larger portions of the building are affected by the application of seismic and energy retrofit technologies with higher costs and longer time to implement the integrated retrofit.

The Level 3 integrated retrofit deals with energy and seismic retrofit interventions aimed at achieving the maximum values of performance targets, thus leading to a highly effective integrated retrofit although resulting into a significant level of disruption in terms of extent of the building, time, and cost. Specifically, very invasive energy retrofit interventions are applied to both the energy consumption systems (e.g. high energy-efficient systems, renewable energy systems, etc.), and the building envelope (e.g. thermal insulation of the external walls). Similarly, seismic retrofit interventions focus on global strengthening technologies applied to the entire structural system of the existing building (e.g. steel bracing or exoskeleton, RC walls, base isolation, etc.). These global retrofit interventions could also require the strengthening of both foundation system and slabs of the existing building to ensure the horizontal load path to the new structural resisting system, thus interrupting the building functionality for a long period with a consequent severe degree of disruption in terms of time and high cost.

Based on the observations above, the outcomes of the Step 2 of the proposed simplified combined assessment method are summarised in Figure 17.

Figure 17. Outcomes of the Step 2 of the proposed simplified combined assessment method



Source: JRC

3.2.3 Step 3 – Integrated retrofit design and assessment

The third step of the proposed simplified combined assessment method – hereinafter indicated as Step 3 - addresses the computational tool for the combined retrofit design and/or assessment of the investigated building, thus representing the core of the method. Step 3 aims to maximise the benefits of a combined retrofit by integrating three key-points, as follows:

— **Life cycle performances** - The simplified combined assessment method focuses on the LCT approach, which is based on a time unit including all the stages of the building's life cycle. The LCT approach is essential to overcome the limitation of evaluating only the initial costs of available separated or combined retrofit solutions to be used as decision criteria for their selection, thus neglecting possible benefits arising from savings accumulated over time (Menna et al., 2022). Indeed, many sources of cost variability, as well as detrimental structural, energy, and environmental impacts are expected during the building lifetime due to the potential occurrence of hazardous events, such as earthquakes, which may damage the building with consequent additional direct costs beyond the initial costs. Hence, it is crucial to assess the building performances after the installation of the retrofit intervention by considering the 'new' extended life cycle of the retrofitted building. Moreover, indirect costs due to downtime or inhabitants/users' relocation after a seismic event could be also taken into account (Passoni et al., 2021). However, the proposed simplified combined assessment method exploits a decision-making process primarily focused on the direct losses within the extended life cycle of the retrofitted building, along with supplementary outcomes in terms of initial and end-of-life equivalent costs of the various separated or combined retrofit technologies. Thus, life cycle performances of the retrofitted building are assessed within its 'new' service life profile consisting of three main stages, namely initial time (t_0) – i.e. time of the retrofit intervention, extended lifetime stage (t_{ext}), and end-of-life time (t_{end}).

— **Generalised performance (GP) results** - A global assessment of the structural, energy, and environmental performances of the retrofitted building would require significant efforts in terms of expertise, data collection, computational tools, etc. in order to achieve detailed analyses. Hence, the proposed combined assessment method aims to provide a simplified tool by summarising the various performance outcomes within the extended lifetime of the building into 'seismic (GP_S) and energy (GP_E) generalised performance results related to representative building classes (RBCs) of the EU existing building stock to which various compatible seismic and energy retrofit technologies are applied.

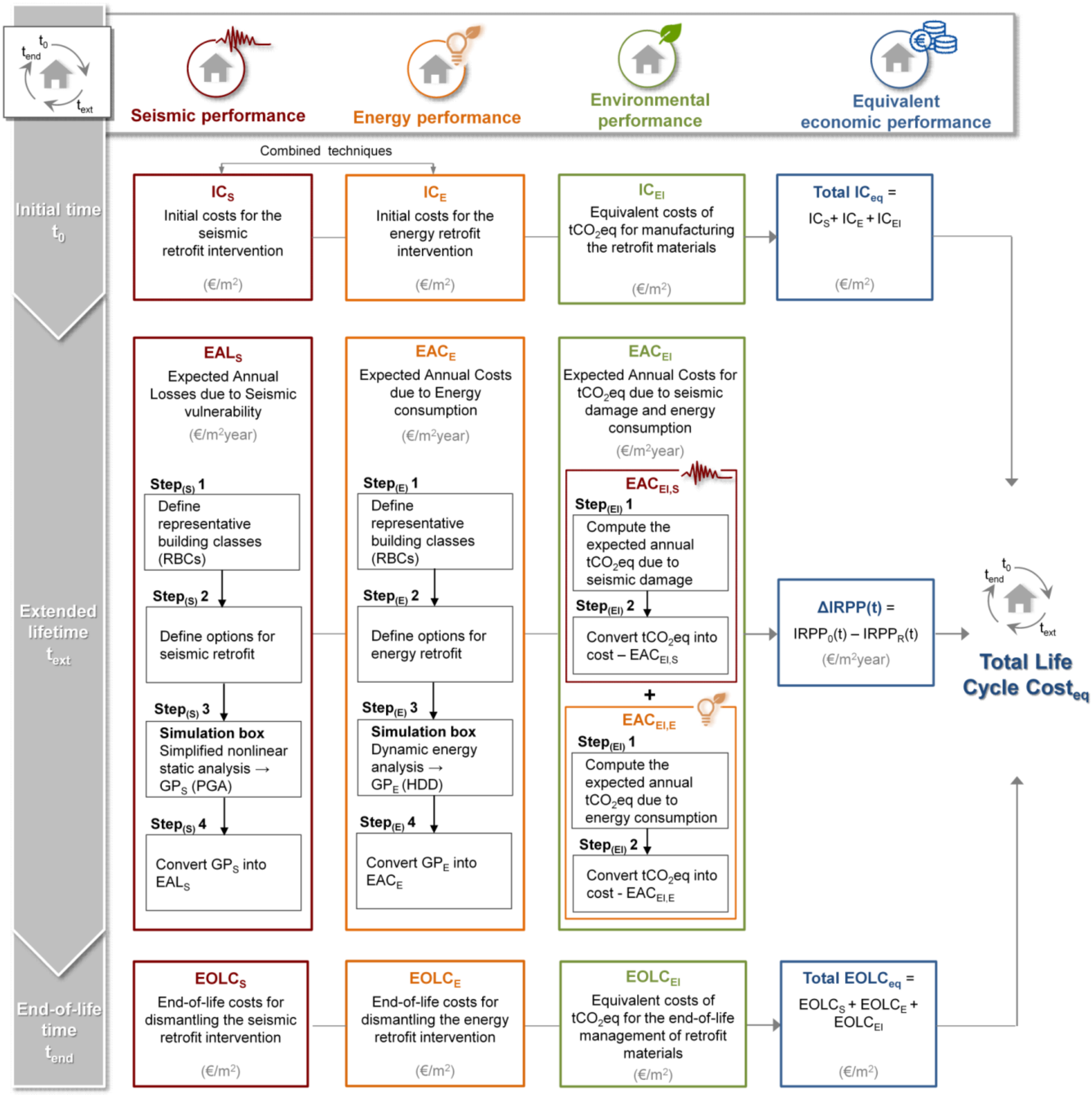
— **Building global performance** - The proposed simplified combined assessment method provides a global metric, which combines seismic, energy, and environmental outcomes in equivalent monetary terms, namely equivalent costs, thus providing a single measure of the overall improved efficiency of the retrofitted building during its entire life cycle.

The framework of the SSD methodology is considered as reference point for developing the Step 3 of the proposed simplified method in order to integrate the assessment of seismic, energy, and environmental performances and convert the corresponding outputs into equivalent costs to be subsequently combined into a global result in monetary units. The total equivalent economic performance of the retrofitted building, expressed as the equivalent Total Life Cycle Cost (Total Life Cycle $Cost_{eq}$), is obtained by combining three main equivalent total cost contributions over time associated with the proposed three different stages of its life cycle, i.e. initial time (t_0), extended lifetime (t_{ext}), and end-of-life time (t_{end}), and related to the combination of seismic, energy, and environmental performance assessment for each of the above time stages, according to the procedure summarised in Figure 18.

The initial (IC) and the end-of-life (EOLC) equivalent costs related to the above three different performances, are obtained through a deterministic approach at time t equal to t_o and t_{end}, respectively. Conversely, the extended lifetime equivalent costs are achieved by assessing the three performances at each time $t \in t_{ext}$, i.e. at each year. Thus, a probabilistic approach is adopted to compute (i) the expected annual loss due to the occurrence of a seismic event (EAL_S), (ii) the expected annual cost due to energy consumption (EAC_E), and (iii) the expected annual cost due to environmental impact generated by the expected seismic damage and energy consumption (EAC_{EI}). Their combination allows the achievement of an economic Integrated Retrofit Performance Parameter (IRPP) to be assessed before ($IRPP_0$) and after ($IRPP_R$) the retrofit in order to estimate the annual economic savings due to the retrofit intervention.

Details of the computations related to the assessment of the seismic, energy, and environmental performances at each of the three stages of the building life cycle, along with the calculation of the corresponding total equivalent economic performance are reported in the following dedicated sub-paragraphs.

Figure 18. Framework of the Step 3 of the proposed simplified combined assessment method



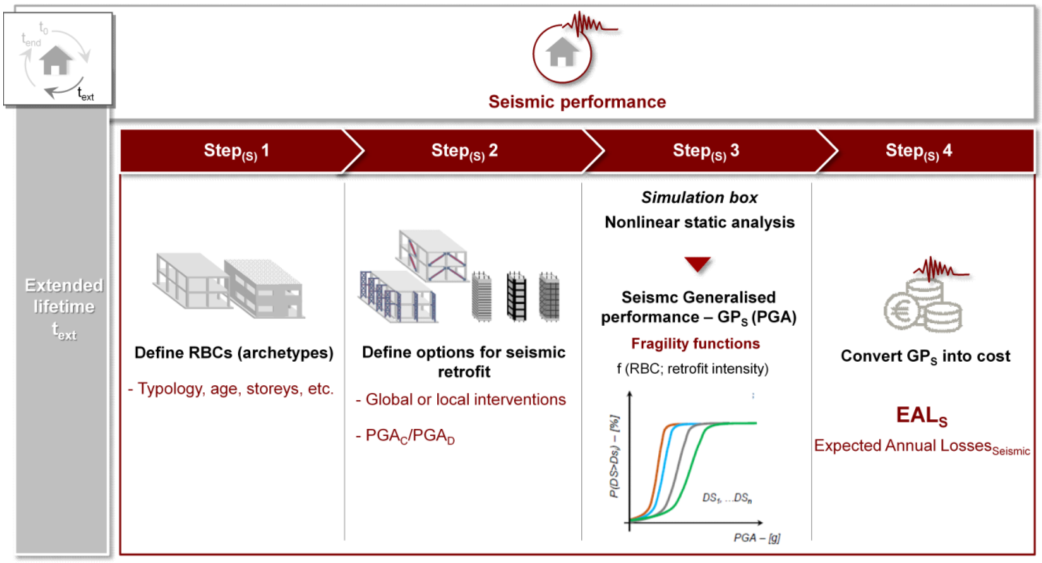
Source: JRC

3.2.3.1 *Seismic performance assessment at the three stages of life cycle*

The assessment of the seismic performance at the **initial time (t_0)** corresponds to the evaluation of the **initial cost** for the **seismic** retrofit intervention **(IC_S)**, expressed in €/m².

The assessment of the seismic performance within the **extended lifetime stage (t_{ext})** follows four main steps (Figure 19), hereinafter indicated as $Steps_{(S)}$, in order to provide its monetary output in terms of **expected annual losses** for **seismic** damage **(EAL_S)**, expressed in €/m²year.

Figure 19. Framework of the seismic performance assessment at the extended lifetime stage (t_{ext})



Source: JRC

The four $Steps_{(S)}$ are described in detail, as follows:

— **$Step_{(S)}$ 1: Representative Building Classes (RBCs)** – The existing building stock is grouped into RBCs according to various classification parameters related to building structural and geometric characteristics, which represent input data for the seismic performance assessment. Specifically, the following classification parameters are considered: (i) structural typology, i.e. reinforced concrete, masonry, other, (ii) period of construction, (iii) geometric details, including number of stories, interstorey height, gross floor area, and window to wall ratio, i.e. percentage of openings. The various RBCs can be obtained by combining each structural typology (N = 1, 2, and 3) with the potential options (i = 1, 2, ..., n) indicating the different building characteristics in terms of construction period and geometric details (Table 3).

Table 3. Representative Building Classes (RBCs) for the seismic performance assessment

$RBC_{(N-i)}$	Construction period	Geometric details: Storey [No]	Geometric details: Interstorey height [m]	Geometric details: Gross floor area [m²]	Geometric details: Window to wall ratio [%]
	Options (i)				
Structural typology (N)	Pre-1946				0 ÷ 9
Reinforced concrete	1946-1971	Low-rise (1 ÷ 3)		50 ÷ 150	10 ÷ 19
Masonry	1972-1981	Mid-rise (4 ÷ 6)	2.50 ÷ 3.50	150 ÷ 350	20 ÷ 29
Other	1982-1991	High-rise (> 6)	> 3.50	350 ÷ 750	30 ÷ 49
	Post-1991			> 750	> 50

Beyond the aforementioned data, additional building characteristics, which refer to the geometry of bearing wall or infill wall (depending on the structural typology considered), the thickness of intermediate slab, and the geometry of roof need to be taken into account as inputs for the seismic performance assessment of the various RBCs.

— **Step$_{(S)}$ 2: Options for seismic retrofit technologies** – Potential seismic retrofit technologies (SRTs) to be applied to the investigated RBCs, as separated or combined with energy retrofit technologies, are considered according to specific classification parameters. These parameters refer to both the outcomes of an interference matrix, according to the Step 2 of the simplified combined assessment method, and the achievable improved seismic performance, as well as to the correlation between the SRTs and the mechanical behaviour of the building after the retrofit. Thus, the following classification parameters are considered (Table 4):

  - **Application level of retrofit intervention**, i.e. local and/or global level, depending if the SRTs aim to strengthen single structural elements and/or the entire structural system of a RBC, respectively.
  - **Performance parameter identification**, which indicates the improvement of the seismic performance achieved by implementing a specific SRT or a combination of different ones, e.g. increasing values of PGA capacity-demand ratio (PGA_C/PGA_D).
  - **Mechanical behaviour of the retrofitted building**.

  Various SRTs can be associated to the different RBCs, based on the potential options (i = 1, 2, ..., n) identifying the classification parameters above.

Table 4. Representative Seismic Retrofit Technologies options for RBCs

$SRT_{(N-i)}$	Application level of retrofit intervention	Performance parameter	Mechanical behaviour
	Options (i)		
RBC $_{(N-1)}$ RBC $_{(N-...)}$ RBC $_{(N-n)}$	Local Global Combination of local and global	Increasing values of PGA_C/PGA_D (%)	Avoid failure mechanisms Increase strength Increase stiffness Increase ductility Other

— **Step$_{(S)}$ 3: Simplified nonlinear static analysis - *Simulation box*** – Data collected within the Step$_{(S)}$ 1 and Step$_{(S)}$ 2 serve as input parameters of a 'simulation box' to assess the seismic performance of either the as-built or the retrofitted building. The analysis provides a set of seismic generalised performances (GP_S), as output, related to the combination of RBCs and SRTs. Specifically, the GP_S are provided in terms of fragility curves by means of the mean value (μ) and standard deviation (σ) of the lognormal distribution functions for each i-th damage state (DS_i). These curves are valid for any site (i.e. depending on the specific PGA value) as a function of different RBCs and selected SRTs, yielding the seismic performance enhancement (i.e. retrofit intensity associated to a pre-defined improvement of safety level, e.g. PGA capacity-demand ratio - PGA_C/PGA_D).

  The simulation procedure to obtain the GP_S (PGA) for each compatible RBC and selected SRT is based on the generalised procedure presented in the following studies (i.e. Gaetani d'Aragona et al., 2018; Polese et al., 2019a, b). First, the structural model of a specific RBC is generated to subsequently carry out the structural analysis and the damage analysis to finally compute the expected annual losses due to seismic damage (EAL_S) in the subsequent Step$_{(S)}$ 4 via a simplified probabilistic procedure based on the four-step general PBEE approach (i.e. hazard analysis, structural analysis, damage analysis and loss analysis), as reviewed in Section 2.1.1.1. In order to provide a simplified tool to carry out the overall procedure, reference is made to available studies by Polese et al., 2019a and Cardone et al., 2017, also enabling to extend the framework to a large set of buildings. Specifically, as for the structural modeling of RBCs, potential uncertainties related to material properties for structural and non-structural components representative of different construction ages of RBCs are considered and a set of structural models is obtained via a simulated design procedure. The building response for each structural model is analysed through a nonlinear static analysis in the form of a simplified pushover analysis, i.e. the N2 method (Fajfar 1999; 2000), according to the procedure proposed in Gaetani d'Aragona et al. (2018). The pushover curve is obtained by adopting a closed-form procedure for two lateral load distributions, namely proportional to the first mode of vibration and mass-proportional. The attainment of different EMS-98-like damage states (DS_i) (e.g. Del Gaudio et al., 2018) is identified on the pushover curve, which is then transformed into the corresponding multi-linear capacity curve and the PGA values corresponding to the attainment of the DS_i are obtained via the incremental N2 method, e.g. for infilled RC frames (Dolšek and Fajfar, 2004), to finally generate the fragility curves for each DS_i.

- **Step$_{(S)}$ 4: Seismic Generalised Performances converted into EALs** – The output of the Step$_{(E)}$ 3, i.e GP_S (PGA), is used to evaluate the expected annual losses due to seismic damages (EAL_S), representing the output of the seismic performance assessment at the time t_{ext}. Specifically, the EAL_S indicate the annual economic losses associated with the repair interventions of the seismic-induced damages based on the potential future earthquakes compatible with the seismic hazard of the building site. The consolidated PBEE methodology is generally adopted for the seismic loss estimation at building and regional level, as reviewed in Section 2.1.1.1. Specifically, the PEER-PBEE framework is considered and adapted to convert the GP_S (PGA) into EAL_S by defining a hazard model and adopting suitable damage-cost functions to compute the EAL_S by using the PEER-PBEE integral formulation (Porter, 2003; Porter et al., 2004). To this end, a suitable hazard model aimed at estimating the PGA exceedance needs to be adopted. According to the SAC/FEMA approach, a linear approximation of the hazard curve is assumed in the log-log space and the extrapolation of hazard data is limited to the upper bound value corresponding to the mean annual frequency (MAF) equal to 10 % (Perrone et al., 2022).

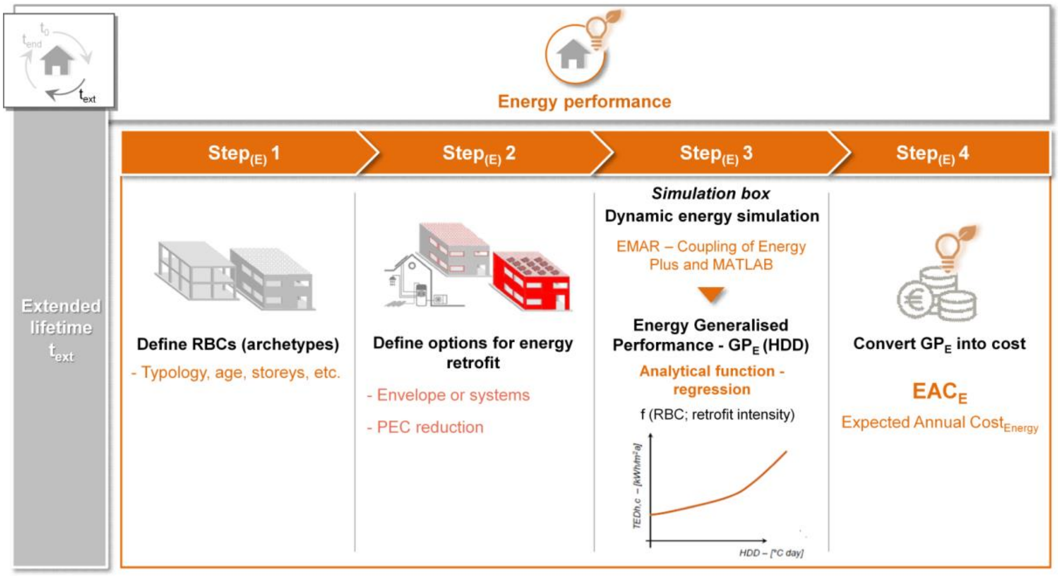
The assessment of the seismic performance at the **end-of-life time (t_{end})** corresponds to the estimation of the **end-of-life cost** for the **seismic** retrofit intervention **($EOLC_S$)**, expressed in €/m^2, which takes into account costs due to its components dismantling and/or materials disposal.

3.2.3.2 Energy performance assessment

The assessment of the energy performance at the **initial time (t_0)** corresponds to the evaluation of the **initial cost** for the **energy** retrofit intervention **(IC_E)**, expressed in €/m^2.

The assessment of the energy performance within the **extended lifetime stage (t_{ext})** follows four main steps (Figure 20), hereinafter indicated as Steps$_{(E)}$, similarly to the assessment of the seismic one, in order to provide its monetary output in terms of **expected annual costs** for **energy** consumption **(EAC_E)**, expressed in €/m^{2}year.

Figure 20. Framework of the energy performance assessment at the extended lifetime stage (t_{ext})



Source: JRC

The four Steps$_{(E)}$ are described in detail, as follows:

- Step$_{(E)}$ **1: Representative Building Classes (RBCs)** – The existing building stock is grouped into RBCs according to various classification parameters related to building structural and geometric characteristics, which represent input data for the energy performance assessment. The same classification parameters identified within the Step$_{(S)}$ 1 have been considered for the energy performance assessment. Thus, the same RBCs reported in Table 3 (Section 3.2.3.1) are obtained.
- **Step$_{(E)}$ 2: Options for energy retrofit technologies** - Potential energy retrofit technologies (ERTs) to be applied to the investigated RBCs, as separated or combined with seismic retrofit technologies, are considered according to specific classification parameters. The latter refer to both the outcomes of an interference matrix, as described into the Step 2 of the simplified assessment method, and the achievable improved energy performance, as well as the correlation between the ERTs and the thermal behavior of the building after the retrofit. Thus, the following classification parameters are considered (Table 5):
  - **Application level of retrofit intervention**, i.e. building envelope, and/or energy consumptions systems (the latter mainly refer to HVAC systems).
  - **Performance parameter identification**, which indicates the performance improvement provided by a specific retrofit technology or a combination of different ones. Energy retrofit affecting the building envelope leads to a drastic reduction of both the Thermal Energy Demand (TED) for space conditioning, i.e. heating and cooling, and the annual percentage of discomfort hours. Conversely, energy retrofit related to the HVAC systems results into a reduction of the non-renewable PEC. The TED depends on specific thermal energy needs representing the 'final energy' (also known as energy delivered) consumed by the end users, such as electricity or natural gas consumed in a household, to cover the energy demands. The PEC, instead, is the energy embodied in energy resources, that has not been subjected to any conversion or transformation process, thus referring to the beginning of the energy chain. Final and primary energies are interconnected since the final energy is provided to the users by subjecting the primary energy to several transformations during which energy losses occur. In this context, PEC is identified as the performance parameter to consider within the simplified combined assessment method since it represents a comprehensive indicator to assess the efficiency and effectiveness of energy retrofit scenarios. Furthermore, the EPBD indicates the primary energy use as the appropriate metric to assess the energy performance of buildings (Directive 2018/844; proposal COM 2021/802). To this end, results in terms of TED will be converted into PEC by means of primary energy factors (PEFs) to account for energy losses during the process of transformation from primary to final energy, e.g. ISO 52000-1 (ISO, 2017b).
  - **Thermal behavior of the retrofitted building**.

  Various ERTs can be associated to the different RBCs, based on the potential options (i = 1, 2, ..., n) identifying the classification parameters above.

Table 5. Representative Energy Retrofit Technologies options for RBCs

ERT$_{(N-i)}$	Application level of retrofit intervention	Performance parameter	Thermal behaviour
	Options (i)		
RBC $_{(N-1)}$	Building envelope HVAC systems Combination of building envelope and HVAC systems	Reduction of Primary Energy Consumption (PEC)	Low thermal transmittance HVAC system efficiency Glazing efficiency Other
RBC $_{(N-...)}$			
RBC $_{(N-n)}$			

- **Step$_{(E)}$ 3: Dynamic energy simulation** - ***Simulation box*** - Data collected within the Step$_{(E)}$ 1 and Step$_{(E)}$ 2 serve as input parameters of a 'simulation box' to assess the energy performance of either the as-built or the retrofitted building. The analysis provides a set of energy generalised performances (GP_E) as output, related to the combination of different RBCs and ERTs. Specifically, the GP_E are provided in terms of analytical curves expressing TED_h versus HDDs by means of the corresponding coefficients of regression functions. These curves are valid for any site (i.e. depending on the HDD value) as a function of different RBCs and selected ERTs, yielding the energy performance improvement (i.e. retrofit intensity associated to a pre-defined reduction of PEC).

The simulation procedure to obtain the GP_E (HDD) for each compatible RBC and selected ERT refers to a novel user-friendly, but reliable tool for accurate building energy modelling and simulation, which was conceived, developed, and validated by Ascione et al. (2021). This tool, which is derived from a deep update of a previous version conceived for office buildings (Ascione et al., 2017), is denoted as EMAR since it is based on the advanced coupling between EnergyPlus™ (US DOE, 2015) and MATLAB® (MathWorks, 2015) addressing Residential building. EMAR works under MATLAB® environment and needs only numerical inputs to generate simplified building models and perform accurate energy simulations. Specifically, EMAR requires only (a maximum of) 63 numerical inputs classified in four groups, related to (i) geometry, (ii) envelope, (iii) HVAC, and (iv) photovoltaics, reported in Annex 1. In such a way, it is possible to overcome the high modeling complexity and the deep simulation expertise needed to use EnergyPlus as a stand-alone tool. The framework of EMAR, based on an EnergyPlus parametrised mother-file, where the geometry, envelope, and energy systems of the building are parametrised, consists of the three following main steps (Ascione et al., 2021):

- Input (Building modelling) - The user sets the 63 EMAR inputs, the weather data, and the required outputs, and EMAR generates the EnergyPlus model of a potential examined building, presenting a simplified geometry to streamline the parametrisation process, as in Mauro et al. (2015).
- Simulation - MATLAB® runs the EnergyPlus simulation via the EMAR coupling function and collects the simulation output data referring to a typical climatic year, i.e. TED for space heating and cooling, electricity demands for direct electric uses, thermal comfort indicators, and produced energy by photovoltaics, if present. In the context of the $Step_{(E)}$ 3, the output considered is the TED_h.
- Post-processing – a post-processing MATLAB® code handles the simulation output data of the previous step to obtain the required final results (e.g. conversion of TED in PEC).

— **$Step_{(E)}$ 4: Energy Generalised Performances converted into EAC_E** – The output of the $Step_{(E)}$ 3, i.e GP_E (HDD), is used to evaluate the expected annual cost due to energy consumptions (EAC_E), representing the output of the energy performance assessment at the time t_{ext}. Specifically, the result of TED_h (expressed in kWh/m^{2}year) is first converted into the corresponding PEC by means of non-renewable primary energy factors (PEF_{nren}). It is worth noting that PEFs are country-specific factors, as recently reviewed in Hamels et al. (2021) in the European context, since the calculation methods and the efficiency of the entire supply change differ from country to country. However, in case of lack of country-based data, the standard ISO 52000-1 (ISO, 2017b) provides default values of PEFs, although the geographical variability is not considered; this standard was recently supported by the release of the European standard EN 17423 (2020). Subsequently, the result of PEC (expressed in kWh/m^{2}year) is transformed into the expected annual cost due to energy consumption (EAC_E) by means of a monetary conversion factor ($CF_{E,M}$), which refers to the unitary energy price related to natural gas or electricity consumptions, both expressed as €/kWh. These prices, provided as bi-annual data from 1985 to 2021, can be retrieved by Eurostat – Energy Statistics, as already described in Section 2.1.4.1. It is worth noting that the post-processing step of the EMAR tool enables the user to directly convert the TED_h in PEC by considering the values of PEF_{nren} for natural gas (PEF_{nren} = 1.05) and electricity (PEF_{nren} = 1.95) provided by the Italian energy regulations (Ministerial Decree 26/06/2015 – Annex 1), and to also compute the related cost based on specific energy prices (Ascione et al., 2021). Finally, the assessment of the energy performance at the **end-of-life time (t_{end})** corresponds to the estimation of the **end-of-life cost** for the **energy** retrofit intervention (**$EOLC_E$**), expressed in €/m^2, essentially derived from its components dismantling and/or materials disposal.

3.2.3.3 Environmental performance assessment at the three stages of life cycle

The environmental performance of a potential investigated building is focused on the evaluation of the effectiveness of its retrofit intervention by quantifying the environmental impacts at the three corresponding time stages of the building's life cycle, i.e. t_0, t_{ext}, and t_{end}, according to a computational approach based on two main steps – hereinafter indicated as $Step_{(EI)}$ - as follows:

- **$Step_{(EI)}$ 1: Environmental impact assessment** - Attention is drawn to the global warming potential (GWP) impact indicator in order to assess the GHG emissions, commonly quantified in terms of mass of equivalent carbon dioxide (CO_2) emissions and expressed as tonnes of CO_2-equivalent (tCO_2eq). It is worth noting that diverse methods will be implemented to estimate the abovementioned output depending on the three time stages of the building life cycle.

- **$Step_{(EI)}$ 2: Conversion into equivalent cost** - The environmental output, calculated in the previous step, is converted into monetary units to enable the computation of the three main equivalent total cost contributions associated with the initial time, extended lifetime, and end-of-life. Specifically, the total amount of CO_2-equivalent emissions achieved at each stage of the building life cycle is transformed into its corresponding economic measure by means of a monetary conversion factor ($CF_{CO2,M}$), which refers to the unitary carbon price, expressed as €/tCO_2eq.

  In order to implement the $Step_{(EI)}$ 2, the same observations on the most significant developments to date within the carbon market, already exposed in the context of the SSD methodology (Section 2.1.4.1), are considered to identify the carbon price. Based on that brief review, the EU-ETS has been selected as the most effective instrument to identify the unitary carbon price (expressed as €/tCO_2eq), defining the $CF_{CO2,M}$, for the proposed simplified combined assessment method. The EEX is selected among the exchange markets providing data on EUA price to identify the $CF_{CO2,M}$ needed to convert the amount of tonnes of CO_2-equivalent emissions, computed in the $Step_{(EI)}$1, into equivalent costs. Specifically, the EEX spot price of one EUA resulted equal to 76.50 €/tCO_2eq at the end of March 2022 (specific date of observation: 24th March 2022).

Details of the two-step computational approach for the assessment of the environmental performance at each stage of the building's life cycle are provided in the following.

The assessment of the environmental performance at the **initial time (t_0)** accounts for the CO_2-equivalent emissions corresponding to the production of materials used for the separated or combined retrofit technologies. Its calculation refers to the production stage (i.e. Module A1 to A3) of the standardised life cycle of a building according to EN 15978 (CEN, 2011). According to the $Step_{(EI)}$ 1 of the computational approach, the ecological burdens in terms of tCO_2eq are achieved by carrying out a LCA analysis compliant with the four-step framework addressed by ISO 14040-44 (ISO, 2006a;b). However, a simplified approach could be alternatively adopted by considering environmental documents provided by manufactures and producers, such as the EPDs according to EN 15804+A2/AC (CEN, 2021). Once the outcome of the CO_2-equivalent emissions is obtained, the $Step_{(EI)}$ 2 of the computational approach is applied by multiplying the total quantity of tCO_2eq by the monetary conversion factor $CF_{CO2,M}$ (€/tCO_2eq), thus leading to the needed output of the **initial cost** for the **environmental impact (IC_{EI})**, expressed in €/m^2, at the time t_0.

The assessment of the environmental performance within the **extended lifetime stage (t_{ext})** accounts for two main sources of Expected Annual Environmental Impacts (EAEI) in terms of CO_2-equivalent emissions depending on the seismic and energy performance assessment at t_{ext}, respectively, as follows:

1. The contribution of the environmental impacts derived from the potential damages of structural and/or non-structural components of the retrofitted building due to seismic events refers to the amount of tonnes of CO_2-equivalent emissions, which may arise from building components replacement, post-earthquake repair interventions, and debris disposal. However, an accurate estimation of the EAEI due to seismic damage results particularly complex due to several issues, such as the difficulty of combining different disciplines, the lack of LCA data availability, the strict dependence from the seismic hazard levels. In the last decade, research efforts in this direction have led to various studies that propose different methodologies to carry out a probabilistic LCA of buildings subjected to seismic damages during their life cycle (e.g. Arroyo et al., 2012; Menna et al., 2013; Wei et al., 2016a).

   As for the proposed simplified method, according to the $Step_{(EI)}$ 1 of the computational approach, the optimum direction to quantify the expected annual environmental impacts derived from seismic damage ($EAEI_S$) should be to define a procedure similar to the ones developed for the seismic and energy performance assessments at the extended lifetime stage. Hence, a set of environmental impact generalised performances (GP_{EI}) should be provided as curves representing the $EAEI_S$, in terms of tCO_2eq/year, (associated to building components replacement, post-earthquake repair interventions, and debris disposal) as function of PGA values for each RBC and its compatible seismic retrofit technologies. However, the development of such a procedure deserves further research efforts, thus a simplified route is adopted. Specifically, a fixed amount of $EAEI_S$, expressed as tCO_2eq/year, might be considered based on data and results carried out in previous studies (e.g. Menna et al., 2013; Belleri and Marini, 2016).

2. The contribution of the environmental impacts derived from the annual consumption of energy for space heating refers to the amount of CO_2-equivalent emissions associated with the TED_h (as function of HHD values for each RBC and its compatible ERTs) carried out according to the $Step_{(E)}$ 3 of the procedure for the energy performance assessment at time t_{ext}. Hence, the expected annual environmental impacts due to energy consumption ($EAEI_E$), expressed as tCO_2eq/year, are obtained by multiplying the TED_h (kWh/year) by a CO_2 emission conversion factor (CF_{CO2}), expressed as tCO_2eq/kWh, according to ISO 52000-1 (ISO, 2017) and the recent European standard EN 17423 (CEN, 2021).

The outputs related to $EAEI_S$ and $EAEI_E$, expressed in tCO_2eq/year, need to be subsequently converted in economic metrics, according to the $Step_{(EI)}$ 2 of the computational approach. Thus, the expected annual cost for the environmental impact due to seismic ($EAC_{EI,S}$) and energy ($EAC_{EI,E}$) performances are achieved by multiplying the two corresponding total amounts of tCO_2eq/year related to $EAEI_S$ and $EAEI_E$ by the monetary conversion factor $CF_{CO2,M}$. Finally, the $EAC_{EI,S}$ and $EAC_{EI,E}$ are summed up to provide the needed output of the **expected annual cost** for the **environmental impact (EAC_{EI})**, expressed in €/m^{2}year, at each time $t \in t_{ext}$.

The assessment of the environmental performance at the **end-of-life time (t_{end})** accounts for the amount of tonnes of CO_2-equivalent emissions corresponding to the dismantling of components and/or materials used for the implemented separated or combined retrofit technologies. These burdens could be counterbalanced by waste management-related environmental benefits consisting of a potential reduction of CO_2-equivalent emissions due to reuse of components, recycle of materials and recovery potential, which are also computed at this time stage. Thus, the environmental performance assessment at the time t_{end} refers to both the end-of-life stage (i.e. Module C) and the benefits and loads beyond the system boundary (i.e. Module D) of the standardised life cycle according to EN 15978 (CEN, 2011). The same procedure used for the environmental performance assessment at the time t_0 is applied to carry out the needed result at the time t_{end}. Hence, according to the $Step_{(EI)}$ 1 of the computational approach, the environmental outcomes in terms of tCO_2eq are achieved by either a LCA analysis or a simplified approach by using data of EPDs. Subsequently, the $Step_{(EI)}$ 2 of the computational approach is applied by converting the total quantity of tCO_2eq into economic terms by means of the monetary conversion factor $CF_{CO2,M}$ (€/tCO_2eq), thus leading to the needed output of the **end-of-life cost** for the **environmental impact ($EOLC_{EI}$)**, expressed in €/m^2, at the time t_{end}.

3.2.3.4 Equivalent economic performance assessment

The combination of seismic, energy, and environmental performances at the time t_0, t_{ext}, and t_{end} with the corresponding outputs expressed in monetary units leads to three main equivalent total costs, namely (i) the equivalent total initial cost - Total IC_{eq} (t_0), (ii) the equivalent total extended lifetime cost (t_{ext}), and (iii) the equivalent total end-of-life cost - Total $EOLC_{eq}$ (t_{end}), respectively.

The **equivalent total initial cost** (Total IC_{eq}, expressed in €/m^2) at the **time t_0** is the sum of the initial costs of seismic (IC_S) and energy (IC_E) retrofit interventions - separated or combined, and the initial costs of the environmental impact (IC_{EI}) for manufacturing the materials adopted in the retrofit intervention, according to Equation (19).

$$Total\ IC_{eq}(t_0) = IC_S + IC_E + IC_{EI} \tag{19}$$

As for the **extended lifetime t_{ext}**, the seismic, energy, and environmental performances assessed on an annual basis, and expressed in economic terms according to the computational procedures previously described (i.e. Section 3.2.3.1, Section 3.2.3.2, and Section 3.2.3.3, respectively), are combined into a global **Integrated Retrofitting Performance Parameter** (IRPP, expressed in €/m^{2}year). Specifically, the IRPP is defined as the sum of expected annual seismic losses (EAL_S), expected annual costs related to energy consumption (EAC_E), and the expected equivalent costs of CO_2-equivalent emissions due to both seismic damage and energy consumption (EAC_{EI}). The IRPP is computed before ($IRPP_0$) and after ($IRPP_R$) the retrofit, according to Equation (20) and Equation (21), respectively.

$$IPRR_0(t) = EAL_{S,0} + EAC_{E,0} + EAC_{EI,0} \tag{20}$$

$$IPRR_R(t) = EAL_S + EAC_E + EAC_{EI} \tag{21}$$

The difference between $IRPP_0$ and $IRPP_R$ represents the **equivalent total extended lifetime cost** (ΔIRPP, expressed in €/m^{2}year) at the **time t_{ext}**. The ΔIRPP includes the annual economic savings due to the retrofit interventions and also provides the opportunity to consider potential fiscal incentives by national governments (e.g., 'Sismabonus' and 'Ecobonus' mechanisms in Italy) by means of a coefficient α(t), according to Equation (22).

$$\Delta IPRR_\alpha(t) = IPRR_0(t) - [\alpha(t) \cdot IPRR_R(t)] \tag{22}$$

Where:

α(t) is an amplification factor > 1 (α(t) is equal to 1, in case of absence of fiscal incentives).

The effect of the coefficient α(t) applied to the economic savings is limited over time, thus ensured for a defined period of years (i.e. $t_0 < t \leq t_{inc}$, with t_{inc} expressing the maximum reference time after the retrofit intervention at time t_0). For sake of simplicity, the coefficient α(t) is considered as a homogeneous factor in the proposed method, although it should be differentiated for the assessment of the seismic, energy, and environmental performances.

The **equivalent total end-of-life cost** (Total EOL_{eq}, expressed in €/m^2) at the **time t_{end}** is the sum of the end-of-life costs for dismantling seismic ($EOLC_S$) and energy ($EOLC_E$) retrofit measures and the end-of-life costs associated with the environmental impact ($EOLC_{EI}$) of dismantling and/or recycle/reuse retrofit materials and components, according to Equation (23).

$$Total\ EOLC_{eq}(t_{end}) = EOLC_S + EOLC_E + EOLC_{EI} \tag{23}$$

The total equivalent economic performance of the retrofitted building is achieved by combing the above three equivalent total cost contributions at time t_0, t_{ext}, and t_{end} obtained by Equations (19), (22), and (23), respectively. This final economic result of the computational step of the proposed simplified combined assessment method expresses the variation of the **equivalent Total Life Cycle Cost** (Total Life Cycle $Cost_{eq}$) over the lifetime of the building, according to Equation (24).

$$Total\ Life\ Cycle\ Cost_{eq}(t) = -Total\ IC_{eq}\ (t_0) + D_R \cdot |\Delta IPRR_\alpha(t)| \cdot t \pm |Total\ EOLC_{eq}\ (t_{end}) \tag{24}$$

Where:

$t_0 < t \leq t_{end}$ (expressed in years).

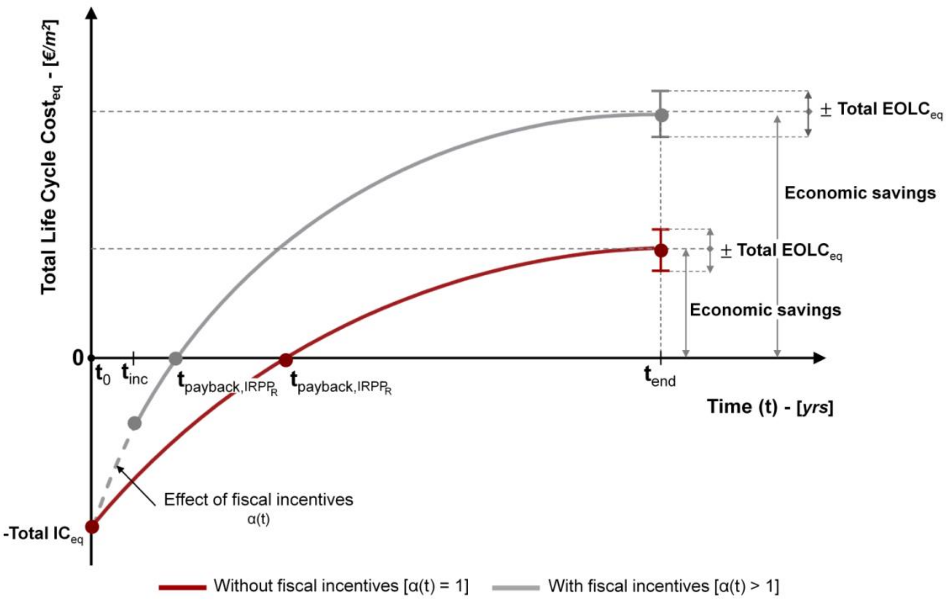
D_R is the actualisation factor or the discount rate.

The three total equivalent total cost contributions enable the representation of the final output of the computational step into a representative **Total Life Cycle Cost$_{eq}$** vs **Time curve**, carried out by means of Equation (24). Two representative qualitative curves differing for the exclusion or inclusion of potential fiscal incentives are depicted in Figure 21.

The red curve (i.e. fiscal incentives are excluded) starts at the initial time (t_0 = 0) with a negative value of cost corresponding to the Total IC_{eq}, which indicates the initial economic investment for the combined retrofit. Subsequently, the positive effects of the combined seismic and energy retrofit intervention (i.e. the reduction of seismic vulnerability, improvement of energy efficiency, and reduction of CO_2-equivalent emissions), expressed by the economic savings in the ΔIPRR term, lead the curve to progress towards the positive quadrant of the graph by crossing the abscissa axis (i.e. time axis). The crossing point corresponds to the total recovery of the Total IC_{eq} at a specific time, defined as the extended payback time ($t_{payback,IPRR}$). The latter is calculated as the ratio between Total IC_{eq} and ΔIPRR, thus representing the time needed (expressed in years) to equal the initial economic investment for the retrofit. This metric assumes a key-value since it can indicate the economic effectiveness of any implemented retrofit intervention; the lower is the $t_{payback,IPRR}$ value, the more cost-effective is the retrofit. Finally, the curve continues to progress into the positive quadrant of the graph, indicating the cumulated annual economic savings, until the end-of-life of the building is reached at the time t_{end}, which corresponds to the end of the service life of a building. Specifically, the total value of the cumulated annual economic savings corresponds to the second term, i.e. $D_R \cdot |\Delta IPRR_{\alpha}(t)| \cdot t$, of the second member of the Equation (24) minus its first term, i.e. $Total\ IC_{eq}(t_0)$. Finally, at the time t_{end}, a positive or negative equivalent total cost, corresponding to the Total $EOLC_{eq}$, is associated. In case the potential for reuse/recycle of materials and/or components of seismic and energy retrofit technologies exists leading to the reduction of environmental impacts and consequently reduced costs, expressing economic benefits, the Total $EOLC_{eq}$ is assumed as 'credit' and indicated in the curve as a positive value, which increases the final economic savings.

The grey curve (i.e. fiscal incentives are included) differs from the red one by a change in the slope, represented by the dashed part in Figure 21, due to a faster recovery of the initial economic investment, with a consequent reduced extended payback time and higher cumulated economic savings. However, the incentives are active for a limited period of time (i.e. $t_0 \leq t \leq t_{inc}$), after which the curve assumes the same trend of the red one.

Figure 21. Qualitative Total Life Cycle $Cost_{eq}$ vs Time curves (with and w/o fiscal incentives), according to Equation (24)



Source: JRC

The representation of the output of the proposed simplified combined assessment methodology through a graphic format provides a useful tool to facilitate the decision-making process. Indeed, it allows stakeholders to easily compare potential solutions based on separated or combined interventions or different retrofit technologies in a life cycle perspective. Furthermore, it enables to verify the retrofit effectiveness over time by monitoring the payback time among different retrofit strategies, thus reducing or extending this parameter depending on the seismic or energy performance targets to satisfy.

3.2.4 Step 4 - Optimised solutions

The fourth step of the proposed simplified combined assessment method – hereinafter indicated as Step 4 – aims to perform a comparative quantitative assessment of potential different combined seismic and energy retrofit solutions applied to an existing building in order to identify the most effective one.

The assessment consists in comparing the results of the total equivalent economic performance, i.e. the Total Life cycle cost over time, of the various solutions carried out according to the Step 3 of the proposed simplified combined method. Based on the sustainability targets set into the Step 1 and the potential combined retrofit strategies selected into the Step 2, the results of the seismic, energy, and environmental performances of a building retrofitted with the various solutions, expressed as a total cost contribution at each stage of the life cycle into the Step 3 allow the selection of the best solution in line with the available budget. Hence, the outcomes in monetary terms of the proposed combined assessment method provide a useful tool to ease and accelerate the decision-making process towards the optimisation of the proposed integrated retrofit solutions.

4 Case studies

4.1 Selection of representative case studies

The selection of four case studies, which are representative of the most widespread EU building typologies in relation to the characteristics of both their structural systems and envelope components to properly investigate the identified buildings in terms of seismic and energy performances before and after the combined retrofit, has been carried out according to the following three-step approach:

1. **Identification of case study categories** – This step deals with the investigation of both construction technologies and building envelope components of the EU existing residential building stock in order to identify four suitable categories of case studies.
2. **Identification of case study location** – In this stage the analysis of both the seismic hazard and the climatic zones of the EU territory is carried out to identify four locations of case studies.
3. **Identification of case studies** – The outcomes of the two previous steps are properly combined to select four case studies, referring to existing buildings needing both seismic and energy retrofit, to which a standard combined assessment method and the new simplified one are subsequently applied.

Each step is illustrated in detail in the following sections.

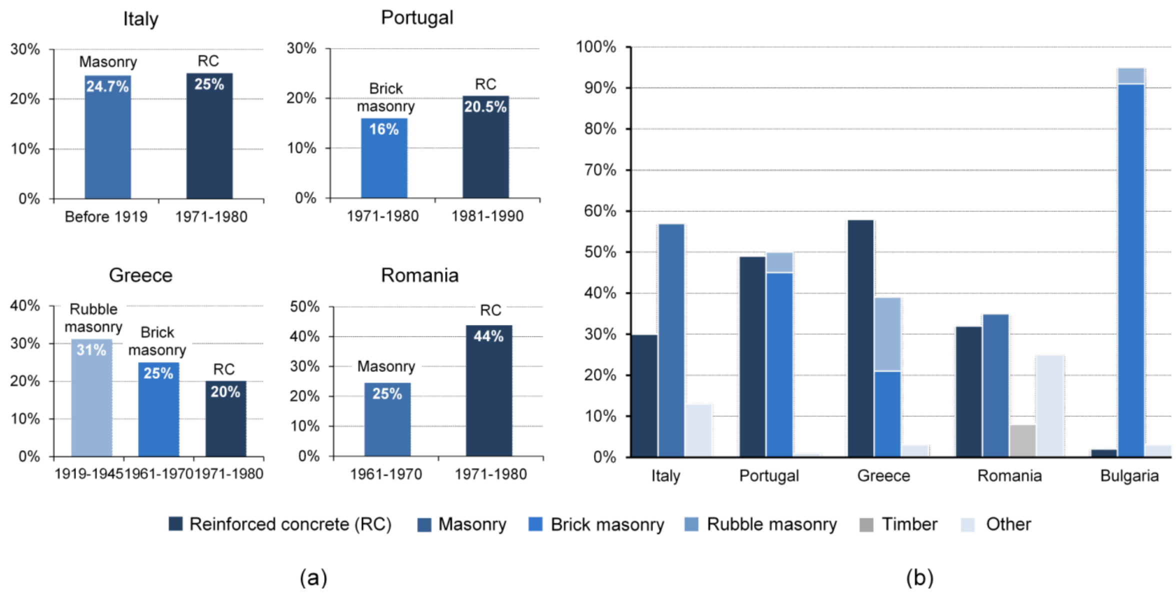
4.1.1 Identification of case study categories

An ad-hoc survey of the EU residential building stock in order to detect the most recurrent construction technologies in terms of construction material (i.e. masonry, reinforced concrete, timber, other) is carried out by means of a twofold procedure. The latter is based on (i) a **quantitative data analysis**, and (ii) a **qualitative data analysis**, depending on the availability of statistical data from the national statistical institutes of the investigated EU Member States.

As for the **quantitative data analysis**, few statistical institutes of the 27 EU Member States (EU-27) provide data of the total number of residential buildings disaggregated by both construction periods and the corresponding construction technologies. Thus, this investigation was carried out for Italy, Greece, Portugal, Romania, for which the aforementioned data are available, and partially for Bulgaria, for which the national statistical institute provides the total number of residential buildings by construction technologies without data on their distribution by construction period. Specifically, the examination of these data allowed the identification of the time periods in which the highest number of residential buildings by construction technology was erected in each investigated country, except for Bulgaria (Figure 22a). Moreover, the analyses of the total percentage distribution of residential buildings by construction technology for the overall period before 1919 to 2011 were carried out for each investigated country. Conclusive remarks of the quantitative data analysis pointed out that the most recurring construction technologies of residential buildings in the five investigated countries are masonry, mainly distinguished in brick masonry and rubble stones, and reinforced concrete (RC), although Bulgaria presents a predominant percentage of brick masonry buildings and Romania also accounts for a low percentage of timber buildings (Figure 22b).

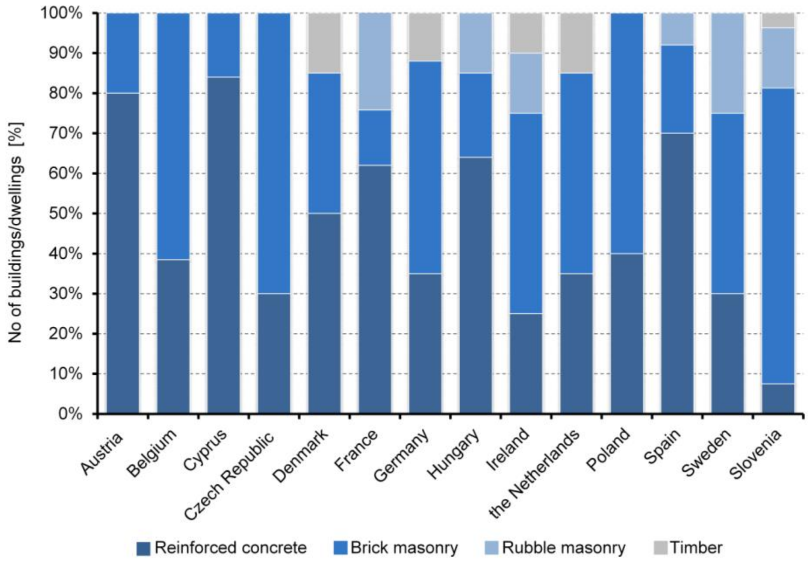
The quantitative data analysis above provides a reliable but partial outcome, as it refers to the residential building stock of a restricted number of the EU-27. Thus, it is essential to enlarge the investigation by means of a **qualitative data analysis**. The latter takes into account two different types of data, namely (i) quantitative, and (ii) qualitative data, in order to overcome the lack of statistics on the building stock distribution by construction technology for the EU Member States not investigated in the previous quantitative analysis. First, quantitative data related to the total number of residential buildings/dwellings by construction period of EU countries, provided by the corresponding national statistical institutes, were examined in order to identify the time periods in which the maximum number of buildings was erected in each analysed country. Second, qualitative data on construction technologies of residential buildings provided by the 2009-2012 Intelligent Energy European (IEE) project 'Typology Approach for Building Stock Energy Assessment' (TABULA) were considered. Specifically, TABULA project has led to the development of a series of databases of the national building typologies representing the residential building stock of 21 European countries, implemented into a dedicated web-based tool, named TABULA WebTool. Each national building typology consists of a classification scheme grouping buildings according to their size, age, and further parameters into a so-called 'Building Type Matrix', also providing a set of exemplary buildings that represent each building type. Furthermore, the tool provides building data on typical floor, roof, and wall components for each building type; the analysis of those data can lead to the identification of the building construction technology. A combination of the quantitative and qualitative data allowed the main construction technologies of several remaining EU countries to be identified. The reliability of the proposed approach was initially investigated by comparing results for Italy, Greece, and Bulgaria carried out by the previous quantitative data analysis with the qualitative one according to the data retrieved by the TABULA WebTool. Specifically, the periods of construction corresponding to the highest percentages of buildings by construction technologies was first considered, according to the results of the previous quantitative analysis. Subsequently, the TABULA web tool has been used to verify the correspondence of the identified construction technology with the building components indicated into the tool. The effectiveness of the outcomes allowed the validation of the proposed qualitative analysis, which was subsequently carried out for the following 14 EU Member States: Austria, Belgium, Cyprus, Czech Republic, Denmark, France, Germany, Hungary, Ireland, the Netherlands, Poland, Spain, Sweden, and Slovenia, also taking into account results provided by the 2010-2014 'Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation' (NERA) project (Ozcebe et al., 2014). Conclusive remarks of the qualitative analysis pointed out that the most recurring construction technologies of the existing building stocks in the aforementioned investigated countries are masonry, mainly distinguished in brick masonry and rubble stones, and RC buildings. However, Denmark, Germany, the Netherlands, Ireland, and Slovenia also account for low percentages of timber buildings (Figure 23).

Figure 22. Quantitative data analysis - Distribution of residential buildings by construction technology in Italy, Greece, Portugal, Romania, and Bulgaria: (a) time periods with the highest percentage distribution of buildings (except Bulgaria – data not available), and (b) total percentage distribution of buildings for the period pre-1919÷2011



Source: Data - Italy (ISTAT, 2011), Greece (ELSTAT, 2011), Portugal (INE, 2011), Romania (INS, 2011), and Bulgaria (NSI, 2011).

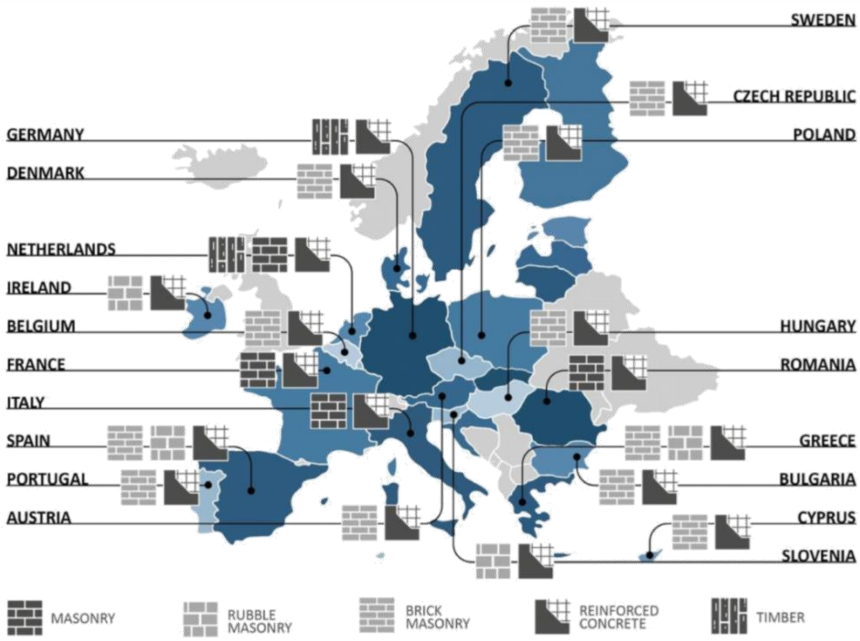
Figure 23. Qualitative data analysis - Total percentage distribution of residential buildings/dwellings by construction technology in 14 EU Member States



Source: Data (* dwellings) - Austria (Statistics Austria, 2011); Belgium* (STATBEL, 2011); Cyprus* (Cystat, 2011); Czech Republic (CZSO, 2011); Denmark* (DST, 2011); Hungary (KSH, 2011), Ireland* (CSO, 2011); Slovenia (SURS, 2002); Spain (INE, 2011); TABULA WebTool, 2013; Ozcebe et al., 2014.

The combination of the results carried out by the quantitative and qualitative analyses leads to the definition of a construction technology map of the majority of the EU territory (Figure 24). Based on the analysed data, the highest percentages of the EU building stock are represented by masonry and RC buildings, in line with the outcomes carried out in Romano et al. (2023). Masonry buildings are mainly brick or rubble stone masonry structures according to the surveyed quantitative and qualitative data. RC buildings predominantly consist of RC framed structures, as reported in research studies in the field of structural engineering (e.g. Masi and Vona, 2012; Masi et al., 2015; Pohoryles et al., 2020; Menna et al. 2021, among others). Indeed, this structural typology was extensively used in low-, mid- and high-rise buildings, initially, due to the need to rapidly accommodate households after the Second World War and, subsequently, due to the increasing urbanisation mainly in industrialised countries.

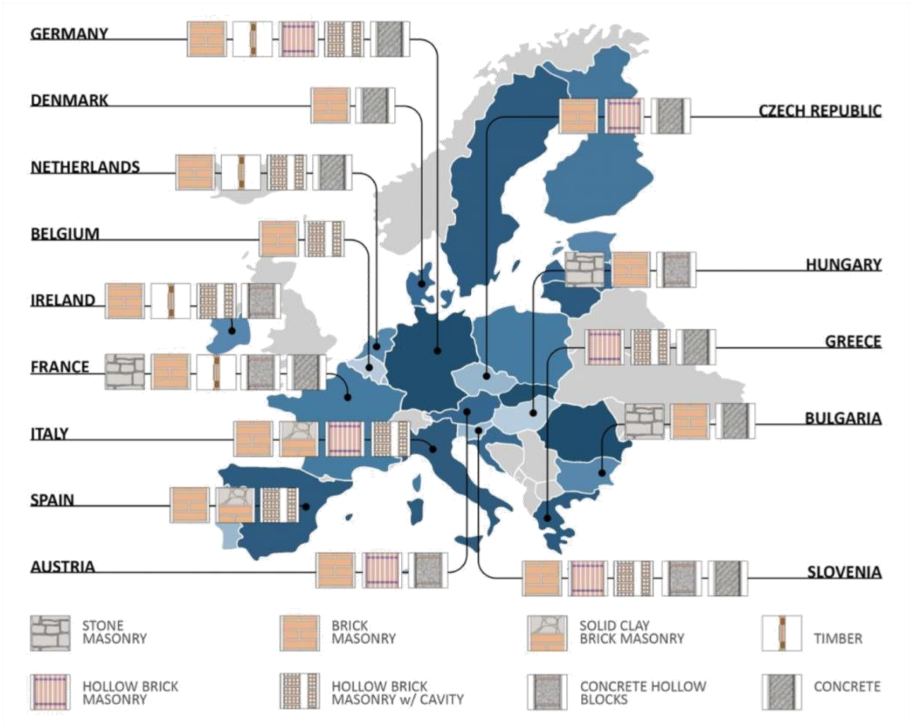
Figure 24. Construction technologies map of the majority of EU member states



Source: JRC

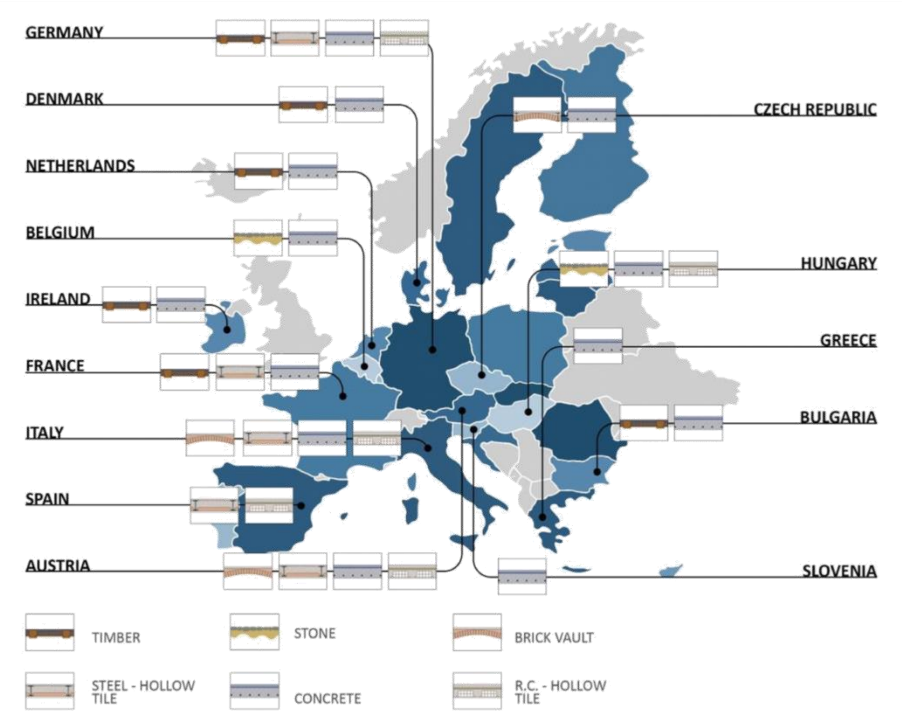
Beyond the construction technologies, it is also essential to inspect the most common envelope components of the EU building stock in terms of both structural and non-structural elements, in order to properly investigate the case studies by means of effective structural and energy/environmental analyses. The TABULA WebTool database provides information about the vertical (i.e. walls) and horizontal (i.e. floors and roofs) envelope components of the most representative residential buildings by construction period for several EU Member States. Although it is not possible to collect quantitative data on the different types of the building envelope elements, the analysis of TABULA database leads to the creation of EU maps reporting the distribution of the main typologies of walls (Figure 25), floors (Figure 26), and roofs (Figure 27) of residential buildings by EU country. Beyond vertical structural elements consisting of brick, and stone masonry walls, mainly used for masonry structures, the vertical envelope components characterising other structural typologies encompass the following infill walls: timber panels, single-layered or double-layered with air chamber hollow bricks walls, and solid or hollow blocks concrete walls. The horizontal envelope components in terms of floors consist of masonry vaults, timber, RC solid flat slabs, and two different typologies of beam-and-clay systems, namely (i) steel beam-and-hollow clay flat block, and (ii) cast-in-place RC beam-and-hollow clay block, both with a concrete topping. Finally, the horizontal envelope components in terms of roofs can be divided into two main groups, namely pitched roofs and flat roofs. The former includes timber, and cast-in-place RC beam-and-hollow clay block roofs. The latter refers to timber, RC solid slab, and the two different typologies of beam-and-clay systems, already indicated for the floor component. According to the maps results, the most widespread typologies of envelope components are the hollow brick masonry wall with air chamber (i.e. cavity walls) (Figure 25), the two different typologies of beam-and-clay floor systems, namely (i) cast-in-place RC beam-and-hollow clay block, and (ii) steel beam-and-hollow clay flat blocks floors (Figure 26), and the pitched timber, and RC-hollow tile roofs, as well as the flat RC-hollow tile roof (Figure 27).

Figure 25. Map of the typical walls of the EU residential building stock



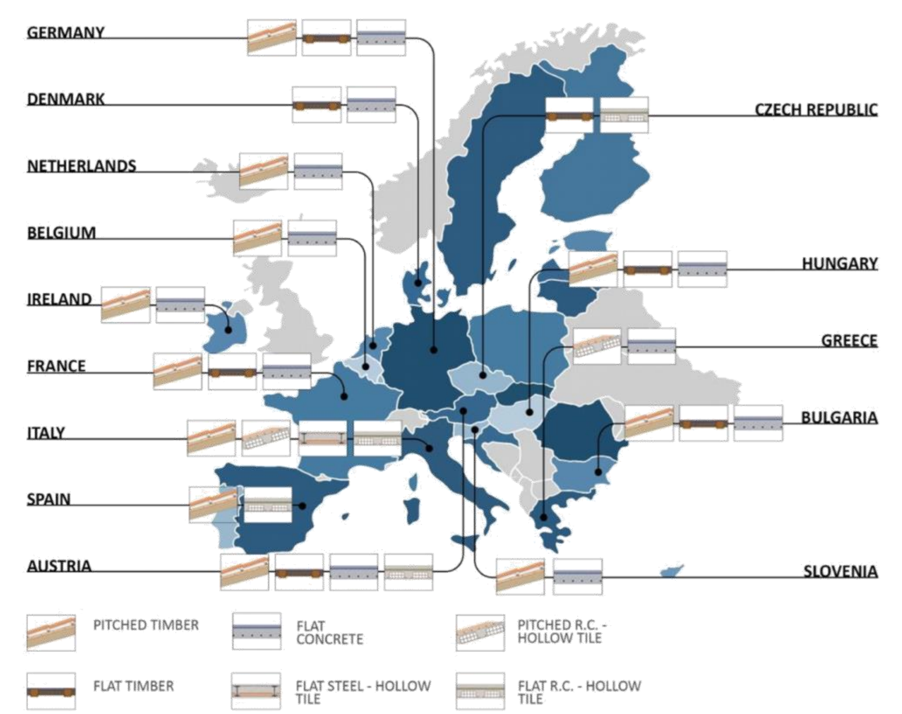
Source: Data - TABULA WebTool, 2013.

Figure 26. Map of the typical floors of the EU residential building stock



Source: Data - TABULA WebTool, 2013.

Figure 27. Map of the typical roofs of the EU residential building stock

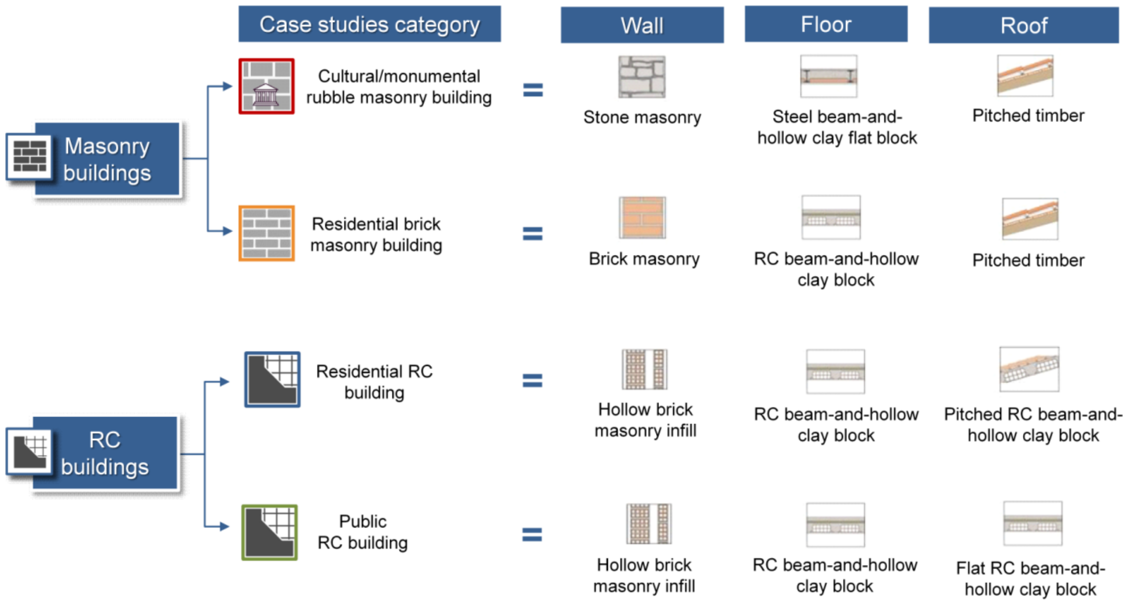


Source: Data - TABULA WebTool, 2013.

It is worth noting that the detailed investigation on both construction technologies and envelope elements refers to residential buildings. However, the selection of the four case studies categories focuses on a wider extent of building use by including a public building and a cultural/monumental building beyond two residential buildings. Indeed, a broader investigation becomes essential due to both the high exposure of public buildings and the importance of preserving the historical buildings value. The combination of the aforementioned outcomes related to the recurrent construction technologies and the prevalent vertical and horizontal elements of the building envelope, along with the building use leads to the identification of the following four representative categories of case studies (Figure 28):

1. Cultural/monumental rubble masonry building with pitched timber roof, and steel beam-and-hollow clay flat block floors.
2. Residential brick masonry building with pitched timber roof, and cast-in-place RC beam-and-hollow clay block floors.
3. Residential RC building with hollow brick infill walls, cast-in-place RC beam-and-hollow clay pitched roofs and cast-in-place RC beam-and-hollow clay block floors.
4. Public RC building with hollow brick infill walls, cast-in-place RC beam-and-hollow clay flat roofs, and cast-in-place RC beam-and-hollow clay block floors.

Figure 28. The four categories of case studies



Source: JRC

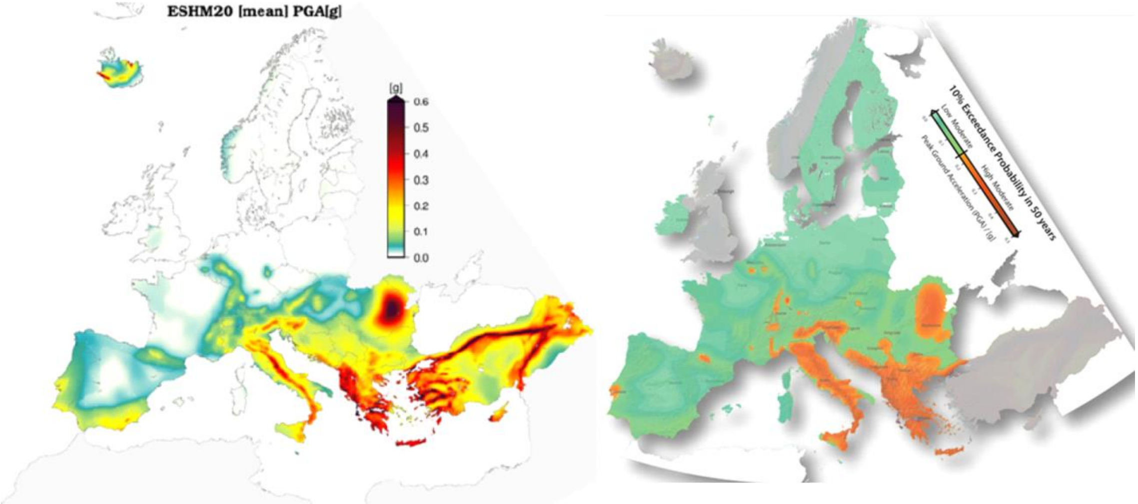
4.1.2 Identification of case studies location

The need to perform combined seismic and energy retrofit interventions of the EU building stock makes essential the classification of the EU territory into seismic hazard and climatic zones. Based on the corresponding outcomes in this direction carried out in Romano et al. (2023), further mapping refinements are considered in the following to identify the appropriate locations of the potential four case studies to be investigated.

4.1.2.1 EU seismic hazard zone map

Seismic risk is determined by the combination of three main factors, namely (i) hazard, (ii) vulnerability, and (iii) exposure. Specifically, the seismic hazard of a territory is represented by the frequency and the intensity of potential earthquakes occurring in that specific area. Thus, seismic hazard can be defined as the probability of a potential earthquake occurring in a geographical area with a ground shaking intensity, expressed as an expected Peak Ground Acceleration (PGA) with a probability to be exceeded in an assumed time period. Focusing on Europe, low, moderate, and high seismic hazard zones can be identified depending on specific PGA ranges in gravity units (g) corresponding to $PGA < 0.1g$, $0.1g \leq PGA < 0.25g$, and $PGA \geq 0.25g$ respectively, with the 10% exceedance probability in 50 years on a uniform rock site condition, according to the 2020 European Seismic Hazard Model (ESHM20) (Danciu et al., 2021), as depicted in Figure 29a. The ESHM20 was recently released as an update of the 2013 ESHM (Giardini et al., 2014); further details are provided in Danciu et al. (2021). In the perspective of the identification of the four representative case studies, the average value of the PGA range defining the moderate seismic hazard zone in the ESHM20 was considered in order to identify two EU macro-seismic hazard zones, i.e. low-to-moderate (PGA < 0.175g) and moderate-to-high (PGA ≥ 0.175g), as illustrated in Figure 29b.

Figure 29. (a) European Seismic Hazard Model 2020 and (b) proposed EU macro-seismic hazard zones map



Seismic hazard zone	Peak Ground Acceleration (PGA)
Low	PGA < 0.1g
Moderate	0.1g ≤ PGA < 0.25g
High	PGA ≥ 0.25g

(a)

Seismic hazard zone	Peak Ground Acceleration (PGA)
Low - Moderate	PGA < 0.175g
Moderate - High	PGA ≥ 0.175g

(b)

Source: (a) ©Danciu et al., 2021 (CC BY 4.0).

4.1.2.2 EU climatic zone map

The EU residential buildings during the use phase of their life cycle consume energy for space conditioning (i.e. heating and cooling), hot water production, cooking, lighting, and electric appliances use. In 2019, the residential building sector accounted for 26.3 % of the EU final energy consumption, mainly due to space heating; the use of space heating resulted equal to 63.6 % of the final energy consumption (Eurostat, 2019). It is recognised that the energy consumptions for space heating and cooling are strictly related to climate conditions of a specific location; energy per heated and cooled floor area is directly proportional to two weather-based technical indexes, namely Heating Degree Days (HDD) and Cooling Degree Days (CDD), respectively. Hence, the HDD and CDD parameters derived from outside air temperature measurements on a daily basis and used to estimate the heating and cooling energy demands of buildings, respectively, become valid tools to identify the EU climatic zones. According to Eurostat, the calculation of the HDD relies on a base temperature, defined as the mean daily outside air temperature above which indoor heating is not required. The base temperature is set to a constant value equal to 15°C, thus the HDD is calculated according to Equation (25).

$$HDD = \begin{cases} \sum_i (18°C - T_m^i), & for\ T_m^i \leq 15°C \\ 0, & for\ T_m^i > 15°C \end{cases} \tag{25}$$

where:

T_m^i is the mean outside air temperature of day i;

18°C is the constant value set for the indoor temperature.

Similarly, the calculation of CDD relies on a base temperature, defined as the mean daily outside air temperature below which indoor cooling is not required. The base temperature is set to a constant value equal to 24°C, thus CDD is calculated according to Equation (26).

$$CDD = \begin{cases} \sum_i (T_m^i - 21°C), & for\ T_m^i \geq 24°C \\ 0, & for\ T_m^i < 24°C \end{cases} \tag{26}$$

where:

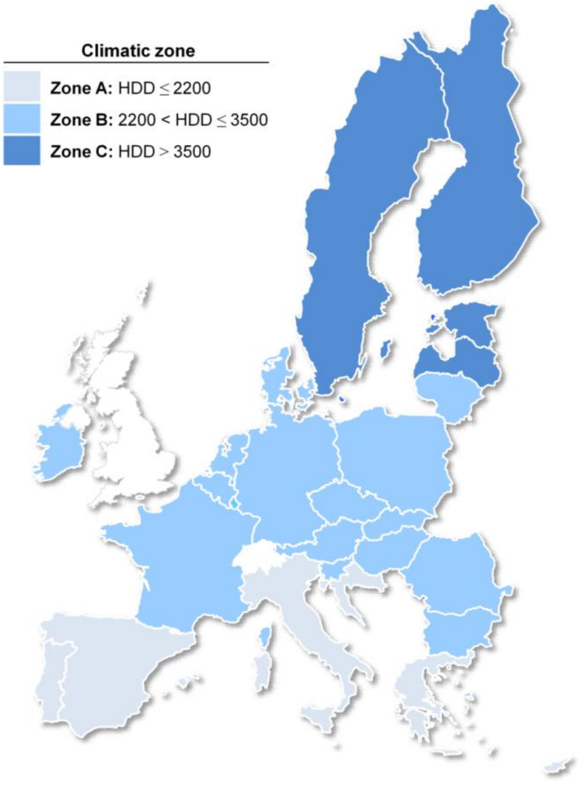
T_m^i is the mean outside air temperature of day i,

21°C is the constant value set for the indoor temperature.

The HDD and CDD are calculated on daily basis to be subsequently aggregated to provide monthly and annual data, available in Eurostat at the EU-27 level, as well as at different regional level within each country according to the Nomenclature of Territorial Units for Statistics (NUTS) classification, i.e. NUTS-2 (basic regions), and NUTS-3 (small regions) levels. Specifically, HDD and CDD statistics over the period 1979-2021 can be retrieved at the different NUTS-levels from Eurostat - Energy statistics.

According to the observations carried out in Romano et al. (2023), the EU territory is mapped in six climatic zones based on the 2019 HDD average annual values at Member State level (Eurostat, 2020a). Starting from the aforementioned map, the HDD range values identifying the six climatic zones are further aggregated to define the three following climatic zones mapping the EU territory (Figure 30): (i) Climatic zone A (HDD < 2200), (ii) Climatic zone B (2200 ≤ HDD < 3500), and (iii) Climatic zone C (HDD ≥ 3500).

Figure 30. EU-27 climatic map based on the 2019 HDD average annual values at Member State level according to three climatic zones



EU country	HDD	Climatic zone
Malta	515	A
Cyprus	693	A
Portugal	1109	A
Greece	1449	A
Spain	1671	A
Italy	1814	A
Croatia	2076	A
Bulgaria	2153	A
France	2247	B
Hungary	2381	B
Netherlands	2514	B
Belgium	2532	B
Romania	2568	B
Slovenia	2601	B
Ireland	2707	B
Luxembourg	2754	B
Germany	2801	B
Slovakia	2899	B
Poland	2952	B
Czechia	2998	B
Denmark	3027	B
Austria	3280	B
Lithuania	3391	B
Latvia	3623	C
Estonia	3883	C
Sweden	5120	C
Finland	5483	C

Source: Data - Eurostat., 2020a

However, different climatic conditions coexist in a single EU Member State depending on the specific HDD average annual values related to its NUTS-3 regions, thus the 2019 HDD data related to all NUTS-3 level regions of the EU-27 (Eurostat, 2020b) were analysed in order to obtain a more precise geographical distribution of the three identified climatic zones in each EU Member State. Specifically, Table 6 indicates the minimum and maximum HDD average annual values at NUTS-3 level in each EU Member State along with the corresponding climatic zone. Based on this investigation, it is possible to identify three categories of EU countries: (i) EU countries characterised by one climatic zone, as inferred by means of the analysis at Member State level (Figure 30), (ii) EU countries including two climatic zones, and (iii) EU countries having all the three climatic zones. Within the first category, Cyprus, Malta, and Portugal are characterized by NUTS-3 regions with HDD average annual values that never exceed 2200, thus all enclosing in the climatic zone A. Similarly, Estonia and Finland are characterized by NUTS-3 regions which have HDD average annual values never lower than 3500, thus belonging exclusively to the climatic zone C. The majority of the EU countries, such as Belgium, Czechia, Denmark, Germany, Ireland, etc., have NUTS-3 regions with HDD average annual values which, although different from each to other, range entirely within the climatic zone B. The second category refers to EU countries with NUTS-3 regions characterised by ranges of HDD average annual values falling within two different climatic zones, namely A and B (e.g. Bulgaria, Greece, Spain, France, Croatia, etc.), or B and C (i.e. Latvia, Austria, Romania, and Sweden). Finally, the third category includes only two Member States (i.e. Italy and France), which represent interesting cases since their NUTS-3 regions have HDD average annual values falling within all the three identified climatic zones A, B, and C.

Table 6. Minimum and maximum HDD average annual values in the EU-27, based on data related to NUTS-3 regions in each EU Member State.

EU Member State	NUTS-3 region	HDD (Min, Max)	Climatic zone
BE – Belgium	Arr. Eeklo	2287	B
	Bezirk Verviers	3002	B
BG - Bulgaria	Yambol	1638	A
	Smolyan	2977	B
CZ - Czechia	Hlavní mesto Praha	2716	B
	Karlovarský kraj	3243	B
DK - Denmark	Byen København	2788	B
	Nordjylland	3146	B
DE – Germany	Mannheim, Stadtkreis	2333	B
	Garmisch-Partenkirchen	3455	B
EE - Estonia	Põhja-Eesti	3891	C
	Lõuna-Eesti	3919	C
IE - Ireland	South-West (IE)	2512	B
	Border	2871	B
EL - Greece	Kalymnos, Karpathos, Kasos, Kos, Rodos	456	A
	Kastoria	2383	B
ES - Spain	Fuerteventura	0	A
	Palencia	2534	B
FR – France (1)	Corse-du-Sud	1373	A
	Loir-et-Cher, Haute-Savoie	2204, 2985	B
	Hautes-Alpes	3616	C

Cont.

EU Member State	NUTS-3 region	HDD (Min, Max)	Climatic zone
HR – Croatia	Dubrovacko-neretvanska zupanija	1256	A
	Licko-senjska zupanija	2529	B
IT – Italy (1)	Trapani	882	A
	Vicenza, Belluno	2212, 3375	B
	Sondrio	4308	C
CY - Cyprus	Kypros	693	A
LV - Latvia	Riga	3403	B
	Vidzeme	3825	C
LT - Lithuania	Klaipedos apskritis	3261	B
	Utenos apskritis	3496	B
LU - Luxembourg	Luxembourg	2753	B
HU - Hungary	Baranya	2225	B
	Nógrád	2650	B
MT - Malta	Gozo and Comino	497	A
	Malta	520	A
NL - Netherlands	Zeeuwsch-Vlaanderen	2298	B
	Oost-Groningen	2667	B
AT - Austria	Wien	2209	B
	Tiroler Oberland	4741	C
PL - Poland	Miasto Wroclaw	2658	B
	Nowotarski	3.445	B
PT - Portugal	Oeste	632	A
	Alto Tâmega	2039	A
RO - Romania	Constanta	2045	B
	Harghita	3536	C
SI - Slovenia	Obalno-kraska	2143	B
	Gorenjska	2900	B
SK - Slovakia	Nitriansky kraj	2495	B
	Zilinský kraj	3368	B
FI - Finland	Åland	3818	C
	Lappi	6672	C
SE - Sweden	Skåne län	3049	B
	Norrbottens län	6629	C

(1) France and Italy are characterised by NUTS 3 regions with HDD values corresponding to all the three identified climatic zones (A, B, and C). Beyond the absolute minimum and maximum HDD values, the NUTS 3 regions and their corresponding minimum and maximum HDD values referring to the climatic zone B are also indicated for both countries.

Source: Data – Eurostat, 2020b.

4.1.2.3 *EU seismic-climatic scenarios: case studies location*

The combination of the three seismic hazard and three climatic zones resulted in a six-column matrix identifying regions with different levels of seismic hazard and climatic conditions (Figure 31). In order to select the most representative seismic-climatic regions where locating the four case studies, the following remarks are made. Two categories of case studies need to be located in moderate-to-high (M-H) seismic hazard zones to be representative of the countries in southern Europe. The other two categories of case studies need to be located in low-to-moderate (L-M) seismic hazard zones, thus being distinctive of the countries in northern and central Europe. As for the climatic zones, all the three possible options are considered due to the large variability of European climatic conditions. Thus, the climatic zones characterised by low (A) and intermediate (B) levels of HDD, typically corresponding to the weather conditions of the southern Europe countries, have been associated to the M-H seismic hazard zones. The climatic zones with intermediate (B) and high (C) levels of HDD, commonly characterising the central and northern Europe countries have been associated to the L-M seismic hazard zones. Consequently, four representative seismic-climatic scenarios have been obtained in the matrix and they correspond to the selected locations of the four case studies (Figure 31). Specifically, Italy is identified as the most suitable country for case studies selection, as it includes all the four aforementioned seismic-climatic scenarios chosen in the matrix.

Figure 31. Seismic-climatic hazard matrix and the selected scenarios for the location of case studies

Seismic zone*	L-M	L-M	L-M	M-H	M-H	M-H
Climatic zone**	A	B	C	A	B	C
Case study		✓	✓	✓	✓	

* **L-M**: Low-to-Moderate (PGA < 0.175g); **M-H**: Moderate-to-High (PGA ≥ 0.175g)

** **A** (HDD < 2200); **B** (2200 ≤ HDD ≤ 3500); **C** (HDD > 3500)

✓ Selected scenarios for location of case studies

Source: JRC

4.1.3 Identification and description of the selected four case studies

The integration of the outcomes related to the identification of categories (Section 4.1.1 - Figure 28) and location (Section 4.1.2 - Figure 31) of case studies leads to the selection of four representative case studies referring to existing buildings in Italy (Figure 32), as follows:

- **Case study 1** - The case study related to the RC residential building refers to a dwelling building located in Toscolano Maderno, a district of Brescia province in Lombardy region (Northern Italy). Toscolano Maderno is characterised by a PGA equal to 0.159 g at Life Safety limit state (NTC 2018 – Ministerial Decree 17/01/2018) and a HDD index equal to 2265 (Decree of President of Republic 412/1993). Hence, the building site is classified as low-to-moderate (L-M) seismic hazard zone and Climatic zone B, according to the seismic-climatic hazard matrix.
- **Case study 2** - The case study related to the brick masonry residential building refers to a dwelling building located in Dalmine, a district of Bergamo province in Lombardy region (North Italy). Bergamo is characterised by a PGA equal to 0.105 g at Life Safety limit state (NTC 2018 – Ministerial Decree17/01/2018) and by a HDD index equal to 2473 (Decree of President of Republic 412/1993). It is evident that this HDD value is indicative of the climatic zone B. However, a HDD index equal to 3600 was assumed for the Case Study 2 to also cover the climatic zone C. Hence, the building site is classified as low-to-moderate (L-M) seismic hazard zone and Climatic zone C, according to the seismic-climatic hazard matrix.
- **Case study 3** - The case study related to the RC public building refers to the 'Pietro Santini' primary school located in Loro Piceno, a district of Macerata province in Marche region (Central Italy). Loro Piceno is characterised by a PGA equal to 0.202 g at Life Safety limit state (NTC 2018 - Ministerial Decree17/01/2018) and by a HDD index equal to 2150 (Decree of President of Republic 412/1993).

Therefore, the building site is classified as moderate-to-high (M-H) seismic hazard zone and climatic zone A according to the seismic-climatic hazard matrix.

— **Case study 4** - The case study related to the cultural monumental rubble masonry building refers to the City Hall of Barisciano, a little municipality in the district of L'Aquila in Abruzzo Region (Central Italy). Barisciano is characterised by a PGA equal to 0.298g at Life Safety limit state (NTC 2018 – Ministerial Decree 17/01/2018) and by a HDD index equal to 2877 (Decree of President of Republic 412/1993). Hence, the building site is classified as moderate-to-high (M-H) seismic hazard zone and climatic zone B according to the seismic-climatic hazard matrix.

Figure 32. The four selected case studies associated with the seismic–climatic hazard matrix

Seismic zone	L-M	L-M	L-M	M-H	M-H	M-H
Climatic zone	A	B	C	A	B	C
Case study		Residential building in Toscolano Maderno	Residential building in Dalmine	'Pietro Santini' primary school in Loro Piceno	City Hall of Barisciano	

Source: JRC

A brief description of each case study needing both seismic and energy retrofit is provided in the following sections by focusing on three main aspects, as follows:

— **General features** of the building in terms of geometry layout, structural typology, and building envelope components.

— **Seismic** and **energy deficiencies** of the building.

— **Seismic and energy retrofit interventions** to be implemented for the subsequent applications of both standard and novel/simplified combined assessment methods to the four case studies.

4.1.3.1 Case study 1 - RC residential building in Toscolano Maderno (Italy)

General features

The RC residential building in Toscolano Maderno (Brescia province), hereinafter indicated as Case Study 1, is a three-storey construction erected in 1967 with all the three levels serving as dwellings. The building, also includes an uninhabitable attic. The building does not fulfil regularity requirements in plan and in elevation. Indeed, it features an L-shaped plan consisting of two staggered building blocks, denoted as 'Block A' and 'Block B' with different heights, exclusively connected by a staircase core. Block A has a rectangular plan with dimensions equal to 12.30 m x 8.12 m and an inter-storey height equal to 3.06 m at the ground floor and 3.15 at the other two levels leading to a total height of the block equal to approximately 9.40 m. Block B is bigger than Block A, but it is characterised by a similar configuration consisting of a rectangular plan with dimensions equal to 13.90 m x 9.80 m. However, Block B is located at +1.05 m over a RC basement and it is characterised by an inter-storey height equal to 3.10 m at the ground and first floor and 2.95 m at the second level, leading to a total height of the block equal to approximately 10.80 m. The total floor area of the entire two-block building is equal to 708.3 m^2.

Both Block A and Block B are RC framed structures consisting of three longitudinal and two transversal one-way RC frames designed only for gravity loads; furthermore, the RC frames of the Block B develop on the RC basement made of 25 cm-thick RC walls. According to the analysis of the most recurrent horizontal and vertical structural and non-structural components of the EU building stock (Section 4.1.1), the two-block building has pitched roofs and floors made of one-way cast-in-place RC beam-and-hollow clay block systems, featuring a 3 cm-thick RC slab for a total floor height equal to 19 cm. The vertical components of the building envelope consist of infill walls composed by two leaves of masonry hollow bricks separated by a 7 cm air chamber without thermal insulation (i.e. cavity wall) and refined with 1.5 cm-thick external and internal plasters. Finally, the staircase core consists of 25 cm-thick masonry walls with solid bricks and cement mortar, laying on an independent beam foundation.

Seismic and energy deficiencies

Data related to the RC structural members and structural details were obtained by means of in-situ diagnostic tests, survey campaigns, and laboratory tests combined with a simulated design based on the requirements and safety verifications indicated in the structural design code in force at the time of the building construction. Furthermore, the mechanical properties of the concrete and steel materials were obtained according to the analysis of some samples extracted from the structural members. Specifically, concrete C20/25 with mean compressive strength (f_{cm} = 28 MPa), and steel Feb32k with mean yielding strength (f_{ym} = 315 MPa) were considered. Furthermore, given the discrete knowledge of materials and structural detailing, where in-situ test results matched quite well with the available documentation, a Knowledge Level 2 (KL2) with a consequent Confidence Factor (CF) equal to 1.20 was assumed (Ministerial Decree 17/01/2018; Eurocode 8 ([7]) – CEN, 2004) for the assessment of the examined building.

The structural assessment of the building in its 'as-is' condition, based on the quality and quantity of available data, pointed out that the main structural vulnerabilities are related to the absence of structural design for horizontal actions, the lack of capacity design in the RC frames leading to a potential detrimental strong beam-weak column mechanism, the torsional behaviour of the two-block building and the high stresses in the connection zone between the two blocks. No previous damages to structural components were observed.

The investigation related to the structural assessment of the residential building pointed out the need for a seismic retrofit to be combined with an energy upgrading to also enhance the thermal performance; the main retrofit interventions are briefly described in the following.

Seismic and energy retrofit interventions

Based on the structural/seismic deficiencies of the building, the **seismic retrofit** of the structure was conceived as a global intervention by introducing a steel exoskeleton built outside the building, thus not requiring disruption time and inhabitants' relocation. Seismic sstrengthening measures to the foundation system, floors and roofs were also implemented, as follows:

— **Steel exoskeleton** – A seismic retrofit of the building has been carried out by introducing a steel X-shaped braced frame exoskeleton composed by different welded S275 steel members, globally forming steel X-braced walls. The new exoskeleton is arranged parallel to the existing façades and connected to the existing building through threaded bars.

— **New foundation system** - A strengthening intervention of the existing foundation system was needed to support the new steel exoskeleton. Thus, a new foundation system, which consists of (70 x 100 cm^2) RC beams and micro-piles placed at the base of the steel braced frames, precisely at the building corners, has been implemented and connected to the existing one.

— **Floor and roof diaphragms strengthening** – A strengthening intervention of the existing floors and roofs has been carried out by introducing steel ties at the intrados of floors and roofs to ensure the latter act as in-plane diaphragms.

The use of the steel exoskeleton also facilitates an integrated structural and energy upgrading of the existing building. The **energy retrofit** of the building aimed at reducing its high energy demand is devoted to interventions related to both the building envelope components and the energy systems. Specifically, an external thermal insulation layer made of 16 cm expanded polystyrene (EPS) panels, locally reduced to 10 cm to comply with architectural needs, has been introduced. The existing hot water generators have been replaced with new electric heat pumps without substituting the heating system.

4.1.3.2 Case study 2 - Masonry residential building in Dalmine (Italy)

General features

The masonry residential building located in Dalmine (Bergamo province), hereinafter indicated as Case Study 2, is a three-storey construction erected in 1955, also composed by a basement and an uninhabitable attic. The building is conceived with a rectangular plan with dimensions 20.8 m x 9.5 m, thus accounting for a total usable gross floor area equal to about 841 m^2. The inter-storey heights of the basement and the three floors above ground are equal to 2.90 m and 3.20 m, respectively, whereas the attic has an average height of 1.40 m.

([7]) Eurocode 8, https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-8-design-structures-earthquake-resistance

The building is a mixed structure consisting of perimeter load-bearing masonry walls with clay hollow bricks, and two internal RC frames and edge ring beams. Finally, the staircase core, made of two RC walls, is placed symmetrically to the central transversal axis of the building. According to the analysis of the most recurrent horizontal and vertical structural and non-structural components of the EU building stock (Section 4.1.1), the building has a pitched timber roof, the floors consist of cast-in-place RC beam-and-hollow clay block systems, and the 30 cm-thick load-bearing walls are made of masonry brick.

Seismic and energy deficiencies

Documents related to the original project of the building were not available, thus there was a lack of data concerning the construction details and material properties. Hence, the use of C20/25 concrete and AQ42 steel and their corresponding properties were assumed for the building based on data retrieved from similar constructions erected in the same construction period of the case study.

The structural assessment of the building in its 'as-is' condition based on the quality and quantity of available data pointed out that the main structural vulnerabilities are related to the absence of structural design for horizontal actions, the poor quality of materials and structural details, the elastic-fragile behaviour of the masonry walls made of hollow bricks arranged with horizontal holes, and the absence of floors engineered to trigger an in-plane diaphragm action. No previous damages to structural components were observed.

The simplified investigations related to the structural assessment of the building pointed out the need for a seismic retrofit to be combined with an energy upgrading to also enhance its thermal performance with the main retrofit interventions briefly described in the following.

Seismic and energy retrofit interventions

The **seismic retrofit** of the building was conceived as a global retrofit intervention through the addition of an exoskeleton system implementing six perimeter steel shear walls, assembled outside the building, thus not requiring disruption time and occupants' relocation. Furthermore, the local strengthening of the attic floor was also foreseen. Both the interventions are briefly described, as follows:

- **Perimeter steel shear walls (Exoskeleton)** – A seismic retrofit of the building was conceived by envisioning an exoskeleton composed by three different types of external steel shear walls (indicated as Solution 1, 2, and 3) compliant with various architectural needs and constraints. The Solution 1 consists of two X-concentric braced shear walls made of steel members with a circular hollow section (CHS), used for the vertical and horizontal boundary elements and diagonal web members. The other two solutions refer to two steel plate shear walls (per type) consisting of the same vertical and horizontal boundary steel elements used for the Solution 1, whereas the web panels are made of 8mm-thick macro-perforated and 4mm-thick solid steel sheets for the Solution 2 and 3, respectively. Thus, the entire exoskeleton accounts for a total of six shear walls, which are all arranged in configurations adjacent to the façades of the existing building, along the longitudinal directions as for the Solutions 1 and 2 and along the transversal ones as for the Solution 3. The three shear wall types are connected to the existing building with one, one and half, and two studs per meter for the Solution 1, 2, and 3, respectively, at each floor level, where a steel ring plate is introduced. The connections between the tubular steel elements are standardized 'knuckle' joints, thus facilitating the assembly due to the use of pre-fabricated connections. Moreover, an independent foundation system consisting of a RC beam and seven micropiles was implemented for each shear wall. The entire intervention results into a quite massive and stiff exoskeleton in order to effectively improve the elastic-fragile behaviour of the existing load-bearing masonry walls, avoiding their out-of-plane collapse.
- **Attic floor diaphragm** – A static and seismic retrofit of the existing floor of the attic was considered by strengthening it through the addition of a 3cm-thick structural high-performance concrete screed.

The need to also improve the poor energy performance of the residential building leads to an **energy efficiency upgrading** with interventions on both the transparent and opaque components of the building envelope. Specifically, the retrofit interventions are devoted to the replacement of windows fixtures, the thermal insulation of both the roof slab with a new EPS thermal layer, and the external walls with expanded polyurethane foam coating panels enveloping the façades.

4.1.3.3 Case study 3 - RC public building: 'Pietro Santini' primary school (Italy)

General features

The 'Pietro Santini' primary school located in Loro Piceno (Macerata province), hereinafter indicated as Case Study 3, is a three-storey RC building erected in 1965. The building is placed next to an embankment along the North and East sides, thus only one storey is visible on the North side facing the main school entrance, whereas two out of three floors are below the ground level on the South and West sides. The access to the school is also enabled by the east side by means of an offset floor. The building features a rectangular plan with dimensions 22.5 m x 18.34 m (although a small plan irregularity is present on the east side of the building), thus accounting for a total usable gross floor area equal to about 1238 m^2. The inter-storey heights differ at each level of the building, resulting equal to 3.6 m, 3.35 m, and 3.95 m at the first, second, and third level, respectively, leading to a total height of the school building equal to about 10.90 m. Finally, the staircase core is eccentric with respect to the building's centre of mass.

The structural system of the building consists of one-way RC Moment Resisting Frames (MRFs) designed only for gravity loads. Indeed, Loro Piceno was classified as seismic zone only in the early '80s. Specifically, four parallel four-bay MRFs and two parallel three-bay MRFs are arranged along the longitudinal and transversal directions of the building, respectively. MRFs along the transversal direction are located only at the building edges. According to the analysis of the most recurrent horizontal and vertical structural and non-structural components of the EU building stock (Section 4.1.1), the building has a flat roof and floors consisting of cast-in-place RC beam-and-hollow clay block systems featuring a 4 cm-thick RC slab for a total height (structural elements of floor) equal to 24 cm. The external frames are infilled with two layers of hollow bricks masonry walls (i.e. the external layer is 8 cm-thick, whereas the internal one is 25 cm-thick), separated by a 4 cm-thick air chamber without thermal insulation (i.e. cavity walls) and refined with 1.5 cm-thick external and internal plasters, for a total thickness of the infill wall equal to 40 cm. Finally, the staircase core is composed by two 30 cm-thick RC walls, arranged perpendicular to the longitudinal MRFs.

Seismic and energy deficiencies

Data related to the structural members and details were obtained by means of in-situ diagnostic tests, survey campaigns, and laboratory tests on material samples extracted from the structure. The in-situ survey was integrated with a simulated design compliant with the requirements and safety verification methods foreseen by the structural design code in force during the construction period of the building. The mechanical properties of the concrete material were obtained according to the analysis of some samples drilled from the structural members. Specifically, different values of the mean cylindrical compressive strength (f_{cm}) of concrete were considered varying at building level, namely 14 MPa, 8 MPa, and 9 MPa from the level 1 to 3. The yield strength of the steel reinforcement was obtained by means of tensile tests leading to an average yield strength (f_{ym}) equal to 310 MPa. Based on the quantity and accuracy of data regarding geometrical configuration, material properties and their deterioration, a KL2 with a consequent CF equal to 1.20 were considered (Ministerial Decree 17/01/2018; Eurocode 8 – CEN, 2004) for the assessment of the examined school building.

The structural assessment of the existing building pointed out that the main seismic deficiencies refer to an inadequate global lateral strength and stiffness in both longitudinal and transverse directions. The building was also damaged by the 2016 Central Italy earthquake sequence with the main damages consisting of several crack patterns in various RC columns and in non-structural elements, as well as in the staircase core.

The analysis of the thermal properties of the envelope components of the school building indicates that the value of the thermal transmittance (U-value) of the external infill walls resulted equal to 0.74 W/m^2K. This value is nearly three times higher than the threshold value, i.e. 0.28 W/m^2K (in force from 1 January 2021), required for opaque vertical components of existing buildings subjected to energy renovation, in the Italian climatic zone E (i.e. 2100<HDD<3000), according to the Italian legislation on energy efficiency (Ministerial Decree 26/06/2015 – Appendix B).

The simplified investigations related to the structural and thermal assessment of the school building pointed out the need for a combined seismic and energy retrofit; the main retrofit interventions are briefly described in the following.

Seismic and energy retrofit interventions

The **seismic retrofit** foresees a global strengthening intervention by implementing a steel exoskeleton built outside the building parallel to its façades, thus not requiring disruption time and inhabitants' relocation and facilitating a combined energy upgrading. The exoskeleton consists of X-shaped concentric braced frames (X-CBF) composed by S355 CHS steel profiles, arranged parallel to the existing structure or at a sufficient distance from the building façades to comply with architectural and functional constraints, such as the regular use of balconies and windows.

The **energy retrofit**, aimed to improve the energy efficiency of the existing building by intervening on the opaque vertical components of its envelope, is conceived to be fully combined with the seismic one. Indeed, the energy upgrading intervention considers the implementation of a continuous façade system with micro-perforated aluminium panels connected to steel beams and columns of the new bracing system devoted to the enhancement of the seismic performance of the building. The panels are combined with transparent insulation material (TIM) consisting of alveolar polycarbonate modules, which provide the two-fold benefit of reducing the heat losses and increasing the solar radiation by using translucent material, while contributing to also improve the daylight comfort of the building allowing the natural light to filtrate indoor.

4.1.3.4 Case study 4 – Rubble masonry cultural monumental building: City hall of Barisciano (Italy)

General features

The masonry cultural monumental building hosting the City Hall of Barisciano (L'Aquila province), hereinafter indicated as Case Study 4, is a four-storey construction dating back to the early 20th century. The building is characterised by a rectangular plan with dimensions 19.24 m x 12.79 m, leading to a total floor area equal to 984.32 m^2. The building is partially buried on its east side, thus only three storeys of the building are visible on its main façade overlooking the town square with different inter-storey heights equal to about 4.30 m, 3.65 m, and 3.35 m, leading to a total height of the east façade equal to 11.3 m. The opposite façade on the west side, making visible all the four storeys (i.e. three levels above the ground plus the semi-basement level) of the building, has a total height equal to nearly 16 m, since it also includes the inter-storey height of the semi-basement level equal to 4.30 m. The rectangular plan of the building can be ideally divided into three main spaces by means of two central walls disposed perpendicular to the main façade. These walls are partially used to host the staircase, which is located on the west side of the building in an eccentric position with respect to the building centre of mass.

The building is a load-bearing masonry construction consisting of different types of masonry walls. Specifically, perimeter walls are made of rubble masonry, while the internal load-bearing walls in both longitudinal and transversal directions are made of concrete blocks. Furthermore, masonry piers consisting of squared rubble blocks feature the semi-basement level. According to the analysis of the most recurrent horizontal and vertical structural and non-structural components of the EU building stock (Section 4.1.1), the building has a pitched timber roof, and the floors consist of steel beam-and-hollow clay block systems. The perimeter load-bearing walls are composed of 50 cm-thick rubble masonry with an external 1.5 cm-thick lime plaster and an internal 1.5 cm-thick gypsum plaster finishes.

Seismic and energy deficiencies

Data related to the geometrical details and quality of masonry of the load-bearing walls were obtained by means of in-situ diagnostic tests and survey campaigns. However, the lack of in-situ experimental tests led to consider compressive strength values of masonry compliant with the Italian structural design code in case of limited knowledge. Specifically, compressive strength values equal to 2.27 MPa, 3.66 MPa, and 5.83 MPa for the rubble masonry, concrete block, and rubble masonry block were assumed, respectively.

Diagnostic tests performed on the building show the reduced efficiency of connections among walls perpendicular to each other and even among walls and floors, leading to potential detrimental out-of-plane collapses. Furthermore, architraves above windows did not result properly constrained to the masonry walls, thus masonry spandrels are unable to resist bending and shear stresses.

The structural deficiencies of the existing building are indicative of its seismic vulnerability, which can be combined with the potential to improve its energy inefficiency, demonstrating the need for a combined seismic and energy retrofit; the main retrofit interventions are briefly described in the following.

Seismic and energy retrofit interventions

The **seismic retrofit** of the building was devoted to provide a box-like behaviour of the structure to avoid a detrimental out-of-plane collapse. Specifically, the following interventions were considered: (i) local repair of cracked masonry walls, (ii) connection between walls and floors, (iii) strengthening of floor diaphragms, and (iv) strengthening of masonry walls.

The **energy retrofit** aims to improve the energy efficiency of the building with interventions concerning both the transparent components of the building envelope and the energy systems. Specifically, the main retrofit measures refer to the replacement of the existing single glass poly vinyl chloride (PVC) windows with new double glass ones, along with the substitution of the existing heating system with a new high performance one.

4.2 Application of a standard combined assessment method to the four case studies

The four case studies are first analysed by means of a standard combined assessment methodology to be subsequently compared with the proposed simplified one (Section 3.2). The SSD methodology was selected among the existing standard combined assessment methodologies (Section 2.1.4 and Section 2.1.5) to fulfil this scope. Indeed, this methodology results into an effective integrated multi-performance design/retrofit assessment method to quantitatively evaluate the structural, energy, and environmental performances of buildings in a life cycle perspective by providing a unique final assessment parameter in economic terms. Furthermore, the SSD methodology provides a good level of versatility in its use, as it can serve for different assessment alternatives, namely the comparison of different structural systems for a new building, the comparison of two retrofit solutions or the alternative of retrofit vs demolition and reconstruction for an existing building, towards the choice of the most effective solution. In the following, the SSD methodology is devoted to the comparison of each of the four selected case studies in their 'as-built' and retrofit scenarios, specifically assessing the energy, environmental, and seismic performance improvements due to the retrofit interventions. It is worth noting that the application of a standard combined assessment methodology to the four case studies, beyond demonstrating the benefit of the retrofit solution, mainly aims to evaluate the feasibility and ease of use of the chosen method, as a cornerstone for subsequently applying the proposed simplified combined assessment method. Specifically, the four main steps of the SSD methodology were considered and applied to the four case studies for both the pre- and post-retrofit scenarios (please, refer to the Section 2.1.4.1 for both a detailed description of each step of the methodology and the reference to the Equations used for the computation of the corresponding results), as follows:

— **STEP I - Energy Performance Assessment** focuses on the calculation of the operational energy needed during the use phase of a building. A dynamic BES analysis before and after the retrofit interventions is carried out for the four buildings in order to assess their annual electricity and heating consumptions (both expressed in kWh/m^2y). The modelling of the pre- and post-retrofit buildings and the two corresponding energy analyses were carried out by means of the user-friendly tool DesignBuilder, which uses EnergyPlus as BES engine. The input data related to the building location, energy systems, and envelope characteristics were first defined to preliminary assess the cooling, heating, and domestic hot water (DHW) systems and to subsequently perform the dynamic energy analyses of the two building models. The partial outputs, expressed in KWh/m^2, indicate the operational energy consumptions in terms of electricity (due to appliance use, lighting, DHW production, and cooling) and natural gas (due to heating) before and after the retrofit interventions according to a monthly schedule. The sum of the monthly results provide the total outputs in terms of annual consumptions of electricity and natural gas (both expressed in kWh/m^2y). It is worth noting that the annual energy consumption due to heating in terms of natural gas could be also transformed in m^3/m^2y, as commonly used in some European countries (e.g. Italy). Specifically, the calorific value of natural gas is equal to 9.6 KWh/m^3, thus this parameter is used as conversion factor to transform the heating consumption from KWh to m^3. Finally, the annual energy consumption results in terms of electricity (kWh/m^2y) and natural gas (kWh/m^2y or m^3/m^2y) were transformed into the total operational energy consumed during the use phase of the building, expressed in kWh (electricity) and kWh or m^3 (gas), by multiplying them by both the total surface (m^2) of the building and its life span (i.e. 50 years for ordinary buildings), according to Equation (8) and (9), respectively.

— **STEP II – Life Cycle Assessment (LCA)** deals with the assessment of the environmental performance of a building during its entire life cycle, according to a cradle-to-grave approach (Section 2.1.2). The application of the LCA methodology to the four case studies, based on the ISO 14040-44 standards (ISO, 2006a, b), aims to assess the GHG emissions of the materials of structural and non-structural components of the buildings related to the production stage (i.e. Module A1 to A3) of the standardised building life cycle – from cradle-to-gate. The LCA is herein performed through the SimaPro software, as it is a consolidated and reliable tool for assessing the environmental impacts of products and services during all the life cycle stages of a building, including several inventory libraries and databases (Section 2.1.2.3). Specifically, among the available databases, the Ecoinvent database, which provides well documented process data for thousands of products, was used for carrying out the LCI step. The selected LCIA methodology for assessing the carbon footprint of the four cases studies before and after the retrofit interventions refers to the single-issue method IPCC 2007. This LCIA method is characterised by a system of equivalent factors to weight the influence of various GHGs, using the amount of tCO_2eq as reference. It lists the GWP of well-mixed GHG for time horizon of 20, 100, and 500 years. The GWP depends on the timespan over which the potential is calculated, as the GHG concentration decays over time in the atmosphere. In the application to the four case studies, the results have been carried out for the timeframe of 100 years, which is the most recommended time horizon for a similar type of analysis.

- **STEP III** – **Structural performance assessment** is based on the application of the four steps of the s-PBA methodology (Negro and Mola, 2017) to assess the expected losses concerning four different limit states of the structure, defined as (i) low damage, (ii) heavy damage, (iii) severe structural damage, and (iv) near collapse in both pre- and post-retrofit scenarios. The first step deals with the definition of these limit states, which are differently defined per each case study depending on the structural typology of the examined buildings. Specific IDRs are associated to each limit state, although in some case studies, the displacements are first considered. The second step refers to the identification of the PGA values corresponding to the attainment of the IDR values defined in the first step. The PGA values for each limit states were estimated by nonlinear static analyses by means of the N2 method (Fajfar, 1999; 2000) carried out through the SAP2000 software. The third step allows the computation of the return periods corresponding to the PGA values obtained in the second step, according to Equation (10). Subsequently, the probability of exceedance of PGA values considering the service life for ordinary structures (i.e. 50 years) are calculated according to Equation (11). The last and fourth step deals with the assessment of the expected losses due to the seismic damages in each limit state, based on the corresponding costs for repairing the damaged structural and non-structural components, as required after an earthquake in order to ensure again an adequate structural performance of the building. The assessment of the total expected losses is calculated according to the Equation (12).

- **STEP IV** – **Global assessment parameter in economic terms** enables the combination of results, obtained by the three previous steps in different measure units, into a global result in monetary units for an effective comparison of the examined buildings between their pre- and post-retrofit scenarios. Thus, the conversion of the operational energy consumptions and the GHG emissions into costs to be combined with the structural safety costs is carried out for the analysed case studies, providing a unique economic parameter (R_{SSD}, expressed in €), according to Equation (17). Specifically, the total operational energy consumptions in terms of electricity and natural gas, computed into the STEP I, are converted into costs by considering the 2019 Eurostat unitary prices of electricity (Eurostat, 2020c, 2020d) and natural gas (Eurostat, 2020e, 2020f) (both expressed in €/kWh) in Italy. These prices were retrieved by Eurostat depending on (i) the building use, thus considering electricity and gas prices for either household consumer (i.e. Case studies 1 and 2) or non-household consumers (Case studies 3 and 4), (ii) the annual consumption bands, based on the STEP I energy consumption results by case study, (iii) the inclusion of taxes, except VAT. Similarly, the environmental impacts in terms of GWP, computed into the STEP II, are converted into costs by considering the EUA price retrieved by the EEX and related to 24th March 2022 (i.e. 76.50 €/tCO_2eq), as already indicated in the Section 2.1.4.1.

Results of each step of the SSD methodology for the four case studies are discussed in the following.

4.2.1 Application of the SSD methodology to Case study 1

The application of the four steps of the SSD methodology to the Case study 1, which refers to the RC residential building located in Toscolano Maderno (Section 4.1.3.1), is described in the following for both the pre- and post-retrofit scenarios, along with the corresponding results.

4.2.1.1 STEP I – Energy performance assessment

The **STEP I** of the SSD methodology deals with the Energy performance assessment. The monthly operational energy consumptions of the investigated building and the corresponding annual results in terms of both electricity (i.e. appliance use, lighting, and DHW production), and natural gas (i.e. heating) during the use phase of the life cycle of the building have been computed for both the pre- and post-retrofit scenario.

In relation to the **pre-retrofit scenario**, monthly and annual operational energy consumption results are provided in Table 7.

The annual operational energy consumptions in terms of electricity and natural gas result equal to 58.79 KWh/m^2y and 73.82 KWh/m^2y, respectively. The latter corresponds to a natural gas consumption equal to 7.69 m^3/m^2y, based on the calorific value of natural gas. Finally, the operational energy consumptions in terms of electricity ($Q_E^{Electricity}$) and natural gas (Q_E^{Gas}) during the use phase of the building are computed according to Equations (8) and (9), as follows:

$$Q_E^{Electricity} = 58.79\ \frac{kWh}{m^2y} \cdot 708.3\ m^2\ \cdot 50\ years = 2082226.8\ kWh$$

$$Q_E^{Gas} = 73.82\ \frac{kWh}{m^2year} \cdot 708.3\ m^2\ \cdot 50\ years = 2614260.9\ kWh$$

In the pre-retrofit scenario, the Case study 1 accounts for a total annual operational energy consumption (i.e. electricity plus natural gas) equal to 132.6 KWh/m^{2}y with a corresponding consumption during the use phase of the building (i.e. service life of 50 years) resulting equal to 4696487.7 kWh.

Table 7. Case study 1 – Annual operational energy consumption of the pre-retrofit building

PRE-RETROFIT SCENARIO				
Month	Electricity			Natural Gas
	Appliance use (kWh/m^2)	Lighting (kWh/m^2)	DHW (kWh/m^2)	Heating (kWh/m^2)
January	1.47	2.54	0.98	18.83
February	1.33	2.30	0.88	12.32
March	1.48	2.54	0.98	7.63
April	1.43	2.46	0.95	1.01
May	1.46	2.54	0.98	0.00
June	1.43	2.46	0.95	0.00
July	1.46	2.54	0.98	0.00
August	1.47	2.54	0.98	0.00
September	1.43	2.46	0.95	0.07
October	1.46	2.54	0.98	2.73
November	1.43	2.46	0.95	9.98
December	1.48	2.54	0.98	21.25
Annual consumption (kWh/m^{2}year)	17.34	29.92	11.53	73.82

In relation to the **post-retrofit scenario**, monthly and annual operational energy consumptions results are provided in Table 8.

The total annual operational energy consumptions in terms of electricity and gas result equal to 57.32 KWh/m^{2}y and 25.38 KWh/m^{2}y, respectively. The latter corresponds to a natural gas consumption equal to 2.64 m^3/m^{2}y, based on the calorific value of natural gas. Finally, the operational energy consumptions in terms of electricity ($Q_E^{Electricity}$) and natural gas (Q_E^{Gas}) during the use phase of the building are computed according to Equations (8) and (9), respectively, as follows:

$$Q_E^{Electricity} = 57.32\ \frac{kWh}{m^2year} \cdot 708.3\ m^2\ \cdot 50\ years = 2030220.70\ kWh$$

$$Q_E^{Gas} = 25.38\ \frac{kWh}{m^2year} \cdot 708.3\ m^2\ \cdot 50\ years =\ 898853.68\ kWh$$

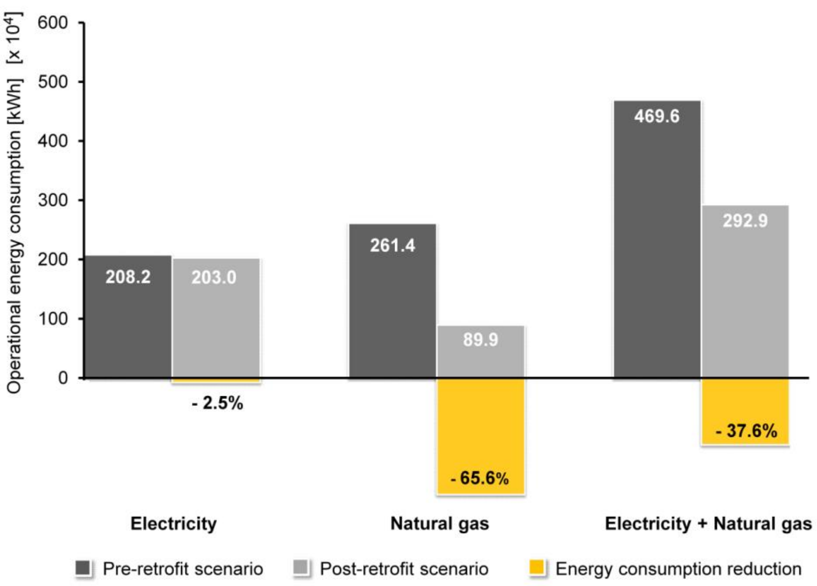
In the post-retrofit scenario, the Case study 1 accounts for a total annual operational energy consumption (i.e. electricity plus natural gas) equal to 82.7 KWh/m^{2}year, with a corresponding consumption during the use phase of the building (i.e. service life of 50 years) equal to 2929074.4 kWh.

Table 8. Case study 1 – Annual operational energy consumption of the post-retrofit building.

POST-RETROFIT SCENARIO				
Month	Electricity			Natural Gas
	Appliance use (kWh/m²)	Lighting (kWh/m²)	DHW (kWh/m²)	Heating (kWh/m²)
January	1.47	2.54	0.85	6.65
February	1.33	2.30	0.77	4.28
March	1.48	2.54	0.85	2.52
April	1.43	2.46	0.83	0.20
May	1.46	2.54	0.85	0.00
June	1.43	2.46	0.83	0.00
July	1.46	2.54	0.85	0.00
August	1.47	2.54	0.85	0.00
September	1.43	2.46	0.83	0.00
October	1.46	2.54	0.85	0.75
November	1.43	2.46	0.83	3.41
December	1.48	2.54	0.85	7.56
Annual consumption (kWh/m²year)	17.34	29.92	10.06	25.38

The comparison of the **STEP I results** between the pre- and post-retrofit scenario of the Case study 1 (Figure 33) underlines that the operational energy consumptions in terms of electricity and natural gas related to the post-retrofit scenario account for reductions equal to 2.5 % and 65.6 %, respectively, due to the corresponding energy reductions for DHW production and space heating, based on the efficacy of the proposed energy retrofit interventions (Section 4.1.3.1). Hence, a total reduction of the operational energy consumption (i.e. electricity plus natural gas) equal to 37.6 % features the examined residential building in the post-retrofit scenario.

Figure 33. Case study 1 - STEP I results for the pre- and post-retrofit scenarios



Source: JRC

4.2.1.2 STEP II – Life cycle assessment (LCA)

The **STEP II** of the SSD methodology focuses on the environmental performance assessment by applying the LCA methodology to evaluate the carbon footprint produced by the structural system and non-structural components of the investigated building for both the pre- and post-retrofit scenario.

In relation to the **pre-retrofit scenario**, the quantity of materials of both structural and non-structural components of the building and their corresponding GHG emissions, expressed in tonnes of CO_2-equivalent emissions (tCO_2eq), related to the production phase of the life cycle of the building, are reported in Table 9.

The structural system produces the highest environmental burdens in terms of GHG emissions, mainly due to the floor component accounting for 52.7 tCO_2eq. The total amount of GHG emissions related to the production phase, due to both structural elements and non-structural components, is equal to 127.23 tCO_2eq in the pre-retrofit scenario.

Table 9. Case study 1 – LCA results related to GWP for the pre-retrofit scenario (Production phase – Module A1-A3)

Component		Material	Quantity	Unit	GWP100 [tCO_2eq]
Structural elements	Columns and beams	Concrete	64.7	m^3	17.1
		Steel	3935.4	kg	8.4
	Foundations	Concrete	30	m^3	7.9
		Steel	6410	kg	15.13
	Floors	/	907.98	m^2	52.7
Total GWP (Structural components)					101.23
Non-structural components	External infill walls	Brick	162.4	m^3	16.2
	Windows	Aluminium and glass	52.5	m^2	6.3
	Roof tiles	Brick	233	m^2	3.5
Total GWP (Non-structural components)					26
Total GWP (Pre-retrofit scenario)					127.23

In relation to the **post-retrofit scenario**, the quantity of materials of both structural elements and non-structural components for the seismic and energy retrofit interventions of the building and their corresponding GHG emissions, related to the production phase of the building life cycle, are summarised in Table 10.

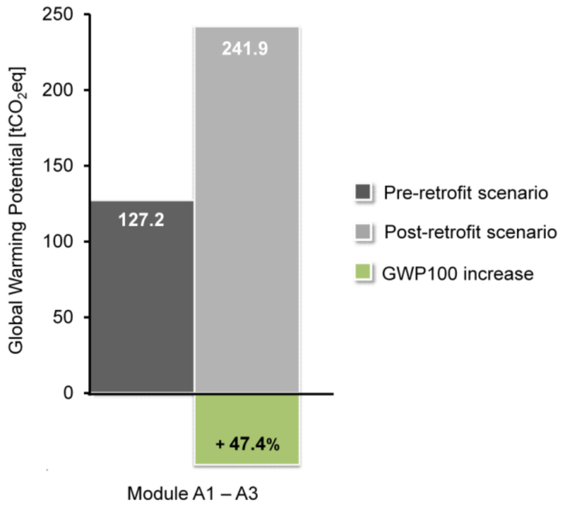
The seismic retrofit interventions produce a higher total amount of GHG emissions, i.e. 98.46 tCO_2eq, than the energy retrofit ones with the steel bracings accounting for the highest level of GHG emissions, i.e. 81.14 tCO_2eq. The total amount of GHG emissions due to both seismic and energy retrofit is equal to 114.66 tCO_2eq. In order to compute the final result of the environmental performance of the building in terms of GWP related to the post-retrofit scenario, the amount of GHG emissions produced by the adopted seismic and energy retrofit technologies needs to be added to the total result of the GWP related to the pre-retrofit scenario. Hence, the total amount of GHG emissions related to the production stage of both the building components and retrofit technologies results equal to 241.89 tCO_2eq in the post-retrofit scenario.

Table 10. Case study 1 – LCA results related to GWP for the post-retrofit scenario (Production phase – Module A1-A3)

Retrofit intervention		Material	Quantity	Unit	GWP100 [tCO_2eq]
Seismic retrofit	Bracing	Steel	32392.36	kg	69.49
		Steel (connections)	5430.46	kg	11.65
	Foundation	Concrete	22.81	m^3	6.03
	Tie	Steel	5261.98	kg	11.29
Total (Seismic retrofit)					98.46
Energy retrofit	External walls insulation	Styrofoam	153.2	m^3	10.3
		Rockwool	37.28	m^3	3.1
		Polyurethane foam	16.31	m^3	2.8
Total (Energy retrofit)					16.2
Total GWP100 (Seismic + Energy retrofit)					114.66
Total GWP100 (Post-retrofit scenario)					241.89

The comparison of the **STEP II results** between the pre- and post-retrofit scenario of the Case study 1 (Figure 34) demonstrates that an increase of the GHG emissions (related to the production phase) equal to 47.4 %, features the examined residential building in the post-retrofit scenario.

Figure 34. Case study 1 - STEP II results for the pre- and post-retrofit scenarios



Source: JRC

4.2.1.3 STEP III - Structural performance assessment

The **STEP III** of the SSD methodology deals with the Structural performance assessment, based on the four main steps of the s-PBA methodology, as follows:

— *Step 1 - Definition of limit states* - The damage limit states can be correlated to suitable IDR values. In this case, the identification of the limit states is correlated to the attainment of displacements, identified on the capacity curve carried out by means of the pushover analysis, to obtain the corresponding IDR values, as follows:

- *Low damage Limit State* – This limit state is characterised by damage initiating to non-structural elements, first affecting the external walls parallel to the seismic direction, along with windows in the storey subjected to the maximum IDR. For this limit state, the maximum allowed displacement results equal to 0.7 δ_y, being δ_y the building yielding displacement.

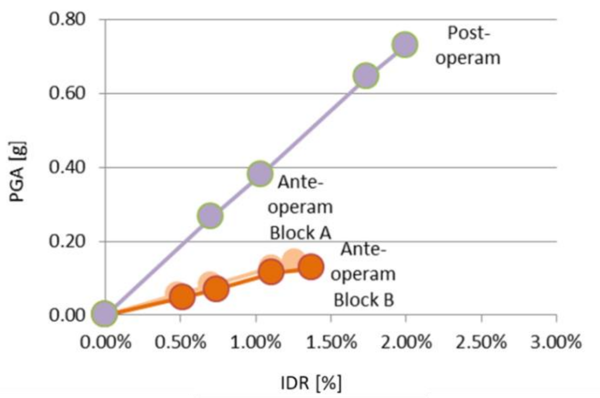
- *Heavy damage Limit State* – The damage occurs into all non-structural elements, specifically affecting the external walls and windows located at all levels of the building, thus requiring repair interventions. Conversely, the structural system is not subjected to damage, thus not requiring any repair intervention. This limit state is attained when the maximum displacement of the building reaches the value equal to δ_y.

- *Severe damage Limit State* – This limit state is based on the no-collapse requirement of the structural system of the building hit by the earthquake. Hence, all non-structural elements exhibit severe damages, thus needing replacement. Furthermore, RC beams located at the first floor parallel to the seismic direction need to be retrofitted due to the creation of plastic hinges. This limit state is attained when the maximum displacement reaches the value $\delta_y + 0.75\ (\delta_u - \delta_y)$, being δ_u the building ultimate displacement

- *Near Collapse Limit State* - This limit state corresponds to the full exploitation of the deformation capacity of structural elements, thus all non-structural and structural elements of the building result into extensive damages. This limit state is attained when the maximum displacement reaches the value equal to δ_u.

— *Step 2 - Structural analysis* – The PGA values corresponding to the attainment of the IDR values identified by means of the Step 1 are obtained by pushover analyses and the relation between the PGA values and IDR ones for both the pre- and post-retrofit scenario are reported in Figure 35.

Figure 35. Case study 1 – PGA vs IDR diagrams



Source: JRC

— *Step 3 - Hazard analysis* – Based on the PGA values obtained in the Step 2, the corresponding T_R values are first computed, according to Equation (10), to subsequently calculate the probability of exceedance in 50 years, i.e. service life of an ordinary building (R_{50}), according to Equation (11) for both the pre- and post-retrofit scenario.

— *Step 4 - Cost analysis* - The repair interventions and the corresponding costs for each limit state are first evaluated according to the official 'Public works price list of the Lombardia region', to be consistent with the typical construction work prices related to the location of the residential building. Specifically, as for the *low damage limit state*, the repair interventions consist in the demolition and reconstruction of the damaged external wall, as well as the replacement of windows related to the storey with the maximum IDR, leading to a total repair cost equal to 7.45 k€ (Block A) and 9.34 k€ (Block B). In relation to the *heavy damage limit state*, the repair interventions considered in the previous limit state need to be applied to all walls and windows of the building, for a total repair cost equal to 36.03 k€ (Block A) and 46.19 k€ (Block

B). As for the *severe damage limit state*, the repair refers to the same interventions provided in the heavy damage limit state, along with the repair of the damaged RC beams, thus accounting for a repair cost equal to 36.75 k€ (Block A) and 46.95 k€ (Block B). Finally, with regard to the *near collapse limit state*, two different repair solutions were assumed depending on the pre- and post-retrofit scenarios. Based on the extensive damage of the building within this limit state, the demolition and reconstruction strategy was foreseen for the pre-retrofit scenario, whereas a seismic retrofit including the interventions indicated in Section 4.1.3.1 was considered for the post-retrofit scenario. These solutions account for a total cost equal to 552.56 k€ (Block A) and 819.44 k€ (Block B) for the pre-retrofit scenario and 327.38 k€ for the post-retrofit one. Based on the aforementioned costs for each limit state (C_i), the corresponding losses (L_i) are computed for the pre- and post-retrofit scenarios to subsequently estimate the total expected losses in both scenarios, i.e. the STEP III results, according to Equation (12).

The results of each step of the s-PBA methodology above, along with the total expected losses for the pre- and post-retrofit scenarios are reported in Table 11 and 12, respectively.

In the **pre-retrofit scenario**, the Case study 1 accounts for a total expected loss due to seismic damage equal to 234.01 k€; the corresponding breakdown indicates that the Block A and B account for an expected total loss equal to 80.18 k€ and 153.83 k€, respectively (Table 11).

Table 11. Case study 1 - Results of the s-PBA methodology and total expected loss of the pre-retrofit building, differentiated between Block A and Block B.

PRE-RETROFIT SCENARIO						
BLOCK A						
Step 1		*Step 2*	*Step 3*		*Step 4*	
Limit state	IDR [%]	PGA [g]	T_R [years]	R_{50} [%]	C_i [€]	L_i [€]
1 - Low damage	0.48	0.056	48	64.9	7447.65	1913.12
2 - Heavy damage	0.70	0.082	101	39.2	36035.44	8269.31
3 - Severe damage	1.11	0.129	282	16.2	36742.94	1409.17
4 - Near collapse	1.26	0.145	378	12.4	552559.46	68590.36
Total expected loss – Block A (€)						80181.96
BLOCK B						
Step 1		*Step 2*	*Step 3*		*Step 4*	
Limit state	IDR [%]	PGA [g]	T_R [years]	R_{50} [%]	C_i [€]	L_i [€]
1 - Low damage	0.52	0.048	37	75	9339.60	2287.93
2 - Heavy damage	0.74	0.069	72	50	46188.72	13303.58
3 - Severe damage	1.11	0.114	207	22	46945.05	2307.85
4 - Near collapse	1.37	0.128	276	17	819434.25	135932.39
Total expected loss – Block B (€)						153831.75
Total expected loss - Blocks (A+B) (€)						234013.70

In the **post-retrofit scenario,** the Case study 1 accounts for a total expected loss due to seismic damage equal to 3.54 k€ (Table 12).

Table 12. Case study 1 - Results of the s-PBA methodology and total expected loss of the post-retrofit building.

POST-RETROFIT SCENARIO						
Step 1		*Step 2*	*Step 3*		*Step 4*	
Limit state	IDR [%]	PGA [g]	T_R [years]	R_{50} [%]	C_i [€]	L_i [€]
1 - Low damage	0.70	0.265	1831	2.7	16787.26	166.48
2 - Heavy damage	1.04	0.380	2912	1.7	82224.16	642.50
3 - Severe damage	1.74	0.645	5403	0.9	83688.00	98.93
4 - Near collapse	2.00	0.730	6202	0.8	327377.12	2629.01
					Total expected loss (€)	3536.92

The comparison of the **STEP III results** between the pre- and post-retrofit scenario underlines that the total expected loss related to the post-retrofit scenario accounts for a reduction equal to 98 % due to the efficacy of the proposed seismic retrofit interventions.

4.2.1.4 STEP IV – Global assessment parameter in economic terms

The **STEP IV** of the SSD methodology deals with the combination of the results, carried out by the previous three steps, into a single global assessment parameter in economic terms. To this end, the energy and environmental performance results are first transformed into costs, as follows:

— **Conversion of operational energy consumption into cost** - The total operational energy in terms of electricity and natural gas during the use phase of the examined building for both the pre- and post-retrofit scenario (results obtained by STEP I) is converted into cost by retrieving the unitary prices of electricity and natural gas for household consumers in Italy in 2019 (second semester of the year). Specifically, the electricity price is equal to 0.205 €/kWh (referred to the annual consumption band DE > 15000 kWh, based on the case study result) (Eurostat, 2020c), whereas the natural gas price results equal to 0.078 €/kWh (referred to the annual consumption band D2 - 20GJ < consumption <200GJ, based on the case study result) (Eurostat, 2020e). It is worth noting that the selected prices already include taxes, except from VAT. Hence, the energy costs due to electricity and natural gas are computed according to Equations (13) and (14) for both the pre- and post-retrofit scenario, as follows:

Pre-retrofit scenario

$$R_E^{Electricty} = 2082226.8\,kWh \cdot 0.205\,\frac{€}{kWh} = 426856.5\,€ = \ 426.8\,k€$$

$$R_E^{Gas} = \ 2616919\,KWh \cdot 0.078\,\frac{€}{kWh} = 203912.3\,€ = 203.9\,k€$$

Post-retrofit scenario

$$R_E^{Electricty} = 2030220.70\,kWh \cdot 0.205\,\frac{€}{kWh} = 416195.2\,€ = 416.2\,k€$$

$$R_E^{Gas} = 899721\, kWh \cdot 0.078\, \frac{€}{kWh} = 70110.6\, € = 70.1\, k€$$

Based on these results, the final costs for the operational energy consumption (R_E) are computed according to Equation (15), resulting equal to 630768.8 € and 486305.8 € for the pre- and post-retrofit scenario, respectively.

— **Conversion of environmental impacts into cost** - The GWP in terms of total amount of GHG emissions of the examined building for both the pre- and post-retrofit scenario (results obtained by STEP II) is converted into cost by means of the unitary carbon price retrieved from the EEX, which provides the EUA price based on the EU ETS cap and trade mechanism, as described in Section 2.1.4.1. Specifically, the EUA spot price observed on the 24th March 2022 is considered; it is equal to 76.50 €/tCO_2eq. Hence, the environmental costs due to GWP are computed according to the Equation (16) for both the pre- and post-retrofit scenario, as follows:

Pre-retrofit scenario

$$R_{CO2} = 127.23\, tCO_2eq \cdot 76.50\, \frac{€}{tCO_2eq} = 9733.1\, €$$

Post-retrofit scenario

$$R_{CO2} = 241.9\, tCO_2eq \cdot 76.50\, \frac{€}{tCO_2eq} = 18505\, €$$

The operational energy (R_E) and environmental (R_{CO2}) costs above can be summed up to the structural costs (i.e. total expected losses) (L) in order to obtain the global assessment parameter in economic terms (R_{SSD}), according to Equation (17) for both the pre- and post-retrofit scenario, as reported in Table 13 and depicted in Figure 36a.

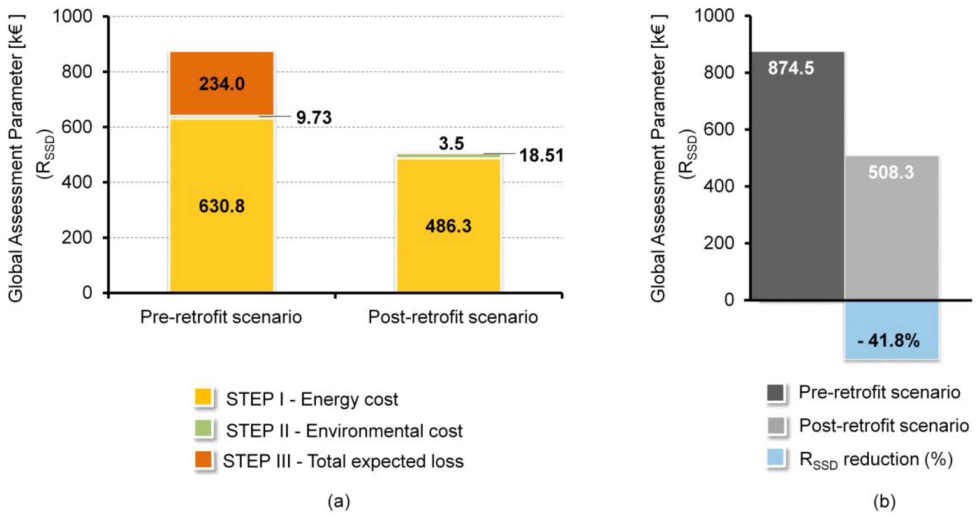
Table 13. Case study 1 – Calculation of the Global Assessment Parameter (R_{SSD})

Results in economic terms			Pre-retrofit Scenario		Post-retrofit Scenario	
STEP I - Energy cost	R_E	[€]	630768.8	72.1%	486305.8	95.7%
STEP II - Environmental cost	R_{CO2}	[€]	9733.1	1.1%	18505	3.6%
STEP III – Total expected loss	L	[€]	234013.7	26.8%	3536.9	0.7%
STEP IV - Global assessment parameter	R_{SSD}	[€]	874515.6	100%	508347.7	100%

The comparison of the **STEP IV results** underline that in both scenarios the energy performance exhibits the highest cost incidence of the total result, accounting for 72 % and more than 95 % of the R_{SSD} in the pre- and post-retrofit scenario, respectively. In the pre-retrofit scenario, the energy cost is followed in order by the seismic (26.8 %) and environmental (1.1 %) performance ones. Conversely, in the post-retrofit scenario, the environmental impacts have a cost incidence higher than the seismic performance one, also demonstrating the importance of considering an adequate unitary carbon price towards the EU decarbonisation path, as occurred in the two last years, to achieve an effective multi-performance analysis.

The combined seismic and energy retrofit of the Case study 1 leads to a total cost reduction, expressed by means of the R_{SSD}, equal to nearly 42 % (compared to the pre-retrofit scenario) (Figure 36b).

Figure 36. Case study 1 - STEP IV results for the pre- and post-retrofit scenarios



Source: JRC

4.2.2 Application of the SSD methodology to Case study 2

The application of the four steps of the SSD methodology to the Case study 2, which refers to the masonry residential building located in Dalmine (Section 4.1.3.2), is described in the following for both the pre- and post-retrofit scenarios, along with the corresponding results.

4.2.2.1 STEP I – Energy performance assessment

The **STEP I** of the methodology deals with the Energy performance assessment. The monthly operational energy consumptions of the investigated building and the corresponding annual results in terms of electricity (i.e. electricity, lighting, cooling, and DHW production) and natural gas (i.e. heating) during the use phase of the life cycle of the building have been computed for both the pre-retrofit and post-retrofit scenarios.

In relation to the **pre-retrofit scenario**, monthly and annual operational energy consumption results are provided in Table 14.

The annual operational energy consumptions in terms of electricity and natural gas result equal to 82.85 kWh/m^{2}y and 181.35 kWh/m^{2}y, respectively. The latter corresponds to a natural gas consumption equal to 18.89 m^3/m^{2}y. Finally, the total energy consumptions in terms of electricity ($Q_E^{Electricity}$) and natural gas (Q_E^{Gas}) during the use phase of the building are computed according to Equations (8) and (9), as follows:

$$Q_E^{Electricity} = 82.85 \frac{kWh}{m^2 year} \cdot 841\ m^2 \cdot 50\ years = 3483737.90\ kWh$$

$$Q_E^{Gas} = 181.35 \frac{kWh}{m^2 year} \cdot 841\ m^2 \cdot 50\ years = 7625913.17\ kWh$$

In the pre-retrofit scenario, the Case study 2 accounts for a total annual operational energy consumption (i.e. electricity plus natural gas) equal to 263.20 KWh/m^{2}y, which corresponds to a consumption during the use phase of the building (i.e. service life of 50 years) equal to 11109650.17 kWh.

Table 14. Case study 2 – Annual operational energy consumption of the pre-retrofit building

PRE-RETROFIT SCENARIO					
Month	Electricity				Natural Gas
	Appliance use (kWh/m^2)	Lighting (kWh/m^2)	DHW (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)
January	1.44	2.48	1.10	0.00	48.48
February	1.30	2.25	1.00	0.00	31.45
March	1.45	2.49	1.12	0.00	14.97
April	1.39	2.41	1.07	0.11	2.87
May	1.44	2.48	1.10	3.11	0.47
June	1.40	2.41	1.09	5.60	0.28
July	1.44	2.48	1.10	5.60	0.28
August	1.44	2.49	1.11	5.60	0.28
September	1.40	2.41	1.08	3.32	0.47
October	1.44	2.48	1.10	0.13	7.74
November	1.40	2.41	1.08	0.00	28.19
December	1.44	2.49	1.11	0.00	45.88
Annual consumption (kWh/m^{2}y)	**16.99**	**29.30**	**13.09**	**23.47**	**181.35**

In relation to the **post-retrofit scenario**, monthly and annual operational energy consumption results are provided in Table 15.

The total annual operational energy consumptions in terms of electricity and gas result equal to 62.40 KWh/m^{2}y and 79.55 KWh/m^{2}y, respectively. The latter corresponds to a natural gas consumption equal to 8.29 m^3/m^{2}y, based on the calorific value of natural gas. Finally, the total energy consumptions in terms of electricity ($Q_E^{Electricity}$) and natural gas (Q_E^{Gas}) during the use phase of the building are computed according to Equations (8) and (9), respectively, as follows:

$$Q_E^{Electricity} = 62.40 \frac{kWh}{m^2 year} \cdot 841\ m^2 \cdot 50\ years = 2623932.43\ kWh$$

$$Q_E^{Gas} = 79.55 \frac{kWh}{m^2 year} \cdot 841\ m^2 \cdot 50\ years = 3344014.26\ kWh$$

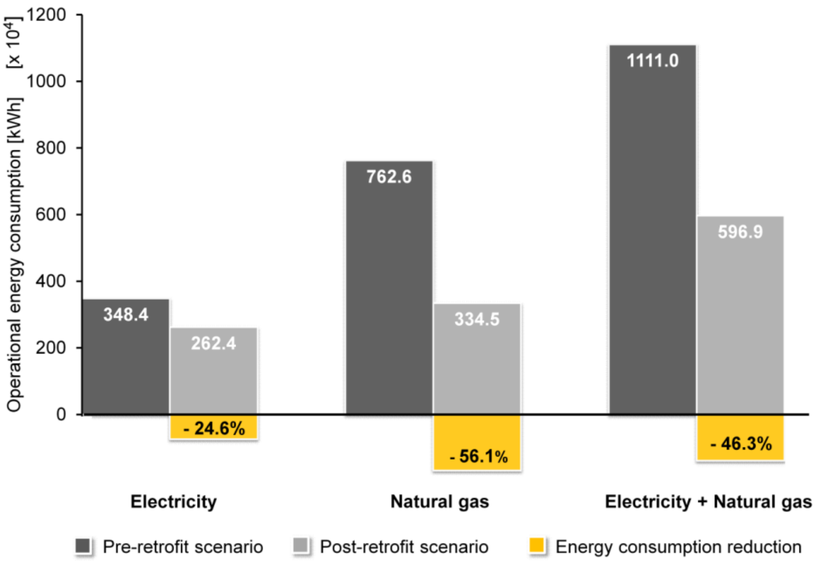
In the post-retrofit scenario, the Case study 2 accounts for a total annual operational energy consumption (i.e. electricity plus natural gas) equal to 141.9 KWh/m^{2}year, which corresponds to a consumption during the use phase of the building (i.e. service life of 50 years) equal to 5967946.43 kWh.

Table 15. Case study 2 - Annual operational energy consumption of the post-retrofit building

POST-RETROFIT SCENARIO					
Month	Electricity				Natural Gas
	Appliance use (kWh/m²)	Lighting (kWh/m²)	DHW (kWh/m²)	Cooling (kWh/m²)	Heating (kWh/m²)
January	1.44	2.48	1.10	0.00	22.90
February	1.30	2.25	1.00	0.00	14.20
March	1.45	2.49	1.12	0.00	5.47
April	1.39	2.41	1.07	0.01	0.34
May	1.44	2.48	1.10	0.70	0.03
June	1.40	2.41	1.09	0.56	0.03
July	1.44	2.48	1.10	0.56	0.03
August	1.44	2.49	1.11	0.56	0.03
September	1.40	2.41	1.08	0.59	0.34
October	1.44	2.48	1.10	0.05	2.27
November	1.40	2.41	1.08	0.00	12.31
December	1.44	2.49	1.11	0.00	21.60
Annual consumption (kWh/m²y)	**16.99**	**29.30**	**13.09**	**3.03**	**79.55**

The comparison of the **STEP I results** between the pre- and post- retrofit scenario of the Case study 2 (Figure 37) underlines that the operational energy consumptions in terms of electricity and natural gas related to the post-retrofit scenario account for reductions equal to 24.6 % and 56 %, respectively, due to the corresponding energy reductions for space cooling and heating, based on the efficacy of energy retrofit interventions (Section 4.1.3.2). Hence, a total reduction of the operational energy consumption (i.e. electricity, plus natural gas) equal to 46.3 % features the examined residential building in the post-retrofit scenario.

Figure 37. Case study 2 - STEP I results for the pre- and post-retrofit scenarios



Source: JRC

4.2.2.2 *Step II – Life cycle assessment (LCA)*

The **STEP II** of the SSD methodology focuses on the environmental performance assessment by applying the LCA methodology to evaluate the carbon footprint produced by the structural system and non-structural components of the investigated building for both the pre- and post-retrofit scenario.

In relation to the **pre-retrofit scenario**, the quantity of materials of both structural and non-structural components of the building and their corresponding GHG emissions, expressed in tonnes of CO_2-equivalent emissions (tCO_2eq), related to the production phase of the life cycle of the building, are reported in Table 16.

The structural system produces the highest negative impact in terms of GHG emissions, mainly due to the floor component, accounting for 51.8 tCO_2eq. The total amount of GHG emissions related to the production phase, due to both structural elements and non-structural components, results equal to 96.5 tCO_2eq in the pre-retrofit scenario.

Table 16. Case study 2 – LCA results related to GWP for the pre-retrofit scenario (Production phase – Module A1-A3)

Component		Material	Quantity	Unit	GWP (tCO_2eq)
Structural elements	Walls	Brick masonry	255.7	m^3	25.6
	Roof	Timber	190	m^2	7.3
	Floors	/	892.8	m^2	51.8
Total GWP (structural components)					84.7
Non-structural components	Windows	Wood and glass	162	m^2	8.9
	Roof tiles	Brick	190	m^2	2.92
Total GWP (non-structural components)					11.8
Total GWP					96.5

In relation to the **post-retrofit scenario**, the quantity of materials of both structural elements and non-structural components for the seismic and energy retrofit interventions of the building and their corresponding GHG emissions, related to the production phase of the building life cycle, are summarised in Table 17.

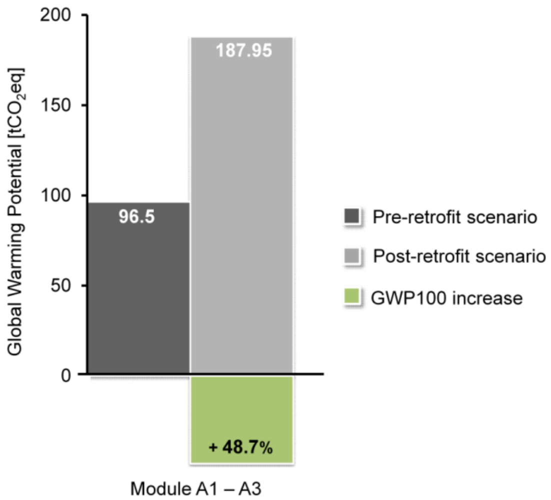
The seismic retrofit interventions produce a higher total amount of GHG emissions, i.e. 61.6 tCO_2eq, than the energy retrofit ones with the new foundation system for the exoskeleton accounting for the highest amount of GHG emissions, i.e. 60.55 tCO_2eq. The total amount of GHG emissions due to the production of the material/components of both seismic and energy retrofit results equal to 91.45 tCO_2eq. In order to compute the final result of the environmental performance of the building in terms of GWP related to the post-retrofit scenario, the amount of GHG emissions produced by the adopted seismic and energy retrofit technologies needs to be added to the total result of the GWP related to the pre-retrofit scenario. Hence, the total amount of GHG emissions related to the production phase of both the building components and retrofit technologies results equal to 187.95 tCO_2eq in the post-retrofit scenario.

Table 17. Case study 2 – LCA results related to GWP for the post-retrofit scenario (Production phase – Module A1-A3)

Retrofit intervention		Material	Quantity	Unit	GWP100 [tCO_2eq]
Seismic retrofit	Shear walls (Exoskeleton)	Steel (Bracings)	488.2	kg	1.04
	New foundations	Concrete	12.96	m^3	3.43
		Steel	1300	kg	3.06
		Micropiles	840	m	54.06
Total (Seismic retrofit)					61.6
Energy retrofit	Window replacement	Aluminium, wood and glass	162	m^2	19.6
	Roof insulation	Vapour barrier	120	m^2	0.04
		Rock wool	10	m^3	0.83
	Wall insulation	Polyurethane foam	48.8	m^3	8.65
		Galvanised metal	122	m^2	0.73
Total (Energy retrofit)					29.85
Total GWP100 (Seismic + Energy retrofit)					91.45
Total GWP100 (Post-retrofit scenario)					187.95

The comparison of the **STEP II results** between the pre- and post-retrofit scenario of the Case study 2 (Figure 38) demonstrates that an increase of the GHG emissions (related to the production phase), equal to 49 %, features the examined residential building in the post-retrofit scenario, based on the system boundaries considered.

Figure 38. Case study 2 - STEP II results for the pre- and post-retrofit scenarios



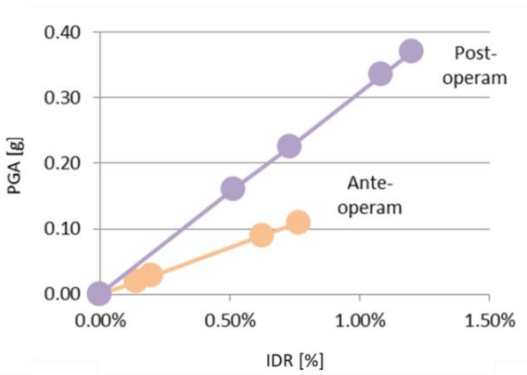
Source: JRC

4.2.2.3 Step III - Structural performance assessment

The **Step III** of the SSD methodology deals with the Structural performance assessment, based on the four main steps of the s-PBA methodology, as follows:

- *Step 1 - Definition of limit states* – The damage limit states can be correlated to suitable IDR values. In this case, the identification of the limit states is correlated to the attainment of displacements identified on the capacity curve carried out by means of the pushover analysis to subsequently define the corresponding IDR values, as follows:
    - *Low damage limit state* - This limit state is characterised by damage initiating to non-structural elements, first affecting internal partitions walls, along with windows in the storey subjected to the maximum IDR. For this limit state, the maximum allowed displacement results equal to 0.7 δ_y, being δ_y the building yielding displacement.
    - *Heavy damage limit state* - The damage occurs into all the non-structural elements, mainly affecting partition walls and windows located at all levels of the building, as well as the perimeter rubble masonry walls located at the storey with the maximum IDR, thus requiring repair interventions. This limit state is attained when the maximum displacement reaches the value 1.5 δ_y.
    - *Severe damage limit state* - This limit state is based on the no-collapse requirement of the structural system of the building hit by the earthquake. Hence, all non-structural elements exhibit damages leading to their replacement. Moreover, rubble masonry walls also exhibit damages, thus requiring retrofit. This limit state is attained when the maximum displacement reaches the value 0.5 (δ_y + δ_u), being δ_u the ultimate displacement of the building.
    - *Near collapse Limit state* - This limit state corresponds to the full exploitation of the deformation capacity of structural elements. Hence, all non-structural and structural elements of the building result into extensive damages. This limit state is reached when the maximum displacement results equal to δ_u.
- *Step 2 - Structural analysis* - The PGA values corresponding to the attainment of the IDR values identified by means of the Step 1 are obtained by pushover analyses and the relation between the PGA values and IDR ones for both the pre- and post-retrofit scenario are reported in Figure 39.

Figure 39. Case-study 2 – PGA vs IDR diagram



Source: JRC

- *Step 3 - Hazard analysis* - Based on the PGA values obtained in the Step 2, the corresponding T_R values are first computed, according to Equation (10), to subsequently calculate the probability of exceedance in 50 years, i.e. service life of an ordinary building (R_{50}), according to Equation (11), for both the pre- and post-retrofit scenario.
- *Step 4 - Cost analysis* - The costs corresponding to the repair interventions for each limit state are first computed according to the official 'Public works price list of the Lombardia region' to be consistent with the construction work prices related to the location where the residential building is erected. Specifically, as for the *low damage limit state*, the repair interventions consist in the demolition and reconstruction of

the damaged internal partition walls, as well as the replacement of windows related to storey with the maximum IDR, leading to a total repair cost equal to 4.6 k€. In relation to the *heavy damage limit state*, the repair interventions considered in the previous limit state need to be applied to all partition walls and windows of the building, along with the retrofit of the load-bearing masonry walls of the storey with the maximum IDR for a total repair cost equal to 9.3 k€. As for the *severe damage limit state*, the repair refers to the same interventions provided in the heavy damage limit state, along with the repair of the damaged RC beams, thus accounting for a repair cost equal to 18.2 k€. Finally, with regard to the *near collapse limit state*, two different repair solutions have been assumed depending on the pre- and post-retrofit scenario. Based on the extensive damage of the building within this limit state, the demolition and reconstruction strategy has been foreseen for the building in its pre-retrofit scenario, whereas a seismic retrofit including the interventions indicated in Section 4.1.3.2 has been considered for the building in its post-retrofit scenario. The demolition and reconstruction option, and the retrofit solution lead to repair costs equal to 1018.3 k€ and 217.7 k€, respectively. Based on these costs, the corresponding losses for each limit state are calculated for both pre- and post-retrofit scenario to achieve the total expected loss, according to Equation (12).

The results of each step of the s-PBA methodology, along with the total expected losses for the pre-and post-retrofit scenario are reported in Table 18 and 19, respectively.

In the **pre-retrofit scenario**, the Case study 2 accounts for a total expected loss due to seismic damage equal to 102.66 k€ (Table 18).

Table 18. Case study 2 - Results of the s-PBA methodology and total expected loss of the pre-retrofit building.

PRE-RETROFIT SCENARIO						
Step 1		*Step 2*	*Step 3*		*Step 4*	
Limit state	IDR [%]	PGA [g]	T_R [years]	R_{50} [%]	C_i [€]	L_i [€]
1 - Low damage	0.14	0.019	14	97.8	4670.39	700.01
2 - Heavy damage	0.20	0.028	29	82.8	9330.43	6369.69
3 - Severe damage	0.63	0.089	318	14.6	18190.35	960.68
4 - Near collapse	0.77	0.109	513	9.3	1018248.4	94637.92
					Total expected loss (€)	102668.30

In the **post-retrofit scenario**, the Case study 2 accounts for a total expected loss due to seismic damage equal to 2.5 k€ (Table 19).

Table 19. Case study 2 - Results of the s-PBA methodology and total expected loss of the post-retrofit building.

POST-RETROFIT SCENARIO						
Step 1		*Step 2*	*Step 3*		*Step 4*	
Limit state	IDR [%]	PGA [g]	T_R [years]	R_{50} [%]	C_i [€]	L_i [€]
1 - Low damage	0.51	0.160	1480	3.3	4670.39	63.02
2 - Heavy damage	0.73	0.225	2508	2.0	9330.43	69.57
3 - Severe damage	1.08	0.335	4044	1.2	18190.35	23.98
4 - Near collapse	1.20	0.370	4533	1.1	217786.89	2389.11
					Total expected loss (€)	2545.67

The comparison of the **STEP III results** between the pre- and post- retrofit scenario underlines that the total expected loss related to the post-retrofit scenario account for a reduction equal to 97.5% due to the efficacy of the proposed seismic retrofit interventions.

4.2.2.4 Step IV – Global assessment parameter in economic terms

The **STEP IV** of the SSD methodology deals with the combination of the results carried out by the previous three steps into a single global assessment parameter in economic terms. To this end, the energy and environmental performance results need to be first transformed into costs, as follows:

— **Conversion of operational energy consumption into cost** - The total operational energy in terms of electricity and natural gas during the use phase of the examined building for both the pre- and post-retrofit scenario (results obtained by STEP I) is converted into cost by retrieving the unitary prices of electricity and natural gas for household consumers in Italy in 2019 (second semester of the year). Specifically, the electricity price is equal to 0.205 €/KWh (referred to the annual consumption band DE > 15000 KWh, based on the case study result) (Eurostat, 2020c), whereas the natural gas price results equal to 0.060 €/KWh (referred to the annual consumption band D3 > 200GJ, based on the case study result) (Eurostat, 2020e). It is worth noting that the selected prices already include taxes except VAT. Hence, the energy costs due to electricity and natural gas are computed according to Equations (13) and (14) for both the pre- and post-retrofit scenario, as follows:

Pre-retrofit scenario

$$R_E^{Electricty} = 3483737.90\ kWh \cdot 0.205\ \frac{€}{kWh} = \ 714.2\ k€$$

$$R_E^{Gas} = \ 7625913.17\ kWh \cdot 0.060\ \frac{€}{kWh} = \ 460.6\ k€$$

Post-retrofit scenario

$$R_E^{Electricty} = 2623932.43KWh \cdot 0.205\ \frac{€}{kWh} = \ 537.9\ k€$$

$$R_E^{Gas} = \ 3344014.26\ KWh \cdot 0.060\ \frac{€}{kWh} = \ 202\ k€$$

Based on these results, the final costs for the operational energy consumption are computed according to Equation (15), resulting equal to 1174.8 k€ and 739.9 k€ for the pre- and post-retrofit scenario, respectively.

— **Conversion of the environmental impacts into cost** - The GWP in terms of total amount of GHG emissions of the examined building for both the pre- and post-retrofit scenario (results obtained by STEP II) is converted into cost by means of the unitary carbon price retrieved from the EEX, which provides the EUA price based on the EU ETS cap and trade mechanism, as described in Section 2.1.4.1. Specifically, the EUA spot price observed on the 24th March 2022 is considered; it is equal to 76.50 €/tCO_2eq. Hence, the environmental costs due to GWP are computed according to the Equation (16) for both the pre- and post-retrofit scenario, as follows:

Pre-retrofit scenario

$$R_{CO2} = 96.5\ tCO_2eq \cdot 76.50\ \frac{€}{tCO_2eq} = 7382.1\ €$$

Post-retrofit scenario $R_{CO2} = 187.9\ tCO_2eq \cdot 76.50\ \frac{€}{tCO_2eq} = 14373.5€$

The operational energy (R_E) and environmental (R_{CO2}) costs above can be summed up to the structural costs (i.e. total expected losses) (L) in order to obtain the global assessment parameter in economic terms (R_{SSD}), according to Equation (17) for both the pre- and post-retrofit scenario, as reported in Table 20 and depicted in Figure 40a.

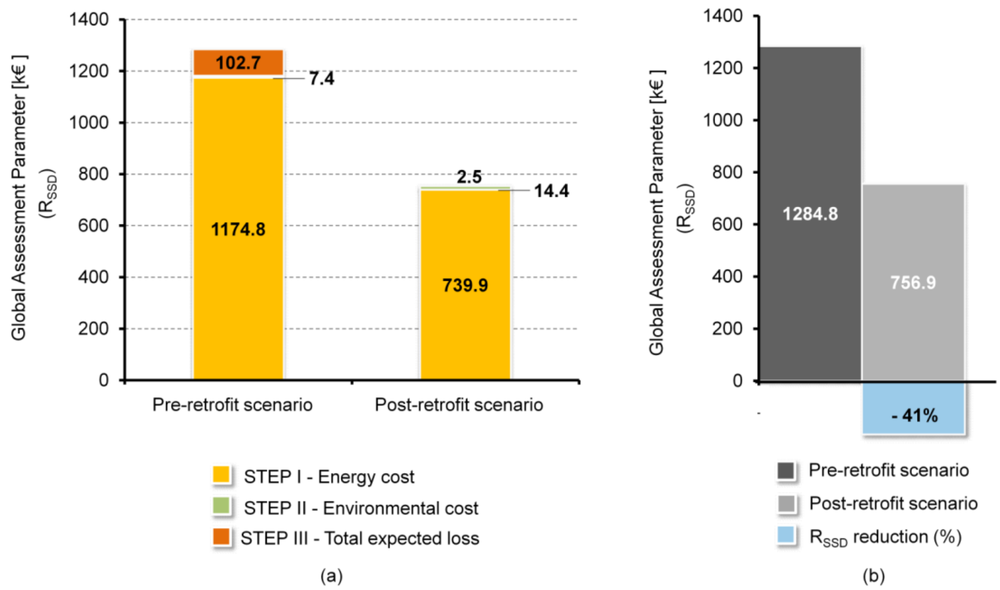
Table 20. Case study 2 – Calculation of the Global Assessment Parameter (R_{SSD})

Results in economic terms			Pre-retrofit Scenario		Post-retrofit Scenario	
STEP I - Energy cost	R_E	[€]	1174800	91.4%	739900	97.8%
STEP II - Environmental cost	R_{CO2}	[€]	7382.1	0.6%	14373.5	1.9%
STEP III – Total expected loss	L	[€]	102668.3	8.0%	2545.67	0.3%
STEP IV - Global assessment parameter	R_{SSD}	[€]	1284821.8	100%	756858.1	100%

The comparison of the **STEP IV results** underlines that in both scenarios the energy performance exhibits the highest cost incidence of the total result, accounting for 91.4 % and 97.8 % of the R_{SSD} in the pre- and post-retrofit scenario, respectively. In the pre-retrofit scenario, the energy cost is followed in order by the seismic (8 %) and environmental (0.6 %) performance ones. Conversely, in the post-retrofit scenario, the environmental impacts have a cost incidence (1.9 %) higher than the seismic performance one (0.3 %), also demonstrating the importance of considering an adequate unitary carbon price towards the EU decarbonisation path, as occurred in the two last years, to achieve an effective multi-performance analysis.

The combined seismic and energy retrofit of the Case study 2 leads to a total cost reduction, expressed by means of the $R_{SSD,}$ equal to 41 % (compared to the pre-retrofit scenario) (Figure 40b).

Figure 40. Case study 2 - STEP IV results for the pre- and post-retrofit scenarios



Source: JRC

4.2.3 Application of the SSD methodology to Case study 3

The application of the four steps of the SSD methodology to the Case study 3, which refers to the RC 'Pietro Santini' primary school located in Loro Piceno (Section 4.1.3.3), is described in the following for both the pre- and post-retrofit scenarios of the building along with the corresponding results.

4.2.3.1 STEP I – Energy performance assessment

The **STEP I** of the SSD methodology deals with the Energy performance assessment. The monthly operational energy consumptions of the investigated school building and the corresponding annual results in terms of electricity (i.e. appliance use, lighting, DHW production, and cooling), and gas (i.e. heating) during the use phase of the life cycle of the building have been computed for both the pre- and post-retrofit scenarios.

In relation to the **pre-retrofit scenario**, monthly and annual operational energy consumption results are provided in Table 21.

The total annual operational energy consumptions in terms of electricity and natural gas result equal to 52.28 KWh/m^{2}year and 121.18 kWh/m^{2}y, respectively. The latter corresponds to a natural gas consumption equal to 12.63 m^3/m^{2}y, based on the calorific value of natural gas. Finally, the total energy consumptions in terms of electricity ($Q_E^{Electricity}$) and natural gas (Q_E^{Gas}) during the use phase of the building are computed according to Equations (8) and (9), as follows:

$$Q_E^{Electricity} = 52.28\,\frac{kWh}{m^2 year} \cdot 1238\,m^2 \cdot 50\,years = 3235847.79\,kWh$$

$$Q_E^{Gas} = 121.18\,\frac{kWh}{m^2 year} \cdot 1238\,m^2 \cdot 50\,years = 7501042\,kWh$$

In the pre-retrofit scenario, the Case study 3 accounts for a total annual operational energy consumption (i.e. electricity plus natural gas) equal to 173.5 KWh/m^{2}year, with a corresponding consumption during the use phase (i.e. service life of 50 years) equal to 10736889.8 kWh.

Table 21. Case study 3 – Annual operational energy consumption of the pre-retrofit building

PRE-RETROFIT SCENARIO					
Month	Electricity				Natural Gas
	Appliance use (kWh/m^2)	Lighting (kWh/m^2)	DHW (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)
January	1.75	0.54	1.47	0.00	29.72
February	1.64	0.51	1.39	0.00	21.82
March	1.61	0.48	1.32	0.01	16.38
April	2.02	0.65	1.78	0.09	7.84
May	2.17	0.71	1.93	0.50	1.81
June	1.89	0.58	1.63	1.43	0.16
July	1.88	0.61	1.62	3.14	0.06
August	0.40	0.00	0.00	0.00	0.00
September	1.96	0.62	1.71	1.31	0.38
October	1.88	0.61	1.62	0.23	3.89
November	2.20	0.72	1.98	0.03	13.12
December	1.72	0.52	1.44	0.00	25.99
Annual consumption (kWh/m^{2}year)	21.12	6.54	17.88	6.73	121.18

In relation to the **post-retrofit scenario**, monthly and annual operational energy consumption results are provided in Table 22.

The total annual operational energy consumptions in terms of electricity and natural gas result equal to 47.02 KWh/m^{2}y and 59.01 KWh/m^{2}y, respectively. The latter corresponds to a natural gas consumption equal to 6.15 m^3/m^{2}y, based on the calorific value of natural gas. Finally, the total energy consumptions in terms of electricity ($Q_E^{Electricity}$) and natural gas (Q_E^{Gas}) during the use phase of the building are computed according to Equations (8) and (9), as follows:

$$Q_E^{Electricity} = 47.02 \frac{kWh}{m^2 year} \cdot 1238\, m^2 \cdot 50\, years = 2910323.27\, kWh$$

$$Q_E^{Gas} = 59.01 \frac{kWh}{m^2 year} \cdot 1238\, m^2 \cdot 50\, years = 3652719\, kWh$$

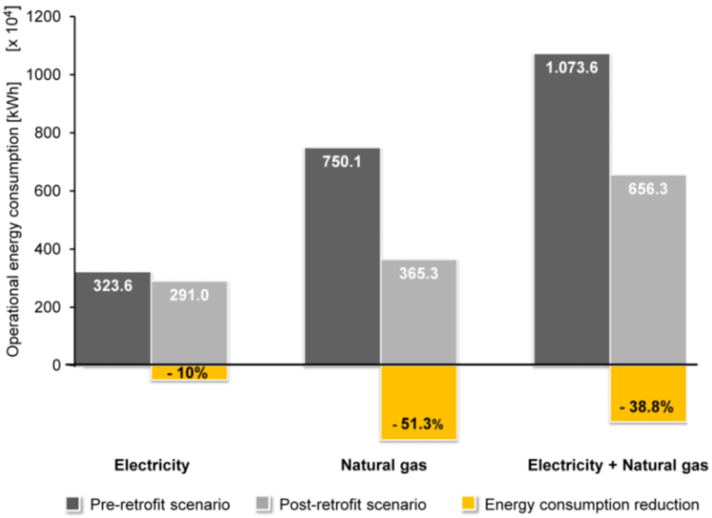
In the post-retrofit scenario, the Case study 3 accounts for a total annual operational energy consumption (i.e. electricity plus natural gas) equal to 106.04 KWh/m^{2}year with a corresponding consumption during the use phase of the building (i.e. service life of 50 years) equal to 6563042.3 kWh.

Table 22. Case study 3 – Annual operational energy consumption of the post-retrofit building

POST-RETROFIT SCENARIO					
Month	Electricity				Natural Gas
	Appliance use [kWh/m^2]	Lighting [kWh/m^2]	DHW (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)
January	1.75	0.54	1.47	0.00	16.72
February	1.64	0.51	1.39	0.00	11.13
March	1.61	0.48	1.32	0.16	7.32
April	2.02	0.65	1.78	0.22	2.73
May	2.17	0.71	1.93	0.24	0.50
June	1.89	0.58	1.63	0.20	0.00
July	1.88	0.61	1.62	0.21	0.00
August	0.40	0.00	0.00	0.00	0.00
September	1.96	0.62	1.71	0.21	0.04
October	1.88	0.61	1.62	0.21	1.33
November	2.20	0.72	1.98	0.03	5.79
December	1.72	0.52	1.44	0.00	13.45
Annual consumption (kWh/m^{2}year)	21.12	6.54	17.88	1.47	59.01

The comparison of the **STEP I results** between the pre- and post- retrofit scenario of the Case study 3 (Figure 41) underlines that the operational energy consumptions in terms of electricity and natural gas related to the post-retrofit scenario account for reductions equal to 10 % and 51.3 %, respectively, due to the corresponding energy reductions for space cooling and heating, based on the efficacy of energy retrofit interventions (Section 4.1.3.3). Hence, a total reduction of the operational energy consumption equal to 38.8% features the examined building in its post-retrofit scenario.

Figure 41. Case study 3 - STEP I results for the pre- and post-retrofit scenarios.



Source: JRC

4.2.3.2 STEP II – Life Cycle Assessment (LCA)

The **STEP II** of the SSD methodology focuses on the environmental performance assessment by applying the LCA methodology to evaluate the carbon footprint produced by the structural system and non-structural components of the investigated building for both the pre- and post-retrofit scenario.

In relation to the **pre-retrofit scenario**, the quantity of materials of both structural and non-structural components of the building and their corresponding GHG emissions, expressed in tonnes of CO_2-equivalent emissions (tCO_2eq), related to the production phase of the life cycle of the building, are reported in Table 23.

The structural system produces the highest negative impact in terms of GHG emissions, mainly due to the foundations (i.e. 76.7 tCO_2eq), resulting into the major contributor of the total GWP100. The total amount of GHG emissions related to the production phase, due to both structural elements and non-structural components, results equal to 260.68 tCO_2eq in the pre-retrofit scenario.

Table 23. Case study 3 – LCA results related to GWP for the pre-retrofit scenario (Production phase – Module A1-A3)

Component		Material	Quantity	Unit	GWP100 [tCO_2eq]
Structural elements	Columns and beams	Concrete	101.09	m^3	28.9
		Steel	10010	kg	23.6
	Foundations	Concrete	240	m^3	63.5
		Steel	6145	kg	13.2
	Floors	/	330024	kg	69.9
Total (Structural components)					199.1
Non-structural components	External infill walls	Brick	274.2	m^3	29.6
	Windows	Aluminium and glass	213.81	m^2	25.8
	Roof tiles	Brick	403	m^2	6.18
Total (Non-structural components)					61.58
Total GWP100 (Pre-retrofit scenario)					260.68

In relation to the **post-retrofit scenario**, the quantity of materials of both structural elements and non-structural components for the seismic and energy retrofit interventions of the building and their corresponding GHG emissions, related to the production phase of the building life cycle, are summarised in Table 24.

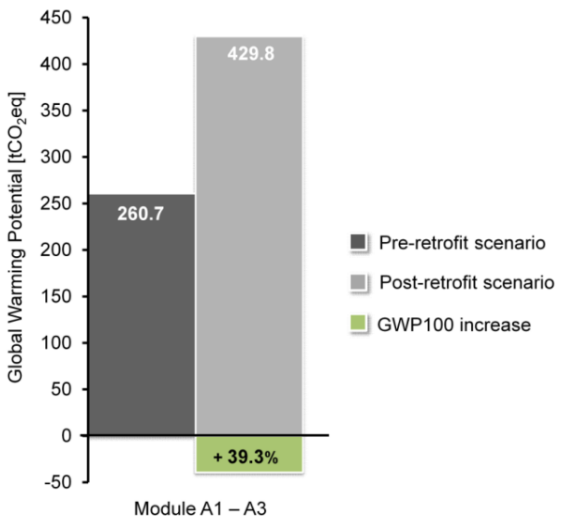
The seismic retrofit interventions result into the main responsible for the GHG emissions equal to 162.6 tCO_2eq, with the foundation system accounting for the highest amount of emissions, i.e. 72.4 tCO_2eq. The total negative impact in terms of GHG emissions due to both seismic and energy retrofit is equal to 169.1 tCO_2eq. In order to compute the global result of the environmental performance of the retrofitted building in terms of GWP related to the post-retrofit scenario, the amount of GHG emissions produced by the bracing, foundations, and façade system for the seismic and energy retrofit of the school building needs to be added to the total result of the GWP related to the pre-retrofit scenario. Hence, the total amount of GHG emissions related to the production phase of both the building components and retrofit technologies results equal to 429.78 tCO_2eq in the post-retrofit scenario.

Table 24. Case study 3 – LCA results related to GWP for the post-retrofit scenario (Production phase – Module A1-A3)

Retrofit intervention		Material	Quantity	Unit	GWP100 [tCO_2eq]
Seismic retrofit	Bracing	Steel	12748	kg	27.3
		Steel (connections)	29035	kg	62.9
	Foundation	Micropiles	1125	m	72.4
				Total (Seismic retrofit)	162.6
Energy retrofit	Façade system	Polycarbonate	36.5	m^3	6.47
				Total (Energy retrofit)	6.47
				Total GWP (Seismic + Energy retrofit)	169.1
				Total GWP100 (Post-retrofit scenario)	429.8

The comparison of the **STEP II results** between the pre- and post-retrofit scenario of the Case study 3 (Figure 42) demonstrates that an increase of the GHG emissions (related to the production phase) equal to 39.3 % features the examined residential building in the post-retrofit scenario.

Figure 42. Case study 3 - STEP II results for the pre- and post-retrofit scenarios



Source: JRC

4.2.3.3 STEP III - Structural performance assessment

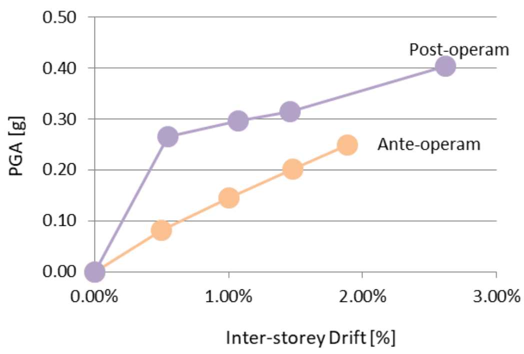
The **STEP III** of the SSD methodology deals with the Structural performance assessment, based on the four main steps of the s-PBA methodology, as follows:

— *Step 1 - Definition of limit states* - The following damage limit states and the corresponding IDR values are defined:

  - *Low damage Limit state* - This limit state is characterised by damage initiating to non-structural elements, first affecting the external walls parallel to the seismic direction, along with windows in the storey subjected to the maximum IDR. According to Eurocode 8 for seismic design of structures (CEN, 2004), the maximum allowed IDR due to frequent earthquakes is 0.5 % for brittle non-structural elements connected to the structure (e.g. brick walls).
  - *Heavy damage Limit state* – The damage occurs into all non-structural elements, mainly affecting external walls and windows located at all levels of the building, thus requiring repair interventions. Conversely, the structural system is not subjected to damage, thus not requiring any repair intervention. This limit state is attained when the maximum IDR reaches twice the threshold deformation value.
  - *Severe damage Limit state* - This limit state is based on the no-collapse requirement of the structural system of the building hit by the earthquake. Hence, all non-structural elements exhibit severe damages, thus needing replacement. Furthermore, RC beams located at the first floor parallel to the seismic direction need to be retrofitted due to the creation of plastic hinges. According to Eurocode 8 (CEN, 2004), no-collapse requirement for public structures is met for a recommended reference seismic action having 10 % exceedance probability in 50 years, i.e. with a 745-years return period.
  - *Near Collapse Limit state* - This limit state corresponds to the full exploitation of the deformation capacity of structural elements, thus all non-structural and structural elements of the building result extensively damaged.

— *Step 2 - Structural analysis* - The PGA values corresponding to the attainment of the IDR values identified by means of the Step 1 are obtained by pushover analyses and the relation between the PGA values and IDR ones for both pre- and post-retrofit scenario are reported in Figure 43.

Figure 43. Case study 3 – PGA vs IDR diagrams



Source: JRC

— *Step 3 - Hazard analysis* - Based on the PGA values obtained in the Step 2, the corresponding T_R values are first computed, according to Equation (10), to subsequently calculate the probability of exceedance in 50 years (i.e. service life of an ordinary building) (R_{50}), according to Equation (11), for both the pre- and post-retrofit scenario.

— *Step 4 - Cost analysis* - The repair interventions and the corresponding costs for each limit state are first computed according to the official 'Public works price list of the Marche region' to be consistent with the typical construction work prices related to the location of the examined school building. Specifically, as for the *low damage limit state*, the repair interventions consist in the demolition and reconstruction of the damaged external walls, as well as the replacement of windows related to the storey with the maximum IDR, leading to a total repair cost equal to 34.5 k€. In relation to the *heavy damage limit state*, the repair interventions considered in the previous limit state need to be applied to all walls and windows of the building, for a total repair cost equal to 135.9 k€. As for the *severe damage limit state*, the repair refers to the same interventions provided in the heavy damage limit state, along with the repair of the damaged RC beams, thus accounting for a repair cost equal to 170.4 k€. Finally, with regard to the *near collapse limit state*, two different repair solutions were assumed depending on the pre- and post-retrofit scenarios. Based on the extensive damage of the building within this limit state, the demolition and reconstruction strategy was foreseen for the pre-retrofit scenario, whereas a seismic retrofit including the interventions indicated in Section 4.1.3.3 was considered for the post-retrofit scenario. The former and latter solutions account for a total cost equal to 1578.5 k€ and 433.3 k€, respectively. Based on the aforementioned costs for each limit state (C_i), the corresponding losses (L_i) are calculated for pre- and post-retrofit scenarios to subsequently achieve the total expected losses in both scenarios, i.e. the STEP III results, according to Equation (12).

The results of each step of the s-PBA methodology above, along with the total expected losses for the pre- and post-retrofit scenarios are reported in Tables 25 and 26, respectively.

In the **pre-retrofit scenario**, the Case study 3 accounts for a total expected loss due to seismic damage equal to 87.9 k€ (Table 25).

Table 25. Case study 3 - Results of the s-PBA methodology and total expected loss of the pre-retrofit building.

PRE-RETROFIT SCENARIO						
Step 1		*Step 2*	*Step 3*		*Step 4*	
Limit state	IDR [%]	PGA [g]	T_R [years]	R_{50} [%]	C_i [€]	L_i [€]
1 - Low damage	0.50	0.082	72	50.2	34542	12152.53
2 - Heavy damage	1	0.145	308	15.0	135912	11152.51
3 - Severe damage	1.48	0.202	713	6.8	170412	5140.42
4 - Near collapse	1.89	0.248	1304	3.8	1578526	59421.30
					Total expected loss (€)	87866.77

In the **post-retrofit scenario**, the Case study 3 accounts for a total expected loss due to seismic damage equal to nearly 6.9 k€ (Table 26).

Table 26. Case study 3 - Results of the s-PBA methodology and total expected loss of the post-retrofit building

POST-RETROFIT SCENARIO						
Step 1		*Step 2*	*Step 3*		*Step 4*	
Limit state	IDR [%]	PGA [g]	T_R [years]	R_{50} [%]	C_i [€]	L_i [€]
1 - Low damage	0.50	0.265	1593	3.1	34542	307.90
2 - Heavy damage	1	0.297	2249	2.2	135912	397.13
3 - Severe damage	1.48	0.314	2598	1.9	170412	1341.93
4 - Near collapse	2.62	0.404	4442	1.1	433300	4850.43
					Total expected loss [€]	6897.40

The comparison of the **STEP III results** between the pre- and post-retrofit scenario underlines that the total expected loss related to the post-retrofit scenario accounts for a reduction equal to 95%, due to the efficacy of the proposed seismic retrofit interventions.

4.2.3.4 Step IV - Global assessment parameter in economic terms

The **STEP IV** of the SSD methodology deals with the combination of the results, carried out by the previous three steps, into a single global assessment parameter in economic terms. To this end, the energy and environmental performance results are first transformed into costs, as follows:

- **Conversion of operational energy consumption into cost** - The total operational energy in terms of electricity and natural gas during the use phase of the examined building for both the pre- and post-retrofit scenario (results obtained by STEP I) is converted into cost by retrieving the unitary prices of electricity and natural gas for non-household consumers in Italy in 2019 (second semester of the year). Specifically, the electricity price is equal to 0.186 €/KWh (referred to the annual consumption band IB - 20 MWh < consumption < 500 MWh, based on the case study result) (Eurostat, 2020d), whereas the natural gas price results equal to 0.060 €/KWh (referred to the annual consumption band I1 < 1000 GJ, based on the case study result) (Eurostat, 2020f). It is worth noting that the selected prices already include taxes, except from VAT. Hence, the energy costs due to electricity and natural gas are computed according to Equations (13) and (14) for both pre- and post-retrofit scenario, as follows:

  Pre-retrofit scenario

  $$R_E^{Electricty} = 3235847.79\ KWh \cdot 0.186\ \frac{€}{KWh} = 601.8\ k€$$

  $$R_E^{Gas} = 7501042\ KWh \cdot 0.060\ \frac{€}{KWh} = 453.8\ k€$$

  Post-retrofit scenario

  $$R_E^{Electricty} = 2910323.27\ KWh \cdot 0.186\ \frac{€}{KWh} = 541.3\ k€$$

  $$R_E^{Gas} = 3652719\ KWh \cdot 0.060\ \frac{€}{KWh} = 220.9\ k€$$

  Based on these results, the final costs for the operational energy consumption (R_E) are computed according to Equation (15), resulting equal to 1055.6 k€ and 762.2 k€ for the pre- and post-retrofit scenario, respectively.

- **Conversion of environmental impacts into cost** - The GWP in terms of total amount of GHG emissions of the examined building for both the pre- and post-retrofit scenario (results obtained by STEP II) is converted into cost by means of the unitary carbon price retrieved from the EEX, which provides the EUA price based on the EU ETS cap and trade mechanism, as described in Section 2.1.4.1. Specifically, the EUA spot price observed on the 24th March 2022 is considered; it is equal to 76.50 €/tCO_2eq. Hence, the environmental costs due to GWP are computed according to the Equation (16) for both the pre- and post-retrofit scenario, as follows:

  Pre-retrofit scenario

  $$R_{CO2} = 260.7\ tCO_2eq \cdot 76.50\ \frac{€}{tCO_2eq} = 19943.5\ €$$

Post-retrofit scenario $$R_{CO2} = 429.8\ tCO_2eq \cdot 76.50\ \frac{€}{tCO_2eq} = 32879.7\ €$$

The operational energy (R_E) and environmental (R_{CO2}) costs above can be summed up to the structural costs (i.e. total expected losses) (L) in order to obtain the global assessment parameter in economic terms (R_{SSD}), according to Equation (17) for both pre- and post-retrofit scenario, as reported in Table 27 and depicted in Figure 44a.

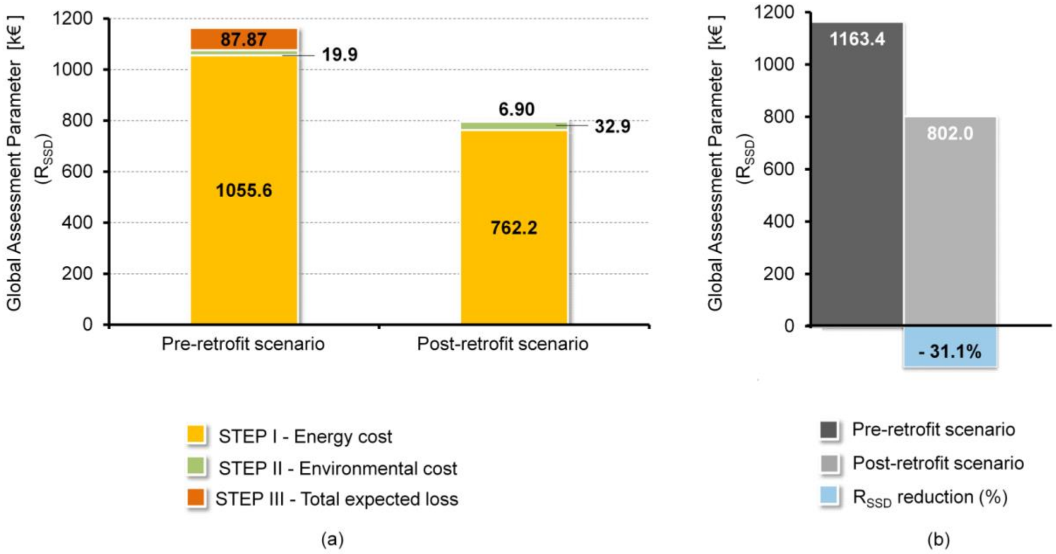
Table 27. Case study 3 - Calculation of the Global Assessment Parameter (R_{SSD})

Results in economic terms			Pre-retrofit Scenario		Post-retrofit Scenario	
STEP I - Energy cost	R_E	[€]	1055600	90.7%	762200	95%
STEP II - Environmental cost	R_{CO2}	[€]	19943.5	1.7%	32879.7	4.1%
STEP III – Total expected loss	L	[€]	87866.7	7.6%	6897.4	0.9%
STEP IV - Global assessment parameter	R_{SSD}	**[€]**	**1163410**	100%	**801977.1**	100%

The comparison of the **STEP IV results** underline that in both scenarios the energy performance exhibits the highest cost incidence of the total result, accounting for 90.7 % and 95 % of the R_{SSD} in the pre- and post-retrofit scenario, respectively. In the pre-retrofit scenario, the energy cost is followed in order by the seismic (7.6 %) and environmental (1.7 %) performance ones. Conversely, in the post-retrofit scenario, the environmental impacts have a cost incidence (4.1 %) higher than the seismic performance one (0.9 %), also demonstrating the importance of considering an adequate unitary carbon price towards the EU decarbonisation path, as occurred in the two last years, to achieve an effective multi-performance analysis.

The combined seismic and energy retrofit of the Case study 3 leads to a total cost reduction, expressed by means of the $R_{SSD,}$ equal to 31 % (compared to the pre-retrofit scenario) (Figure 44b).

Figure 44. Case study 3 - STEP IV results for the pre- and post-retrofit scenarios



Source: JRC

4.2.4 Application of the SSD methodology to Case study 4

The application of the four steps of the SSD methodology to the Case study 4, which refers to the masonry cultural/monumental building, namely the city hall of Barisciano (Section 4.1.3.4), is described in the following for both the pre- and post-retrofit scenarios of the building, along with the corresponding results.

4.2.4.1 STEP I – Energy performance assessment

The **STEP I** of the SSD methodology deals with the Energy performance assessment. The monthly operational energy consumptions of the investigated building and the corresponding annual results in terms of both electricity (i.e. appliance use, lighting, DHW production, and cooling), and natural gas (i.e. heating) during the use phase of the life cycle of the building have been computed for both the pre- and post-retrofit scenario.

In relation to the **pre-retrofit scenario**, monthly and annual operational energy consumption results are provided in Table 28.

The annual operational energy consumptions in terms of electricity and natural gas result equal to 103.55 KWh/m^2y and 144.72 KWh/m^2y, respectively. The latter corresponds to a natural gas consumption equal to 15.07 m^3/m^2y, based on the calorific value of natural gas. Finally, the total energy consumptions in terms of electricity ($Q_E^{Electricity}$) and natural gas (Q_E^{Gas}) during the use phase of the building are computed according to Equations (8) and (9), as follows:

$$Q_E^{Electricity} = 103.55\ \frac{kWh}{m^2 year} \cdot 984.32\ m^2\ \cdot 50\ years = 5096097.90\ kWh$$

$$Q_E^{Gas} = 144.72\ \frac{kWh}{m^2 year} \cdot 984.32\ m^2\ \cdot 50\ years = 7122539.52\ kWh$$

In the pre-retrofit scenario, the Case study 4 accounts for a total annual operational energy consumption (i.e. electricity plus natural gas) equal to 248.3 KWh/m^2y, with a corresponding consumption during its use phase equal to 12218809.83 kWh.

Table 28. Case study 4 – Annual operational energy consumption of the pre-retrofit building

PRE-RETROFIT SCENARIO					
Month	Electricity				Natural Gas
	Appliance use (kWh/m^2)	Lighting (kWh/m^2)	DHW (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)
January	1.44	2.83	0.14	0.00	34.51
February	1.26	2.50	0.12	0.00	25.93
March	1.33	2.60	0.13	0.00	20.32
April	1.38	2.71	0.14	0.07	9.21
May	1.44	2.87	0.14	2.54	1.08
June	1.27	2.45	0.12	8.14	0.04
July	1.43	2.72	0.14	17.42	0.00
August	1.38	2.62	0.13	14.56	0.00
September	1.32	2.51	0.13	10.01	0.06
October	1.44	2.87	0.14	0.80	4.90
November	1.33	2.62	0.13	0.00	16.01
December	1.38	2.67	0.14	0.00	32.68
Annual consumption (kWh/m^2y)	**16.42**	**31.98**	**1.61**	**53.54**	**144.72**

In relation to the **post-retrofit scenario**, monthly and annual operational energy consumption results are provided in Table 29.

The total annual operational energy consumptions in terms of electricity and natural gas result equal to 55.35 KWh/m^{2}y and 60.17 KWh/m^{2}y, respectively. The latter corresponds to a natural gas consumption equal to 6.27 m^3/m^{2}year, based on the calorific value of natural gas. Finally, the total energy consumptions in terms of electricity ($Q_E^{Electricity}$) and natural gas (Q_E^{Gas}) during the use phase of the building are computed according to Equations (8) and (9), as follows:

$$Q_E^{Electricity} = 55.35 \frac{kWh}{m^2 year} \cdot 984.32\ m^2\ \cdot 50\ years = 2723992.33\ kWh$$

$$Q^{Gas} = 60.17\ \frac{kWh}{m^2 year} \cdot 984.32\ m^2\ \cdot 50\ years = 2961326.72\ kWh$$

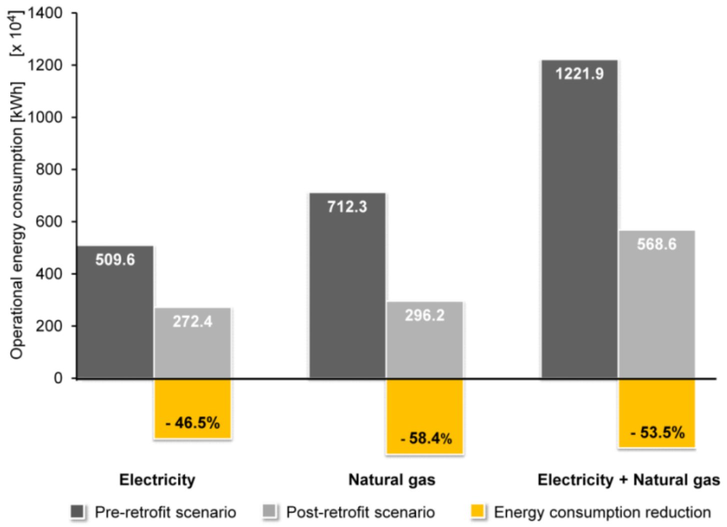
In the post-retrofit scenario, the Case study 4 accounts for a total annual operational energy consumption (i.e. electricity plus natural gas) equal to 113.52 KWh/m^{2}year, with a corresponding consumption during the use phase equal to 5685529.61 kWh.

Table 29. Case study 4 – Annual operational energy consumption of the post-retrofit building

POST-RETROFIT SCENARIO					
Month	Electricity				Natural Gas
	Appliance use (kWh/m^2)	Lighting (kWh/m^2)	DHW (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)
January	1.44	2.83	0.14	0.00	13.71
February	1.26	2.50	0.12	0.00	10.61
March	1.33	2.60	0.13	0.00	8.67
April	1.38	2.71	0.14	0.00	4.49
May	1.44	2.87	0.14	0.13	0.77
June	1.27	2.45	0.12	0.70	0.04
July	1.43	2.72	0.14	2.11	0.00
August	1.38	2.62	0.13	1.59	0.00
September	1.32	2.51	0.13	0.79	0.05
October	1.44	2.87	0.14	0.02	2.36
November	1.33	2.62	0.13	0.00	6.60
December	1.38	2.67	0.14	0.00	12.88
Annual consumption (kWh/m^{2}year)	**16.42**	**31.98**	**1.61**	**5.34**	**60.17**

The comparison of the **STEP I results** between the pre- and post- retrofit scenario of the Case study 4 (Figure 45) underlines that the total energy consumptions in terms of electricity and natural gas related to the post-retrofit scenario account for reductions equal to 46 % and 58 %, respectively, due to the corresponding energy reductions for space cooling and heating, based on the efficacy of energy retrofit interventions (Section 4.1.3.4). Hence, a total reduction of the operational energy consumption (i.e. electricity plus natural gas) equal to 53.4 % features the examined residential building in the post-retrofit scenario.

Figure 45. Case study 4 - STEP I results for the pre- and post-retrofit scenarios



Source: JRC

4.2.4.2 STEP II – Environmental performance assessment (LCA)

The **STEP II** of the SSD methodology focuses on the environmental performance assessment by applying the LCA methodology to evaluate the carbon footprint produced by the structural system and non-structural components of the investigated building for both the pre- and post-retrofit scenario.

In relation to the **pre-retrofit scenario**, the quantity of materials of both structural and non-structural components of the building and their corresponding GHG emissions, expressed in tonnes of CO_2-equivalent emissions (tCO_2eq), related to the production phase of the life cycle of the building, are reported in Table 30.

The structural elements contribute to the highest environmental impacts related to the GWP with the load-bearing walls made of concrete blocks producing the highest amount of GHG emissions, i.e. 90.7 tCO_2eq. The total amount of GHG emissions related to the production phase, due to both structural elements and non-structural components, results equal to 166.37 tCO_2eq in the pre-retrofit scenario.

Table 30. Case study 4 – LCA results related to GWP for the pre-retrofit scenario (Production phase – Module A1-A3)

Component		Material	Quantity	Unit	GWP100 [tCO_2eq]
Structural elements	Load-bearing walls	Rubble masonry	550	m^3	5.3
		Concrete blocks	360	m^3	90.7
		Limestone blocks	25	m^3	0.2
	Floors	/	720	m^2	44.06
	Roof	Timber	30	m^3	7.06
Total (Structural components)					147.32
Non-structural components	Partition walls	Masonry	1.35	m^3	0.13
	Windows	Aluminium and glass	138	m^2	16.69
	Roof tiles	Brick	145	m^2	2.23
Total (Non-structural components)					19.05
Total GWP100 (Pre-retrofit scenario)					166.37

In relation to the **post-retrofit scenario**, the quantity of materials of both structural elements and non-structural components for the seismic and energy retrofit interventions of the building and their corresponding GHG emissions, related to the production phase of the building life cycle, are summarised in Table 31.

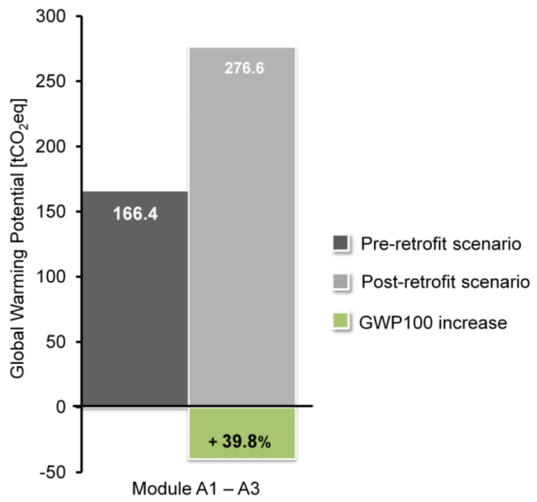
The seismic retrofit interventions produce a higher total amount of GHG emissions, i.e. 93.5 tCO2eq, than the energy retrofit ones. The total amount of GHG emissions due to both seismic and energy retrofit is equal to 110.2 tCO_2eq. In order to compute the final result of the environmental performance of the building in terms of GWP related to the post-retrofit scenario, the amount of GHG emissions produced by the adopted seismic and energy retrofit technologies needs to be added to the total result of the GWP related to the pre-retrofit scenario. Hence, the total amount of GHG emissions related to the production stage of both the building components and retrofit technologies results equal to 276.57 tCO_2eq in the post-retrofit scenario.

Table 31. Case study 4 - LCA results related to GWP for the post-retrofit scenario (Production phase – Module A1-A3)

Retrofit intervention		Material	Quantity	Unit	GWP100 [tCO_2eq]
Seismic retrofit	Local strengthening	Masonry	279.5	m^2	28.9
		Concrete	255.9	m^3	64.6
Total (Seismic retrofit)					93.5
Energy retrofit	Window replacement	Aluminium and glass	138	m^2	16.7
Total (Energy retrofit)					16.7
Total GWP100 (Seismic + Energy retrofit)					110.2
Total GWP100 (Post-retrofit scenario)					276.57

The comparison of the **STEP II results** between the pre- and post-retrofit scenarios of the case study 4 (Figure 46) indicates that a GWP increase equal to 40 % features the city hall building in the post-retrofit scenario.

Figure 46. Case study 4 - STEP II results for the pre- and post-retrofit scenarios



Source: JRC

4.2.4.3 STEP III - Structural performance assessment

The **STEP III** of the SSD methodology deals with the Structural performance assessment, based on the four main steps of the s-PBA methodology, as follows:

— *Step 1 - Definition of damage limit states* - The damage limit states can be correlated to suitable IDR values. In this case, the identification of the limit states is correlated to the attainment of displacements, identified on the capacity curve carried out by means of the pushover analysis, to obtain the corresponding IDR values, as follows:

- *Low damage limit state* - This limit state is characterised by damage initiating to non-structural elements, first affecting internal partitions walls, along with windows in the storey subjected to the maximum IDR. This limit state is attained when the maximum displacement reaches the value 0.7 δ_y, being δ_y the yielding displacement.

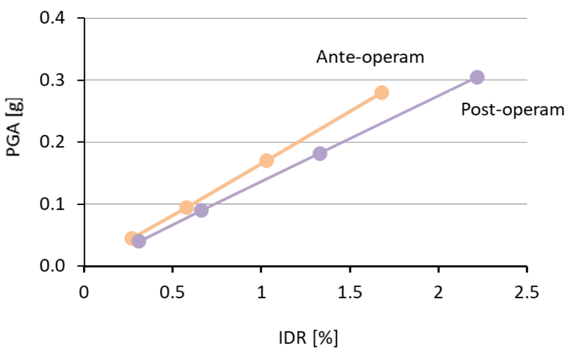
- *Heavy damage limit state* - The damage occurs into all non-structural elements, mainly affecting partition walls and windows located at all levels of the building, as well as the perimeter rubble masonry walls located at the storey with the maximum IDR, thus requiring repair interventions. This limit state is attained when the maximum displacement reaches the value 1.5 δ_y.

- *Severe damage limit state* - This limit state is based on the no-collapse requirement of the structural system of the building hit by the earthquake. Hence, all non-structural elements exhibit damages, thus needing their replacement. Moreover, rubble masonry walls also exhibit damages, thus requiring retrofit. This limit state is attained when the maximum displacement reaches the value 0.5 (δ_y + δ_u), being δ_u the ultimate displacement of the building.

- *Near collapse Limit state* - This limit state corresponds to the full exploitation of the deformation capacity of structural elements. Hence, all non-structural and structural elements of the building result into extensive damages. This limit state is reached when the maximum displacement results equal to δ_u.

— *Step 2 - Structural analysis* - The PGA values corresponding to the attainment of the IDR values identified by means of the Step 1 are obtained by pushover analyses and the relation between the PGA values and IDR ones for both pre- and post-retrofit scenario are reported in Figure 47.

Figure 47. Case study 4 – PGA vs IDR diagrams



— Source: JRC *Step 3 - Hazard analysis* - Based on the PGA values obtained in the Step 2, the corresponding T_R values are first computed, according to Equation (10), to subsequently calculate the probability of exceedance in 50 years (i.e. service life of an ordinary building) (R_{50}), according to Equation (11), for both the pre- and post-retrofit scenario.

— *Step 4 - Cost analysis* - The repair interventions and the corresponding costs for each limit state are first computed according to the official 'Public works price list of Abruzzo region', due to the location of the examined building. Specifically, as for the *low damage limit state*, the repair interventions consist in the demolition and reconstruction of the damaged internal partition walls, as well as the replacement of windows related to the storey with the maximum IDR, leading to a total repair cost equal to 10.9 k€. In relation to the *heavy damage limit state*, the repair interventions considered in the previous limit state need to be applied to all partition walls and windows of the building, along with the retrofit of the perimeter rubble masonry walls related to the storey exhibiting the maximum IDR, for a total repair cost equal to 46.7 k€. As for the *severe damage limit state*, the repair refers to the same interventions provided in the heavy damage limit state, along with the retrofit of all the perimeter rubble masonry walls, thus accounting for a repair cost equal to 66.9 k€. Finally, with regard to the *near collapse limit state*, the demolition and reconstruction strategy was excluded due to the monumental/cultural value of the building. Hence, a seismic retrofit including the interventions indicated in Section 4.1.3.4 was considered as repair option for the building in both the pre- and post-retrofit scenarios, leading to a cost equal to 619.7 k€. Based on the aforementioned costs for each limit state (C_i), the corresponding losses (L_i) are calculated for the pre- and post-retrofit scenarios to subsequently achieve the total expected losses in both scenarios, i.e. the STEP III results, according to Equation (12).

The results of each step of the s-PBA methodology above, along with the total expected losses for the pre- and post-retrofit scenarios are reported in Table 32 and 33, respectively.

In the **pre-retrofit scenario**, the Case study 4 accounts for a total expected loss due to seismic damage equal to 85.9 k€ (Table 32).

Table 32. Case study 4 - Results of the s-PBA methodology and total expected loss of the pre-retrofit building.

PRE-RETROFIT SCENARIO						
Step 1		*Step 2*	*Step 3*		*Step 4*	
Limit state	IDR [%]	PGA [g]	T_R [years]	R_{50} [%]	C_i [€]	L_i [€]
1 - Low damage	0.27	0.045	11	99.3	10914	3264.66
2 - Heavy damage	0.58	0.095	43	69.4	46789	19483.26
3 - Severe damage	1.03	0.170	155	27.7	66958	13158.05
4 - Near collapse	1.68	0.280	595	8.1	619792	50003.50
					Total expected loss (€)	85909.47

In the **post-retrofit scenario**, the Case study 4 accounts for a total expected loss due to seismic damage equal to 76.9 k€ (Table 33).

Table 33. Case study 4 - Results of the s-PBA methodology and total expected loss of the post-retrofit building.

POST-RETROFIT SCENARIO						
Step 1		*Step 2*	*Step 3*		*Step 4*	
Limit state	IDR [%]	PGA [g]	T_R [years]	R_{50} [%]	C_i [€]	L_i [€]
1 - Low damage	0.31	0.040	9	99.8	10914	2927.98
2 - Heavy damage	0.66	0.090	39	73.0	46789	22896.36
3 - Severe damage	1.33	0.182	182	24.0	66958	11847.45
4 - Near collapse	2.22	0.305	763	6.3	619792	39323.54
					Total expected loss (€)	76995.32

The comparison of the **STEP III results** between the pre- and post- retrofit scenario underlines that the total expected loss related to the post-retrofit scenario accounts for a reduction equal to 10.4 % due to the efficacy of the proposed seismic retrofit interventions.

4.2.4.4 Step IV - Global assessment parameter in economic terms

The **STEP IV** of the SSD methodology deals with the combination of the results, carried out by the previous three steps, into a single global assessment parameter in economic terms. To this end, the energy and environmental performance results are first transformed into costs, as follows:

— **Conversion of operational energy into cost** - The total operational energy in terms of electricity and natural gas during the use phase of the examined building for both the pre- and post-retrofit scenario (results obtained by STEP I) is converted into cost by retrieving the unitary prices of electricity and natural gas for non-household consumers in Italy in 2019 (second semester of the year). Specifically, the electricity price is equal to 0.186 €/KWh (referred to the annual consumption band IB - 20 MWh < consumption < 500 MWh, based on the case study results) (Eurostat, 2020d), whereas the natural gas price results equal to 0.060 €/KWh (referred to the annual consumption band I1 < 1000 GJ, based on the case study results) (Eurostat, 2020f). It is worth noting that the selected prices already include taxes, except from VAT. Hence, the energy costs due to electricity and natural gas are computed according to Equations (13) and (14) for both the pre- and post-retrofit scenario, as follows:

$$R_E^{Electricty} = 5096097.90\ kWh \cdot 0.186\ \frac{€}{kWh} = 947.8\ k€$$

Pre-retrofit scenario

$$R_E^{Gas} = 7122539.52\ kWh \cdot 0.060\ \frac{€}{kWh} = 430.9\ k€$$

$$R_E^{Electricty} = 2723992.33\ kWh \cdot 0.186\ \frac{€}{kWh} = 506.6\ k€$$

Post-retrofit scenario

$$R_E^{Gas} = 2961326.72\ kWh \cdot 0.060\ \frac{€}{kWh} = 177.7\ k€$$

Based on these results, the final costs for the operational energy consumption (R_E) are computed according to Equation (15), resulting equal to 1378.7 k€ and 684.3 k€ for the pre- and post-retrofit scenario, respectively.

— **Conversion of the environmental impacts into cost -** The GWP in terms of total amount of GHG emissions of the examined building for both the pre- and post-retrofit scenario (results obtained by STEP II) is converted into cost by means of the unitary carbon price retrieved from the EEX, which provides the EUA price based on the EU ETS cap and trade mechanism, as described in Section 2.1.4.1. Specifically, the EUA spot price observed on the 24th March 2022 is considered; it is equal to 76.50 €/tCO_2eq. Hence, the environmental costs due to GWP are computed according to the Equation (16) for both the pre- and post-retrofit scenario, as follows:

Pre-retrofit scenario $$R_{CO2} = 166.4\ tCO_2eq \cdot 76.50\ \frac{€}{tCO_2eq} = 12729.6\ €$$

Post-retrofit scenario $$R_{CO2} = 276.6\ tCO_2eq \cdot 76.50\ \frac{€}{tCO_2eq} = 21159.9\ €$$

The operational energy (R_E) and environmental (R_{CO2}) costs above can be summed up to the structural costs (i.e. total expected losses) (L) in order to obtain the global assessment parameter in economic terms (R_{SSD}), according to Equation (17) for both the pre- and post-retrofit scenario, as reported in Table 34 and depicted in Figure 48a.

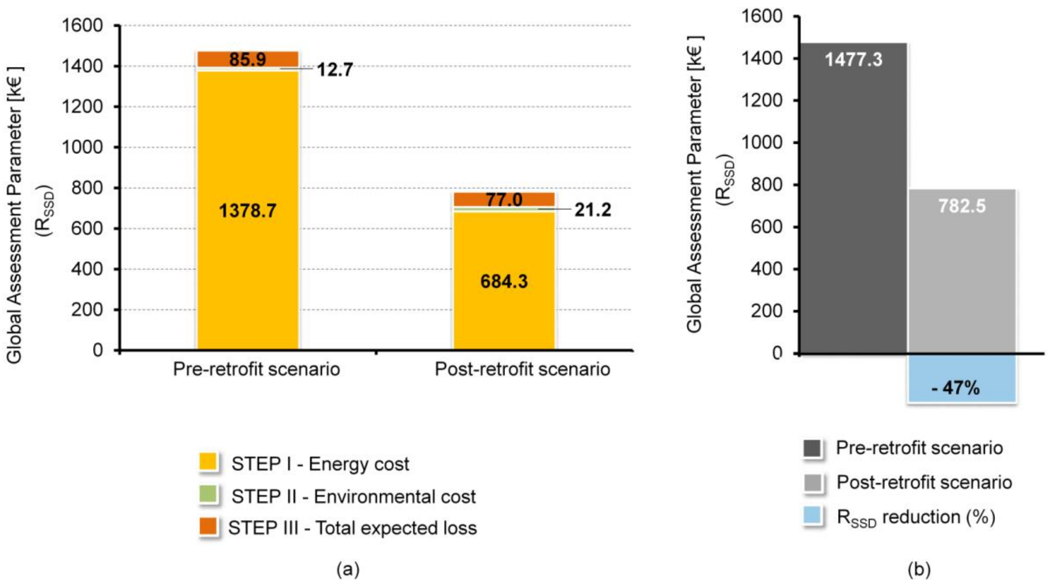
Table 34. Case study 4 – Calculation of the Global Assessment Parameter (R_{SSD})

Results in economic terms			Pre-retrofit Scenario		Post-retrofit Scenario	
STEP I - Energy cost	R_E	[€]	1378700	93.3%	684300	87.5%
STEP II - Environmental cost	R_{CO2}	[€]	12729.6	0.9%	21159.9	2.7%
STEP III - Total expected loss	L	[€]	85909.5	5.8%	76995.3	9.8%
STEP IV - Global assessment parameter	R_{SSD}	[€]	1477339.1	100%	782455.2	100%

The comparison of the **STEP IV results** underline that in both scenarios the energy performance exhibits the highest cost incidence of the total result, accounting for more than 93 % and 87 % of the R_{SSD} in the pre- and post-retrofit scenario, respectively. In the pre-retrofit scenario, the energy cost incidence is followed by the seismic (5.8 %) and environmental (0.9 %) performance ones. Similarly, in the post-retrofit scenario the cost incidence of the seismic performance is higher than the environmental one.

The combined seismic and energy retrofit of the Case study 4 leads to a total cost reduction, expressed by means of the R_{SSD}, equal to 47 % (compared to the pre-retrofit scenario) (Figure 48b).

Figure 48. Case study 4 - STEP IV results for the pre- and post-retrofit scenarios



Source: JRC

4.2.5 Remarks on the application of the SSD methodology to the four case studies

The four case-studies differ each other in terms of various factors, including geometric and structural features (e.g. structural system, construction technologies, etc.), building use, seismic hazard and climatic zone parameters, seismic and energy retrofit technologies applied, in order to cover a wide range of the most spread and representative EU existing buildings. However, a common target of the application of a standard combined assessment method, i.e. SSD methodology, refers to the evaluation of the seismic and energy performances of the four case studies after a combined retrofit intervention.

Based on the results carried out for each step of the SSD methodology, it is possible to note the combined retrofit benefits in economic terms. Specifically, the reduction of the energy consumptions due to the energy retrofit interventions for the case studies 1, 2, 3, and 4 leads to a corresponding cost reduction, compared to the non-retrofitted buildings, equal to 23 %, 37 %, 28 %, and 50 %, respectively. Similarly, the seismic retrofit interventions enable a reduction of the expected losses due to seismic damages for the case studies 1, 2, 3, and 4 equal to approximately 98 %, 95 %, 92 %, and 10 %, respectively. Although the energy and seismic retrofit technologies lead to an increase of the environmental costs for all the four case studies compared to the non-retrofitted buildings, as the LCA only refers to the production phase of the building life cycle, a total cost reduction taking into account the energy, environmental, and seismic performances of the case studies 1, 2, 3, and 4, expressed through the global assessment parameter R_{SSD}, is achieved for all the four case studies. Specifically, the latter corresponds to a total monetary reduction for the case studies 1, 2, 3, and 4 equal to 42 %, 41 %, 31 %, and 47 %, respectively.

4.3 Application of the proposed simplified combined assessment method to the four case studies

The four case studies are subsequently analysed by means of the proposed simplified combined assessment method (Section 3.2). The data collection related to the *Step 1* and the selection of seismic and energy retrofit technologies related to the *Step 2* were previously identified to carry out the application of the SSD methodology (see Section 4.1.3 for specific details). Hence, attention is drawn on the *Step 3 - Integrated retrofit design and evaluation* of the proposed method since it represents the computational step to assess the seismic, energy, and environmental performance of a building needing retrofit at three stages of its 'new' life cycle: (i) initial time (t_0) – i.e. time of the retrofit intervention, (ii) extended lifetime stage (t_{ext}), and (iii) end-of-life time (t_{end}). Results of each performance assessment are expressed as equivalent costs in order to provide the equivalent economic performance assessment corresponding to three main total cost contributions associated with each of three time stages above to finally build the equivalent Total Life Cycle Cost vs Time curve. The latter represents the variation of the equivalent economic performance over time by representing the economic results for each of the three time stages, i.e. t_0, t_{ext}, and t_{end}, indicating the initial economic investment for the combined retrofit, its recovery and the annual economic savings, and the end-of-life cost, also including the potential benefits due to the recycle and/or reuse of materials and components, respectively.

Details of the application of the Step 3 of the proposed simplified combined assessment method to the four case studies are provided in the following (see Section 3.2.3 for both a detailed description of the Step 3 framework, summarised in Figure 18, and the references to the equations used for the computation of the corresponding results).

4.3.1 Application of the Step 3 of the simplified method to Case study 1

The application of the Step 3 of the proposed simplified combined assessment method to the Case study 1, which refers to the RC residential building located in Toscolano Maderno (Section 4.1.3.1), is described in the following along with the corresponding results related to each of the three stages of the 'new' lifetime of the retrofitted building and the final outcome in terms of Total Life Cycle Cost.

4.3.1.1 Performance assessment at the initial time (t_0)

The assessment of the **seismic** and **energy performances** at the initial time (t_0) corresponds to the computation of the initial costs of the seismic (IC_S), and energy (IC_E) retrofit interventions. Specifically, the ICs and the IC_E are computed according to the official Italian 'Public works price list of Lombardia region', resulting equal to 463 €/m^2 and 400 €/m^2, respectively.

The assessment of the **environmental performance** at the initial time (t_0) is carried out according to the two-step approach introduced in Section 3.2.3.3 to compute the initial cost for the environmental impact (IC_{EI}). According to the $Step_{(EI)}$ 1, the amount of GHG emissions related to the production stage (Module A1-A3) of the seismic and energy retrofit technologies is first computed by referring to the corresponding results of the LCA carried out within the application of the SSD methodology, equal to 114.66 tCO_2eq (Table 10). Subsequently, according to the $Step_{(EI)}$ 2, the environmental output is converted into equivalent cost by means of the monetary conversion factor $CF_{CO2,M}$ (i.e. the EUA spot price observed on 24 March 2022 from EEX, equal to 76.50 €/tCO_2eq, was selected), leading to an IC_{EI} equal to 12.4 €/m^2

The **equivalent total initial cost** (Total IC_{eq}, expressed in €/m^2) at the **time t_0** is computed according to Equation (19), based on the aforementioned results related to the seismic, energy, and environmental performances and reported in Table 35.

Table 35. Case study 1 – Results related to the initial time (t_0)

Initial time (t_0)	Seismic performance	Energy performance	Environmental performance	Equivalent economic performance
	IC_S [€/m^2]	IC_E [€/m^2]	IC_{EI} [€/m^2]	Total IC_{eq} [€/m^2]
	463	400	12.4	875.4

4.3.1.2 Performance assessment at the extended lifetime stage (t_{ext})

The assessment of the **seismic performance** at the extended lifetime stage (t_{ext}) is carried out according to the four-step approach introduced in Section 3.2.3.1 to compute the expected annual losses for seismic damage (EAL_S).

Table 36 and 37 indicate the outcomes of the $Step_{(S)}$ 1 and 2, respectively, dealing with the identification of the RBC and the classification of the compatible SRT. Specifically, based on the data related to the year of construction and geometric details of the Case study 1 (see Section 4.1.3.1), the corresponding RBC is selected according to the classification parameters reported in Table 3. Similarly, based on the selected SRT, its corresponding classification is provided according to the parameters reported in Table 4.

Table 36. Case study 1 - Outcomes of $Step_{(S)}$1 related to the identification of the RBC

$RBC_{(N-i)}$	Construction period	Geometric details			
		Storey [No]	Interstorey height [m]	Gross floor area [m^2]	Window to wall ratio [%]
Structural typology Reinforced concrete	1946-1971	Low-rise (1 ÷ 3)	2.50 ÷ 3.50	350 ÷ 750	10 ÷ 19
Case study 1 data ([1])					
Residential building in Toscolano Maderno	1967	3	Block A / Block B 3.06 / 3.10 3.15 / 2.95	708.3	10

([1]) See Section 4.1.3.1 for a full description of the building.

Table 37. Case study 1 - Outcomes of $Step_{(S)}$ 2 related to the classification of the SRT

$SRT_{(N-i)}$	Application level of retrofit intervention	Performance parameter	Mechanical behaviour
$RBC_{(N-1)}$ Reinforced concrete	Global	PGA_C/PGA_D > 40%	Enhance global strength and stiffness

Based on the outcomes above, the seismic performance of the Case study 1 in its pre- and post-retrofit scenario is assessed according to the $Step_{(S)}$ 3 to define the GP_S (PGA) for the identified RBC of the Case study 1 and its selected SRT. The GP_S (PGA) are provided in terms of fragility curves characterised by the mean value μ and the standard deviation σ of the lognormal distribution functions for each damage state DS_i (Table 38) to subsequently compute the corresponding EAL_S, according to the $Step_{(S)}$ 4. Specifically, the EAL_S related to the pre- ($EAL_{S,0}$) and post-retrofit (EAL_S) scenario result equal to 43.26 €/m^{2}year and 13.11 €/m^{2}year, respectively.

Table 38. Case study 1 - Parameters of fragility curves for pre- and post-retrofit scenarios

Scenario		DS_1	DS_2	DS_3	DS_4	DS_5
Pre-retrofit	μ	0.02	0.11	0.04	0.18	0.23
	σ	0.32	0.24	0.32	0.13	0.09
Post-retrofit	μ	0.02	0.11	0.16	0.26	0.28
	σ	0.33	0.25	0.29	0.16	0.14

The assessment of the **energy performance** at the extended lifetime (t_{ext}) is carried out according to the four-step approach introduced in Section 3.2.3.2 to compute the expected annual cost for energy consumption (EAC_E).

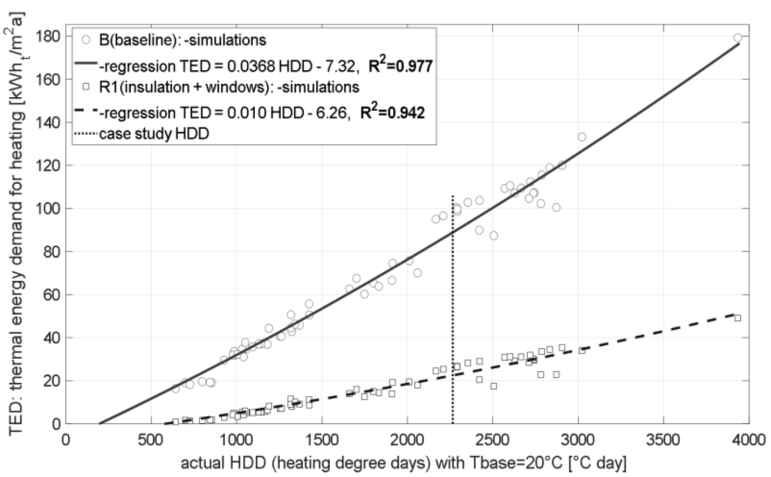
The outcomes of the $Step_{(E)}$ 1 are the same ones presented in Table 36 within the framework of the seismic performance assessment. Table 39 indicates the outcomes of the $Step_{(E)}$ 2 dealing with the classification of the ERT compatible with the identified RBC. Based on the selected ERT, its corresponding classification is provided according to the parameters reported in Table 5.

Table 39. Case study 1 - Outcomes of $Step_{(E)}$ 2 related to the classification of the ERT

$ERT_{(N-i)}$	Application level of retrofit intervention	Performance parameter	Thermal behaviour
RBC $_{(N-1)}$ Reinforced concrete	Envelope and HVAC systems	PEC < 15%	Low thermal transmittance Systems efficiency

Based on the outcomes above, the energy performance of the examined building in its pre- and post-retrofit scenario is assessed according to the $Step_{(E)}$ 3 to define the GP_E (HDD) for the identified RBC of the Case study 1 and its compatible ERT. The GP_E (HDD) are provided in terms of TED_h vs HDD curves (Figure 49) to subsequently compute the corresponding EAC_E, according to the $Step_{(E)}$ 4. It is worth nothing that the conversion of the TED_h result in PEC to be subsequently transformed into equivalent costs by means of PEFs is obtained directly by applying the EMAR procedure, as described in Section 3.2.3.2. Specifically, the EAC_E related to the pre- ($EAC_{E,0}$) and post-retrofit (EAC_E) scenarios result equal to 23.02 €/m^{2}year and 5.68 €/m^{2}year, respectively.

Figure 49. Case study 1 - TED_h vs HDD curve



The assessment of the **environmental performance** at the extended lifetime (t_{ext}) is carried out according to the two-step approach introduced in Section 3.2.3.3 to compute the expected annual cost for the environmental impact (EAC_{EI}).

According to the Step$_{(EI)}$ 1, the annual amount of GHG emissions due to both seismic damage and energy consumption are first defined. Subsequently, according to the Step$_{(EI)}$ 2, the environmental output is converted into cost by means of the monetary conversion factor $CF_{CO2,M}$ (i.e. the EUA spot price observed on 24 March 2022 from EEX, equal to 76.50 €/tCO_2eq, was selected). Specifically, the EAC_{EI} related to the pre- ($EAC_{EI,0}$) and post-retrofit (EAC_{EI}) scenario result equal to 9 €/m^{2}year and 2.9 €/m^{2}year, respectively.

Once the aforementioned results of the seismic, energy, and environmental performances are carried out for both the pre- and post-retrofit scenario, they are combined into the corresponding $IRPP_0$ and $IRPP_R$ according to Equation (20) and (21), respectively, to subsequently calculate the **equivalent total extended lifetime cost** (ΔIRPP, expressed in €/m^{2}year and indicating the annual economic savings due to retrofit) at the **time t_{ext},** according to Equation (22) and reported in Table 40. Hence, a cost reduction between the pre- and post-retrofit scenario equal to 71 % is obtained.

Table 40. Case study 1 – Results related to the extended lifetime (t_{ext}) stage

	Seismic performance	Energy performance	Environmental performance	Equivalent economic performance
Extended lifetime (t_{ext})	$EAL_{S,0}$ [€/m^{2}year]	$EAC_{E,0}$ [€/m^{2}year]	EAC_{EI} [€/m^{2}year]	$IRPP_0$ [€/m^{2}year]
	43.26	23.02	9.0	75.28
	EAL_S [€/m^{2}year]	EAC_E [€/m^{2}year]	EAC_{EI} [€/m^{2}year]	$IRPP_R$ [€/m^{2}year]
	13.11	5.68	2.9	21.69
			ΔIRPP [€/m^{2}year]	53.59

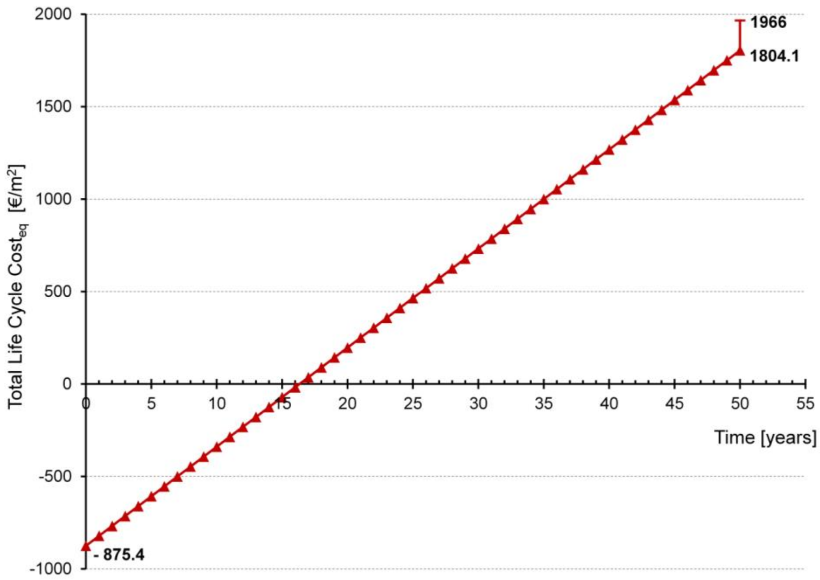
4.3.1.3 Performance assessment at the end of life time (t_{end})

The **equivalent total end-of-life cost** (Total $EOLC_{eq}$, expressed in €/m^2) at the **time t_{end}** is computed according to Equation (23), referring to the cost for dismantling the seismic and energy retrofit technologies, plus the equivalent cost related to the amount of GHG emissions for the end-of-life phase of building life cycle (i.e. Module C and D). The environmental benefits achieved by means of recycle of materials of retrofit technologies, based on EPD documents, lead to a total $EOLC_{eq}$ equal to −161.9 €/m^2, thus indicating economic savings due to the reduced environmental impacts.

4.3.1.4 Total equivalent economic performance

The three total equivalent cost contributions are combined to build the equivalent 'Total Life Cycle Cost vs Time' curve, according to Equation (24), considering a lifetime of the retrofitted building equal to 50 years and the absence of fiscal incentives. The representative curve related to the Case study 1 (Figure 50) starts with a negative value of equivalent cost, corresponding to the Total IC_{eq}, which indicates the initial economic investment at the time t_0 = 0 (i.e. first term of the second member of Equation 24). Subsequently, the curve progresses towards the positive quadrant of the graph since the annual economic savings due to the positive effects of the combined retrofit, corresponding to the ΔIPRR, lead to the recovery of the initial investment, which is reached at the extended payback time ($t_{Payback,IPRR}$) equal to 16.3 years, when the curve crosses the Time axis. Afterwards, the curve continues to progress into the positive quadrant of the graph, indicating the effective annual economic savings, resulting into a cumulated value until the time t_{end} (i.e. 50 years) equal to 1804.1 €/m^2 (i.e. sum of the first and second term of the second member of Equation 24). Furthermore, a negative value of equivalent cost, corresponding to the Total $EOLC_{eq}$, is achieved at the time t_{end} (i.e. third term of the second member of Equation 24), thus indicating that the recycle and reuse of materials and components enable the achievement of potential 'credits' for the Case study 1, increasing the total value of the economic savings to 1966 €/m^2 at the time t_{end}.

Figure 50. Case study 1 – Representative Total Life Cycle Cost$_{eq}$ vs Time curve



Source: JRC

4.3.2 Application of the Step 3 of the simplified method to Case study 2

The application of the Step 3 of the proposed simplified assessment method to the Case study 2, which refers to the masonry residential building located in Dalmine (Section 4.1.3.2), is presented in the following along with the corresponding results related to each of the three stages of the 'new' lifetime of the retrofitted building and the final outcome in terms of Total Life Cycle Cost.

4.3.2.1 Performance assessment at the initial time (t_0)

The assessment of the **seismic** and **energy** performances at the initial time (t_0) corresponds to the computation of the initial costs of the seismic (IC_S), and energy (IC_E) retrofit interventions. Specifically, the IC_S and the IC_E are computed according to the official Italian 'Public works price list of Lombardia region', resulting equal to 258.9 €/m^2 and 237.8 €/m^2, respectively.

The assessment of the **environmental** performance at the initial time (t_0) is carried out according to the two-step approach introduced in Section 3.2.3.3 to compute the initial cost for the environmental impact (IC_{EI}). According to the Step$_{(EI)}$ 1, the amount of GHG emissions related to the production stage (Module A1-A3) of the seismic and energy retrofit technologies is first computed by referring to the corresponding results of the LCA carried out in the SSD methodology, equal to 91.45 tCO_2eq (Table 17). Subsequently, according to the Step$_{(EI)}$ 2, the environmental output is converted into cost by means of the monetary conversion factor $CF_{CO2,M}$ (i.e. the EUA spot price observed on 24 March 2022 from EEX, equal to 76.50 €/tCO_2eq, was selected), leading to a IC_{EI} equal to 8.3 €/m^2.

The **equivalent total initial cost** (Total IC_{eq}, expressed in €/m^2) at the **time t_0** is computed according to Equation (19), based on the results related to the seismic, energy, and environmental performances and reported in Table 41.

Table 41. Case study 2 – Results related to the initial time (t_0)

Initial time (t_0)	Seismic performance	Energy performance	Environmental perfomance	Equivalent economic performance
	IC_S [€/m^2]	IC_E [€/m^2]	IC_{EI} [€/m^2]	Total IC_{eq} [€/m^2]
	258.9	237.8	8.3	505

4.3.2.2 *Performance assessment at the extended lifetime stage (t_{ext})*

The assessment of the **seismic performance** at the extended lifetime stage (t_{ext}) is carried out according to the four-step approach introduced in Section 3.2.3.1 to compute the expected annual losses for seismic damage (EAL_S).

Table 42 and 43 indicated the outcomes of the $Step_{(S)}$ 1 and 2, respectively, dealing with the identification of the RBC and the classification of the compatible SRT. Based on the data related to the year of construction and geometric details of the Case study 2 (see Section 4.1.3.2), the corresponding RBC is selected according to the classification parameters reported in Table 3. Similarly, based on the selected SRT, its corresponding classification is provided according to the parameters reported in Table 4.

Table 42. Case study 2 – Outcomes of the $Step_{(S)}$1 related to the identification of the RBC

$RBC_{(N-i)}$	Construction period	Geometric details			
		Storey [No]	Interstorey height [m]	Gross floor area [m^2]	Window to wall ratio [%]
Structural typology: Masonry	1946-1971	Low-rise (1 ÷ 3)	2.50 ÷ 3.50	350 ÷ 750	10 ÷ 19
Case study 2 ([1])					
Residential building in Dalmine	1955	3	All 3 levels = 3.20	841	10

([1]) See Section 4.1.3.2 for a full description of the building.

Table 43. Case study 2 - Outcomes of $Step_{(S)}$ 2 related to the classification of the SRT

$SRT_{(N-i)}$	Application level of retrofit intervention	Performance parameter	Mechanical behaviour
$RBC_{(N-1)}$ Masonry	Global	PGA_C/PGA_D >40%	Enhance global strength and stiffness

Based on the outcomes above, the seismic performance of the Case study 2 in its pre- and post-retrofit scenario is assessed according to the $Step_{(S)}$ 3 to define the GP_S (PGA) for the identified RBC of the case study 2 and its selected SRT. The GP_S (PGA) are provided in terms of fragility curves characterised by the mean value μ and the standard deviation σ of the lognormal distribution functions for each damage state DS_i (Table 44) to subsequently compute the corresponding EAL_S, according to the $Step_{(S)}$ 4. Specifically, the EAL_S related to the pre- ($EAL_{S,0}$) and post-retrofit (EAL_S) scenario result equal to 29.97 €/m^{2}year and 11.66 €/m^{2}year, respectively.

Table 44. Case study 2 - Parameters of fragility curves for pre- and post-retrofit scenarios

Scenario		DS_1	DS_2	DS_3	DS_4	DS_5
Pre-retrofit	μ	0.135	0.170	0.203	0.210	0.205
	σ	0.085	0.108	0.119	0.120	0.114
Post-retrofit	μ	0.246	0.454	0.994	0.994	2.332
	σ	0.175	0.323	0.707	0.707	1.659

The assessment of the **energy performance** at the extended lifetime (t_{ext}) is carried out according to the four-step approach introduced in Section 3.2.3.2 to compute the expected annual cost for energy consumption (EAC_E).

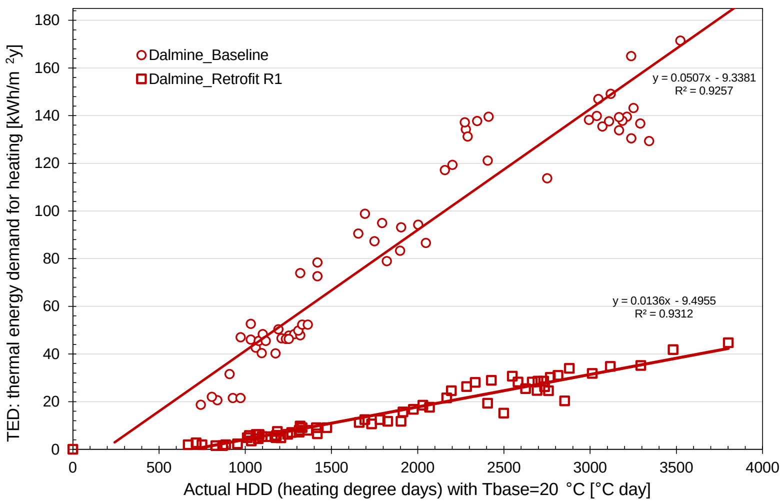
The outcomes of the $Step_{(E)}$ 1 are the same ones presented in Table 42 within the framework of the seismic performance assessment. Table 45 indicates the outcomes of the $Step_{(E)}$ 2 dealing with the classification of the ERT compatible with the identified RBC. Based on the selected ERT, its corresponding classification is provided according to the parameters reported in Table 5.

Table 45. Case study 2 - Outcomes of $Step_{(E)}$ 2 related to the classification of the ERT

$SRT_{(N-i)}$	Application level of retrofit intervention	Performance parameter	Thermal behaviour
RBC $_{(N-1)}$ Reinforced concrete	Envelope and windows	< 15%	Low thermal transmittance Glazing efficiency

Based on the outcomes above, the energy performance of the examined building in its pre- and post-retrofit scenario is assessed according to the $Step_{(S)}$ 3 to define the GP_E (HDD) for the identified RBC of the case study 2 and its compatible ERT. The GP_E (HDD) are provided in terms of TED_h vs HDD curves (Figure 51) to subsequently compute the corresponding EAC_E, according to the $Step_{(S)}$ 4. It is worth nothing that the conversion of the TED_h result in PEC to be subsequently transformed into equivalent costs by means of PEFs is obtained directly by applying the EMAR procedure, as described in Section 3.2.3.2. Specifically, the EAC_E related to the pre-retrofit ($EAC_{E,0}$) and post-retrofit (EAC_E) scenarios result equal to 19.86 €/m^{2}year and 9.96 €/m^{2}year, respectively.

Figure 51. Case study 2 - TED_h vs HDD curve



The assessment of the **environmental performance** at the extended lifetime (t_{ext}) is carried out according to the two-step approach introduced in Section 3.2.3.3 to compute the expected annual cost for the environmental impact (EAC_{EI}).

According to the $Step_{(EI)}$ 1, the expected annual amount of GHG emissions due to both seismic damage and energy consumption are first defined. Subsequently, according to the $Step_{(EI)}$ 2, the environmental output is converted into cost by means of the monetary conversion factor $CF_{CO2,M}$ (i.e. the EUA spot price observed on 24 March 2022 from EEX, equal to 76.50 €/tCO_2eq, was selected). Specifically, the EAC_{EI} related to the pre- ($EAC_{EI,0}$) and post-retrofit (EAC_{EI}) scenario result equal to 3.87 €/m^{2}year and 2.09 €/m^{2}year, respectively.

Once the aforementioned results of the seismic, energy, and environmental performances are carried out for both the pre- and post-retrofit scenario, they are combined into the corresponding $IRPP_0$ and $IRPP_R$ according to Equation (20) and (21), respectively, to subsequently calculate the **equivalent total extended lifetime cost** (ΔIRPP, expressed in €/m^{2}year and indicating the annual economic savings due to retrofit) at the **time t_{ext},** according to Equation (22) and reported in Table 46. Hence, a cost reduction between the pre- and post-retrofit scenario equal to nearly 55 % is obtained.

Table 46. Case study 2 – Assessment results related to the extended lifetime (t_{ext}) stage

	Seismic performance	Energy performance	Environmental performance	Equivalent economic performance
Extended lifetime (t_{ext})	$EAL_{S,0}$ [€/m²year]	$EAC_{E,0}$ [€/m²year]	$EAC_{EI,0}$ [€/m²year]	$IRPP_0$ [€/m²year]
	29.97	19.86	3.87	53.70
	EAL_S [€/m²year]	EAC_E [€/m²year]	EAC_{EI} [€/m²year]	$IRPP_R$ [€/m²year]
	11.66	9.96	2.09	23.71
			ΔIRPP (€/m²year)	29.99

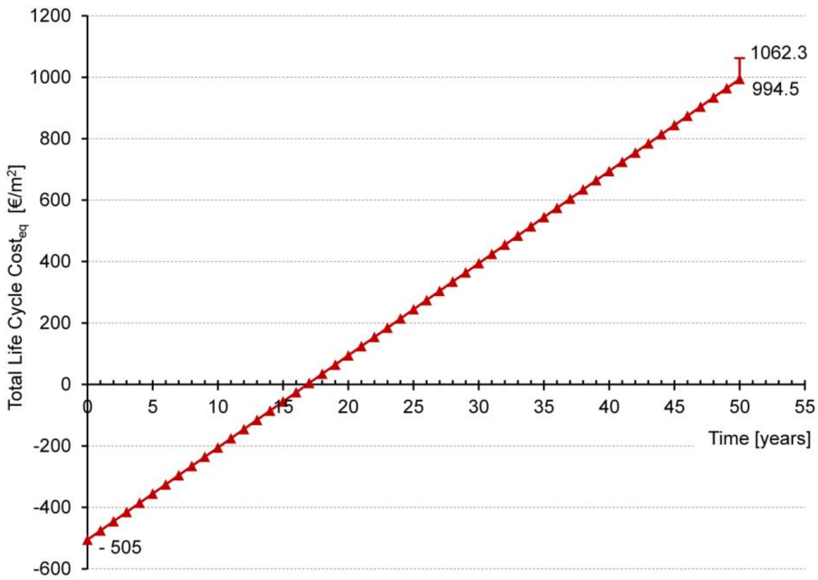
4.3.2.3 Performance assessment at the end-of-life time (t_{end})

The **equivalent total end-of-life cost** (Total $EOLC_{eq}$, expressed in €/m²) at the **time t_{end}** is computed according to Equation (23), referring to the cost for dismantling the seismic and energy retrofit technologies, plus the equivalent cost related to the amount of GHG emissions for the end-of-life phase of building life cycle (i.e. Module C and D). The environmental benefits achieved by means of recycle of materials of retrofit technologies, based on EPD documents, lead to a total $EOLC_{eq}$ equal to –67.87 €/m², thus indicating economic savings at the time t_{end} due to the reduced environmental impacts.

4.3.2.4 Total equivalent economic performance

The three total equivalent cost contributions are combined to build the equivalent 'Total Life Cycle Cost vs Time' curve, according to Equation (24), considering a lifetime of the retrofitted building equal to 50 years and the absence of fiscal incentives. The representative curve related to the Case study 2 (Figure 52) starts with a negative value of equivalent cost, corresponding to the Total IC_{eq}, which indicates the initial economic investment at the time t_0 = 0 (i.e. first term of the second member of Equation 24). Subsequently, the curve progresses towards the positive quadrant of the graph since the annual economic savings due to the positive effects of the combined retrofit, corresponding to the ΔIPRR, lead to the recovery of the initial investment, which is reached at the extended payback time ($t_{Payback,IPRR}$) equal to 16.8 years, when the curve crosses the Time axis. Afterwards, the curve continues to progress into the positive quadrant of the graph, indicating the effective annual economic savings, resulting into a cumulated value until the time t_{end} (i.e. 50 years) equal to 994.5 €/m² (i.e. sum of the first and second term of the second member of Equation 24). Furthermore, a positive value of equivalent cost, corresponding to the Total $EOLC_{eq}$, is achieved at the time t_{end} (i.e. third term of the second member of Equation 24), thus indicating that the recycle and reuse of materials and components enable the achievement of potential 'credits' for the Case study 2, increasing the total value of the economic savings to 1062.3 €/m² at the time t_{end}.

Figure 52. Case study 2 – Representative Total Life Cycle Cost$_{eq}$ vs Time curve



Source: JRC

4.3.3 Application of the Step 3 of the simplified method to Case study 3

The application of the Step 3 of the proposed simplified assessment method to the Case study 3, which refers to the RC school building 'Pietro Santini' located in Loro Piceno (Section 4.1.3.3), is described in the following along with both the corresponding results related to each of the three stages of the 'new' lifetime of the retrofitted building and the final outcome in terms of Total Life Cycle Cost.

4.3.3.1 Performance assessment at the initial time (t_0)

The assessment of the **seismic** and **energy** performances at the initial time (t_0) corresponds to the computation of the initial costs of the seismic (IC_S), and energy (IC_E) retrofit interventions. Specifically, the IC_S and the IC_E are computed according to the official Italian 'Public works price list of Marche region', resulting equal to 350 €/m^2 and 320 €/m^2, respectively.

The assessment of the **environmental** performance at the initial time (t_0) is carried out according to the two-step approach introduced in Section 3.2.3.3 to compute the initial cost for the environmental impact (IC_{EI}). According to the Step$_{(EI)}$ 1, the amount of GHG emissions related to production stage (Module A1-A3) of the seismic and energy retrofit technologies is first estimated by referring to the corresponding results of the LCA carried out in the application of the SSD methodology, equal to 169.1 tCO_2eq (Table 24). Subsequently, according to the Step$_{(EI)}$ 2, the environmental output is converted into equivalent cost by means of the monetary conversion factor $CF_{CO2,M}$ (i.e. the EUA spot price observed on 24 March 2022 from the EEX, equal to 76.50 €/tCO_2eq, was selected), leading to an IC_{EI} equal to 10.5 €/m^2.

The **equivalent total initial cost** (Total IC_{eq}, expressed in €/m^2) at the **time t_0** is computed according to Equation (19), based on the aforementioned results related to the seismic, energy, and environmental performances and reported in Table 47.

Table 47. Case study 3 – Results related to the initial time (t_0)

	Seismic performance	Energy performance	Environmental perfomance	Equivalent economic performance
Initial time (t_0)	IC_S (€/m^2)	IC_E (€/m^2)	IC_{EI} (€/m^2)	Total IC_{eq} (€/m^2)
	350	320	10.5	680.5

4.3.3.2 Performance assessment the extended lifetime stage t_{ext}

The assessment of the **seismic performance** at the extended lifetime stage (t_{ext}) is carried out according to the four-step approach introduced in Section 3.2.3.1 to compute the expected annual losses for seismic damage (EAL_S).

Table 48 and 49 indicate the outcomes of the $Step_{(S)}$ 1 and 2, respectively, dealing with the identification of the RBC and the classification of the compatible SRT. Specifically, based on the data related to the year of construction and geometric details of the Case study 3 (Section 4.1.3.3), the corresponding RBC is selected according to the classification parameters reported in Table 3. Similarly, based on the selected SRT, its corresponding classification is provided according to the parameters reported in Table 4.

Table 48. Case study 3 - Outcomes of $Step_{(S)}$1 related to the identification of the RBC

$RBC_{(N-i)}$	Construction period	Geometric details				
		Storey [No]	Interstorey height [m]	Gross floor area [m^2]	Window to wall ratio [%]
Structural typology: Reinforced concrete	1946-1971	Low-rise (1 ÷ 3)	2.50 ÷ 3.50	> 750	10 ÷ 19
Case study 3 data (1)					
'Santini' primary school	1965	3	1 level = 3.60 2 level = 3.35 3 level = 3.95	1238	10

(1) See Section 4.1.3.3 for a full description of the building.

Table 49. Case study 3 - Outcomes of $Step_{(S)}$ 2 related to the classification of the SRT

$SRT_{(N-i)}$	Application level of retrofit intervention	Performance parameter	Mechanical behaviour
$RBC_{(N-1)}$ Reinforced concrete	Global	PGA_C/PGA_D >40%	Enhance global strength and stiffness

Based on the outcomes above, the seismic performance of the Case study 3 in its pre- and post-retrofit scenario is assessed according to the $Step_{(S)}$ 3 to define the GP_S (PGA) for the identified RBC of the Case study 3 and its selected SRT. The GP_S (PGA) are provided in terms of fragility curves characterised by the mean value μ and the standard deviation σ of the lognormal distribution functions for each damage state DS_i (Table 50) to subsequently compute the corresponding EAL_S, according to the $Step_{(S)}$ 4. Specifically, the EAL_S related to the pre- ($EAL_{S,0}$) and post-retrofit (EAL_S) scenario result equal to 37.25 €/m^{2}year and 11.29 €/m^{2}year, respectively.

Table 50. Case study 3 - Parameters of fragility curves for pre- and post-retrofit scenarios

Scenario		DS_1	DS_2	DS_3	DS_4	DS_5
Pre-retrofit	μ	0.028	0.171	0.243	0.281	0.325
	σ	0.121	0.206	0.302	0.213	0.209
Post-retrofit	μ	0.102	0.221	0.315	0.527	0.598
	σ	0.083	0.225	0.328	0.415	0.514

The assessment of the **energy performance** at the extended lifetime (t_{ext}) is carried out according to the four-step approach introduced in Section 3.2.3.2 to compute the expected annual cost for energy consumption (EAC_E).

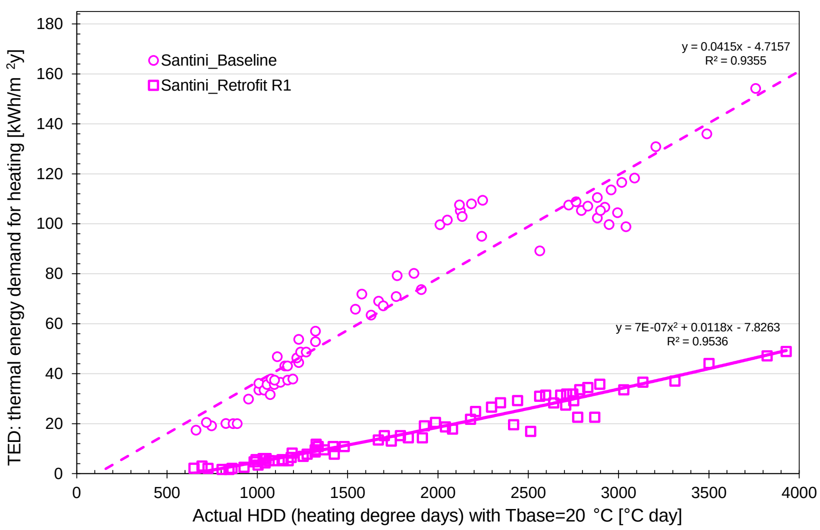
The outcomes of the $Step_{(E)}$ 1 are the same ones presented in Table 48 within the framework of the seismic performance assessment. Table 51 indicates the outcomes of the $Step_{(E)}$ 2 dealing with the classification of the ERT compatible with the identified RBC. Based on the selected ERT, its corresponding classification is provided according to the parameters reported in Table 5.

Table 51. Case study 3 - Outcomes of $Step_{(E)}$ 2 related to the classification of the ERT

$ERT_{(N-i)}$	Application level of retrofit intervention	Performance parameter	Thermal behaviour
RBC $_{(N-1)}$ Reinforced concrete	Envelope	< 15%	Low thermal transmittance

Based on the outcomes above, the energy performance of the examined building in its pre- and post-retrofit scenario is assessed according to the $Step_{(S)}$ 3 to define the GP_E (HDD) for the identified RBC of the Case study 3 and its compatible ERT. The GP_E (HDD) are provided in terms of TED_h vs HDD curves (Figure 53) to subsequently compute the corresponding EAC_E, according to the $Step_{(S)}$ 4. It is worth nothing that the conversion of the TED_h result in PEC to be subsequently transformed into equivalent costs by means of PEFs is obtained directly by applying the EMAR procedure, as described in Section 3.2.3.2. Specifically, the EAC_E related to the pre-retrofit ($EAC_{E,0}$) and post-retrofit (EAC_E) scenarios result equal to 17.81 €/m^{2}year and 9.12 €/m^{2}year, respectively.

Figure 53. Case study 3 - TED_h vs HDD curve



The assessment of the **environmental performance** at the extended lifetime (t_{ext}) is carried out according to the two-step approach introduced in Section 3.2.3.3 to compute the expected annual cost for the environmental impact (EAC_{EI}).

According to the $Step_{(EI)}$ 1, the annual amount of GHG emissions due to both seismic damage and energy consumption are defined. Subsequently, according to the $Step_{(EI)}$ 2, the environmental output is converted into cost by means of the monetary conversion factor $CF_{CO2,M}$ (i.e. the EUA spot price observed on 24 March 2022 from EEX, equal to 76.50 €/tCO_2eq, was selected). Specifically, the EAC_{EI} related to the pre- ($EAC_{EI,0}$) and post-retrofit (EAC_{EI}) scenarios result equal to 7.2 €/m^{2}year and 3.9 €/m^{2}year, respectively.

Once the aforementioned results of the seismic, energy, and environmental performances are carried out for both the pre- and post-retrofit scenario, they are combined into the corresponding $IRPP_0$ and $IRPP_R$ according to Equation (20) and (21), respectively, to subsequently calculate the **equivalent total extended lifetime cost** (ΔIRPP, expressed in €/m^{2}year and indicating the annual economic savings due to retrofit) at the **time** t_{ext}, according to Equation (22) and reported in Table 52. Hence, a cost reduction between the pre- and post-retrofit scenario equal to nearly 61 % is obtained.

Table 52. Case study 3 – Results related to the extended lifetime (t_{ext}) stage

	Seismic performance	Energy performance	Environmental performance	Equivalent economic performance
Extended lifetime (t_{ext})	$EAL_{S,0}$ [€/m²year]	$EAC_{E,0}$ [€/m²year]	$EAC_{EI,0}$ [€/m²year]	$IRPP_0$ [€/m²year]
	37.25	17.81	7.2	62.26
	EAL_S [€/m²year]	EAC_E [€/m²year]	EAC_{EI} [€/m²year]	$IRPP_R$ [€/m²year]
	11.29	9.12	3.9	24.31
			ΔIRPP [€/m²year]	37.59

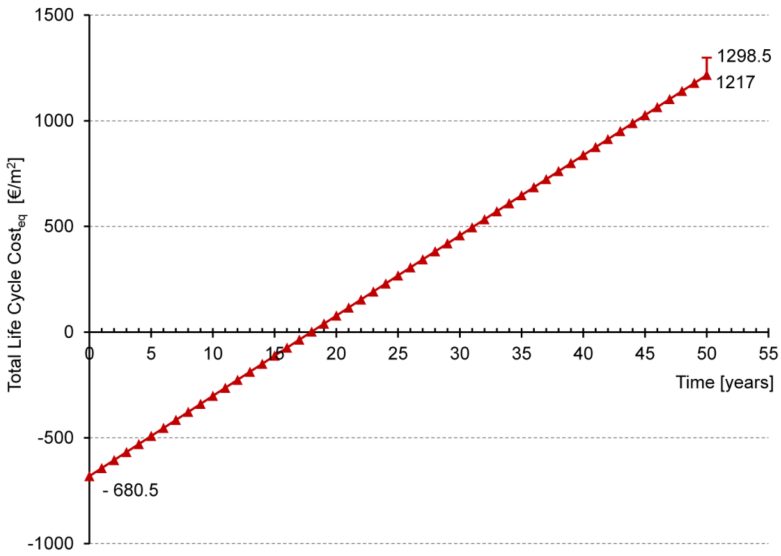
4.3.3.3 Performance assessment at the end-of-life time (t_{end})

The **equivalent total end-of-life cost** (Total $EOLC_{eq}$, expressed in €/m²) at the **time t_{end}** is computed according to Equation (23), referring to the cost for dismantling the seismic and energy retrofit technologies, plus the equivalent cost related to the amount of GHG emissions for the end-of-life phase of building life cycle (i.e. Module C and D). The environmental benefits achieved by means of recycle of materials of retrofit technologies, based on EPD documents, lead to a total $EOLC_{eq}$ equal to -81.45 €/m², thus indicating economic savings due to the reduced environmental impacts.

4.3.3.4 Total equivalent economic performance

The three total equivalent cost contributions are combined to build the equivalent 'Total Life Cycle Cost vs Time' curve, according to Equation (24), considering a lifetime of the retrofitted building equal to 50 years and the absence of fiscal incentives. The representative curve related to the Case study 3 (Figure 54) starts with a negative value of equivalent cost, corresponding to the Total IC_{eq}, which indicates the initial economic investment at the time t_0 = 0 (i.e. first term of the second member of Equation 24). Subsequently, the curve progresses towards the positive quadrant of the graph since the annual economic savings due to the positive effects of the combined retrofit, corresponding to the ΔIPRR, lead to the recovery of the initial investment, which is reached at the extended payback time ($t_{Payback,IPRR}$) equal to 17.9 years. Afterwards, the curve continues to progress into the positive quadrant of the graph, indicating the effective annual economic savings, resulting into a cumulated value until the time t_{end} (i.e. 50 years) equal to 1217 €/m² (i.e. sum of the first and second term of the second member of Equation 24). Furthermore, a positive value of equivalent cost, corresponding to the Total $EOLC_{eq}$, is achieved at the time t_{end} (i.e. third term of the second member of Equation 24), thus indicating that the recycle and reuse of materials and components of the selected retrofit technologies enable the achievement of potential credits for the Case study 3, increasing the total value of the economic savings to 1298.5 €/m² at the time t_{end}.

Figure 54. Case study 3 – Representative Total Life Cycle Cost vs Time curve



Source: JRC

4.3.4 Application of the Step 3 of the simplified method to Case study 4

The application of the Step 3 of the proposed simplified combined assessment method to the Case study 4, which refers to the masonry cultural/monumental building hosting the City Hall of Barisciano (Section 4.1.3.4), is described in the following along with the corresponding results related to each of the three stages of the 'new' lifetime of the retrofitted building and the final outcome in terms of Total Life Cycle Cost.

4.3.4.1 Performance assessment at the initial time (t_0)

The assessment of the **seismic** and **energy performances** at the initial time (t_0) corresponds to the computation of the initial costs of the seismic (IC_S), and energy (IC_E) retrofit interventions. Specifically, the IC_S and the IC_E are computed according to the official Italian 'Public works price list of Abruzzo region', resulting equal to 200 €/m^2 and 250 €/m^2, respectively.

The assessment of the **environmental performance** at the initial time (t_0) is carried out according to the two-step approach introduced in Section 3.2.3.3 to compute the initial cost for the environmental impact (IC_{EI}). According to the Step$_{(EI)}$ 1, the amount of GHG emissions related to the production stage (Module A1-A3) of the seismic and energy retrofit technologies is first computed by referring to the corresponding results of the LCA carried out within the SSD methodology, equal to 110.2 tCO_2eq (Table 31). Subsequently, according to the Step$_{(EI)}$ 2, the environmental output is converted into cost by means of the monetary conversion factor $CF_{CO2,M}$ (i.e., the EUA spot price observed on 24 March 2022 from EEX, equal to 76.50 €/tCO_2eq, was selected), leading to a IC_{EI} equal to 8.5 €/m^2.

The **equivalent total initial cost** (Total IC_{eq}, expressed in €/m^2) at the **time t_0** is computed according to Equation (19), based on the aforementioned results related to the seismic, energy, and environmental performances and reported in Table 53.

Table 53. Case study 4 – Results related to the initial time (t_0)

	Seismic performance	Energy performance	Environmental perfomance	Equivalent economic performance
Initial time (t_0)	IC_S (€/m^2)	IC_E (€/m^2)	IC_{EI} (€/m^2)	Total IC_{eq} (€/m^2)
	200	250	8.5	458.5

4.3.4.2 *Performance assessment at the extended lifetime stage (t_{ext})*

The assessment of the **seismic performance** at the extended lifetime stage (t_{ext}) is carried out according to the four-step approach introduced in Section 3.2.3.1 to compute the expected annual losses for seismic damage (EAL_S).

Table 54 and 55 indicate the outcomes of the $Step_{(S)}$ 1 and 2, respectively, dealing with the identification of the RBC and the classification of the compatible SRT. Specifically, based on the data related to the year of construction and geometric details of the Case study 4 (Section 4.1.3.4), the corresponding RBC is selected according to the classification parameters reported in Table 3. Similarly, based on the selected SRT, its corresponding classification is provided according to the parameters reported in Table 4.

Table 54. Case study 4 - Outcomes of $Step_{(S)}$1 related to the identification of the RBC

$RBC_{(N-i)}$	Construction period	Geometric details			
		Storey [No]	Interstorey height [m]	Gross floor area [m^2]	Window to wall ratio [%]
Structural typology Masonry	Pre-1946	Mid-rise (4 ÷ 6)	> 3.50	> 750	10 ÷ 19
Case study 4 data ([1])					
City Hall of Barisciano	Early 20th century	4	1 and 2 level = 4.30 3 level = 3.65 4 level = 3.35	984.32	10

([1]) See Section 4.1.3.4 for a full description of the building.

Table 55. Case study 4 - Outcomes of $Step_{(S)}$ 2 related to the classification of the SRT

$SRT_{(N-i)}$	Application level of retrofit intervention	Performance parameter	Mechanical behaviour
RBC $_{(N-1)}$ Reinforced concrete	Global	PGA_C/PGA_D >40%	Box behaviour without brittle failure

Based on the outcomes above, the seismic performance of the Case study 4 in its pre- and post-retrofit scenario is assessed according to the $Step_{(S)}$ 3 to define the GP_S (PGA) for the identified RBC of the Case study 4 and its selected SRT. The GP_S (PGA) are provided in terms of fragility curves characterised by the mean value μ and the standard deviation σ of the lognormal distribution functions for each damage state DS_i (Table 56) to subsequently compute the corresponding EAL_S, according to the $Step_{(S)}$ 4. Specifically, the EAL_S related to the pre- ($EAL_{S,0}$) and post-retrofit ($EAL_{S,R}$) scenario result equal to 31.58 €/m^2year and 21.78 €/m^2year, respectively.

Table 56. Case study 4 - Parameters of fragility curves for pre- and post-retrofit scenarios

Scenario		DS_1	DS_2	DS_3	DS_4	DS_5
Pre-retrofit	μ	0.129	0.167	0.203	0.210	0.235
	σ	0.084	0.108	0.117	0.120	0.114
Post-retrofit	μ	0.206	0.398	0.835	0.847	1.926
	σ	0.168	0.303	0.688	0.697	1.564

The assessment of the **energy performance** at the extended lifetime (t_{ext}) is carried out according to the four-step approach introduced in Section 3.2.3.2 to compute the expected annual cost for energy consumption (EAC_E).

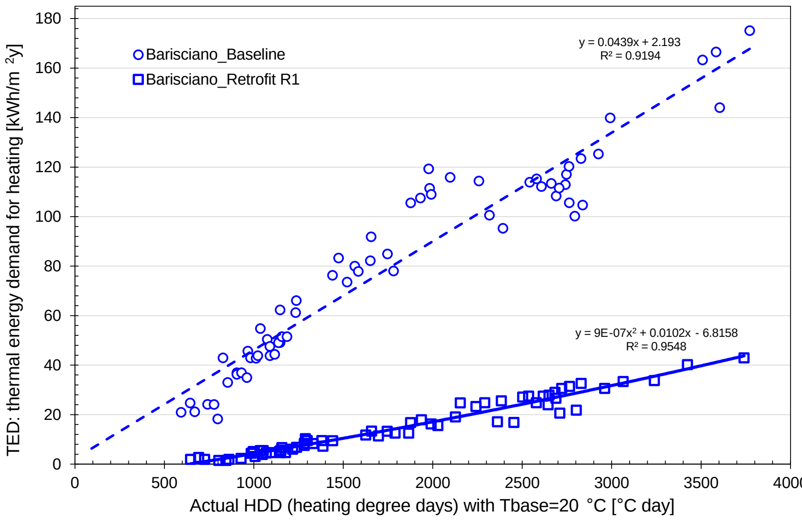
The outcomes of the $Step_{(E)}$ 1 are the same ones presented in Table 54 within the framework of the seismic performance assessment. Table 57 indicates the outcomes of the $Step_{(E)}$ 2 dealing with the classification of the ERT compatible with the identified RBC. Based on the selected ERT, its corresponding classification is provided according to the parameters reported in Table 5.

Table 57. Case study 4 - Outcomes of $Step_{(E)}$ 2 related to the classification of the ERT

$ERT_{(N-i)}$	Application level of retrofit intervention	Performance parameter	Thermal behaviour
RBC $_{(N-1)}$ Reinforced concrete	Windows and HVAC systems	< 15%	Glazing efficiency Systems efficiency

Based on the outcomes above, the energy performance of the examined building in its pre- and post-retrofit scenario is assessed according to the $Step_{(S)}$ 3 to define the GP_E (HDD) for the identified RBC of the Case study 4 and its compatible ERT. The GP_E (HDD) are provided in terms of TED_h vs HDD curves (Figure 55) to subsequently compute the corresponding EAC_E, according to the $Step_{(S)}$ 4. It is worth nothing that the conversion of the TED_h result in PEC to be subsequently transformed into equivalent costs by means of PEFs is obtained directly by applying the EMAR procedure, as described in Section 3.2.3.2. Specifically, the EAC_E related to the pre-retrofit ($EAC_{E,0}$) and post-retrofit (EAC_E) scenarios result equal to 25.21 €/m^{2}year and 13.90 €/m^{2}year, respectively.

Figure 55. Case study 4 - TED_h vs HDD curve



The assessment of the **environmental performance** at the extended lifetime (t_{ext}) is carried out according to the two-step approach introduced in Section 3.2.3.3 to compute the expected annual cost for the environmental impact (EAC_{EI}).

According to the $Step_{(EI)}$ 1, the expected annual amount of GHG emissions due to both seismic damage and energy consumption are defined. Subsequently, according to the $Step_{(EI)}$ 2, the environmental output is converted into cost by means of the monetary conversion factor $CF_{CO2,M}$ (i.e. the EUA spot price observed on 24 March 2022 from EEX, equal to 76.50 €/tCO_2eq, was selected). Specifically, the EAC_{EI} related to the pre-($EAC_{EI,0}$) and post-retrofit (EAC_{EI}) scenarios result equal to 4.05 €/m^{2}year and 1.93 €/m^{2}year, respectively.

Once the aforementioned results of the seismic, energy, and environmental performances are carried out for both the pre- and post-retrofit scenario, they are combined into the corresponding $IRPP_0$ and $IRPP_R$ according to Equation (20) and (21), respectively, to subsequently calculate the **equivalent total extended lifetime cost** (ΔIRPP, expressed in €/m^{2}year and indicating the annual economic savings due to retrofit) at the **time t_{ext},** according to Equation (22) and reported in Table 58. Hence, a cost reduction between the pre- and post-retrofit scenario equal to nearly 38.2 % is obtained.

Table 58. Case study 4 – Results related to the extended lifetime (t_{ext}) stage

	Seismic performance	Energy performance	Environmental performance	Equivalent economic performance
Extended lifetime (t_{ext})	$EAL_{S,0}$ (€/m^{2}year)	$EAC_{E,0}$ (€/m^{2}year)	$EAC_{EI,0}$ (€/m^{2}year)	$IRPP_0$ (€/m^{2}year)
	31.58	25.21	4.05	60.84
	EAL_S (€/m^{2}year)	EAC_E (€/m^{2}year)	EAC_{EI} (€/m^{2}year)	$IRPP_R$ (€/m^{2}year)
	21.78	13.90	1.93	37.61
			ΔIRPP (€/m^{2}year)	**23.22**

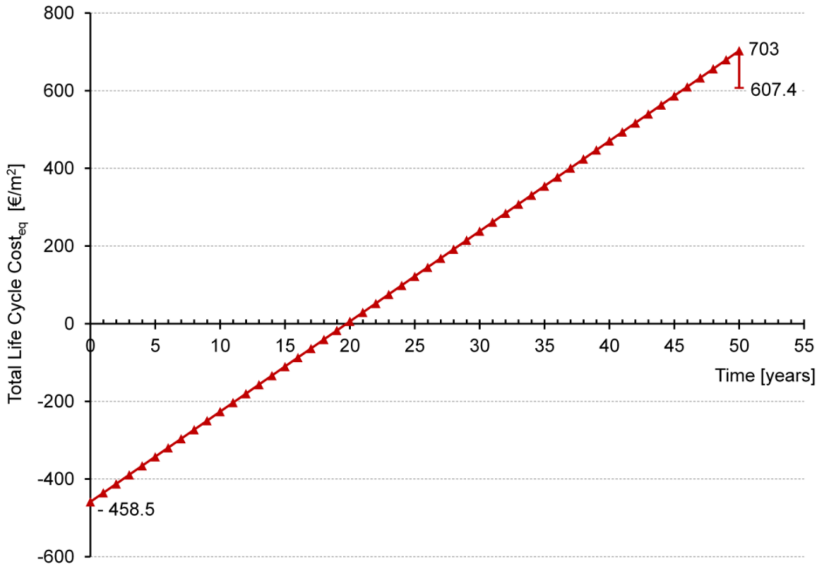
4.3.4.3 Performance assessment at the end of life stage (t_{end})

The **equivalent total end-of-life cost** (Total $EOLC_{eq}$, expressed in €/m^2) at the **time t_{end}** is computed according to Equation (23), referring to the cost for dismantling the seismic and energy retrofit technologies, plus the equivalent cost related to the amount of GHG emissions for the end-of-life phase of building life cycle (i.e. Module C and D). In this case, the total $EOLC_{eq}$ results equal to 95.65 €/m^2, thus indicating the absence of economic savings at the time t_{end}, due to the lack of environmental benefits related to the recycle of materials of retrofit technologies.

4.3.4.4 Total equivalent economic performance

The three total equivalent cost contributions are combined to build the equivalent 'Total Life Cycle Cost vs Time' curve, according to Equation (24), considering a lifetime of the retrofitted building equal to 50 years and the absence of fiscal incentives. The representative curve related to the Case study 4 (Figure 56) starts with a negative value of equivalent cost, corresponding to the Total IC_{eq}, which indicates the initial economic investment at the time t_0 = 0 (first term of the second member of Equation 24). Subsequently, the curve progresses towards the positive quadrant of the graph since the annual economic savings due to the positive effects of the combined retrofit, corresponding to the ΔIPRR, lead to the recovery of the initial investment, which is reached at the extended payback time ($t_{Payback,IPRR}$) equal to 19.7 years, when the curve crosses the Time axis. Afterwards, the curve continues to progress into the positive quadrant of the graph, indicating the effective annual economic savings, resulting into a cumulated value until the time t_{end} (i.e. 50 years) equal to 703 €/m^2 (i.e. sum of the first and second term of the second member of Equation 24). Furthermore, a positive value of equivalent cost corresponding to the Total $EOLC_{eq}$ is achieved at the time t_{end}, thus indicating that the recycle and reuse of materials and components do not enable the achievement of potential credits for the Case study 4, reducing the total value of economic savings to 607.4 €/m^2 at the time t_{end}.

Figure 56. Case study 4 – Representative Total Life Cycle Cost vs Time curve



Source: JRC

4.3.5 Remarks on the application of the simplified methodology to the four case studies

The application of the proposed simplified combined assessment method enables the identification of some key advantages. Specifically, it allows users to take into account the mechanical interactions of different potential seismic and energy retrofit technologies to select the most effective one by easily comparing the results of the seismic, energy, and environmental performances of a retrofitted building. Indeed, they are expressed in monetary terms facilitating their understanding and the corresponding benefits of an integrated retrofit to different stakeholders.

The assessment procedure related to the Step 3 of the proposed method leads to the assessment of the energy, seismic and environmental performances of the retrofitted building at three different time of its life cycle: initial, extended lifetime, end of life. One of the main key-simplifications refers to the performance assessment at the extended lifetime. Indeed, it consists in directly using generalised performances obtained from simulation procedures for the combination of representative building classes (RBCs) and compatible retrofit technologies. As for the energy performance assessment, the generalised performances are provided in terms of analytical thermal energy demand for space heating (TED_h) vs heat degree days (HDDs) curves. These curves are valid for any site (i.e. depending on the HDD value) and for a selection of combined retrofit technologies, yielding a given improvement of the energy performance level (i.e. retrofit intensity associated to a predefined reduction of PEC). Similarly, as for the seismic performance assessment, the proposed simplified method allows users to reduce the analysis time with respect to traditional methods, where the seismic assessment procedure is performed through complex and time-consuming non-linear analyses of the building before and after retrofit interventions. In order to exploit the benefits of the proposed method, which can be applied at a more general level with respect to the traditional assessment methods, where evaluation analysis is performed case-by-case, a significant step forwards refers to the effort of enriching the inventory of generalised performances for different RBCs and compatible retrofit technologies indicative of different EU areas.

Finally, the possibility to analyse the final outcomes of the assessment procedure by means of a 'total life cycle cost vs time' curve simplifies the decision-making process, since it is possible to directly know the initial investment, the corresponding payback time, as well as the effective economic savings during the whole residual lifetime of the building after its retrofit. Moreover, the potential increase or reduction of these savings at the end-of-life of the building are also indicated due to the potential recycle and reuse of materials and/or components of the retrofit technologies used.

5 Conclusions

The need of a simplified assessment methodology aimed at evaluating the effects of a combined seismic and energy retrofit of ageing buildings is a priority-issue. Indeed, a simplified method provides an effective tool to easily assess the benefits gained by a combined upgrading in the view of the urgent action for a large-scale renovation of the EU building stock in line with the Renovation Wave strategy and the European Green Deal to also meet the climate-neutrality by 2050.

The first part of the study presented the **review of existing methodologies** for the combined assessment of the upgrading of existing buildings, serving as a state-of-the-art to propose a novel simplified combined assessment method. The analysed methods and tools were classified in two key-streams: (i) sector-specific methods, and (ii) multi-performance assessment methods. The former key-stream includes methods and tools devoted to the independent quantitative assessment of seismic and energy/environmental performances of new and existing buildings. The latter key-stream refers to qualitative and quantitative integrated assessment methods. Although the sector-specific methods refer to single-performance assessment procedures, their analysis was essential since these methods are usually implemented in the development of combined/integrated methods. Both key-streams lead to a total group of four categories of assessment methodologies. As for the **first category**, seismic loss estimation methods at building and regional level, generally based on a probabilistic four-step quantitative assessment consisting of hazard, structural, damage and loss analysis, were presented. Within this group the PBEE methodology, developed by PEER, is recognised as one of the most robust procedure aimed at assessing the so-called 3D's variables; deaths (loss of life), dollars (economic losses), and downtime (temporary loss of use of the facility). However, this methodology is particular complex, thus several research efforts were carried out over time to develop procedures more accessible to engineering practice, such as the FEMA P-58 methodology, among others. The first category also includes resilience-rating systems, aimed at assessing the post-disaster functionality beyond the loss assessment, such as REDi™. The **second category** refers to the Life Cycle Assessment (LCA) methodology and a streamlined LCA, namely the Life Cycle Energy Assessment (LCEA), to quantitatively assess the environmental impacts and the energy consumption of buildings during their entire life cycle, respectively. The generic four-step framework of the LCA methodology according to the ISO14040-44:2006 standards was presented, along with an overview of the main developments of the LCA in the construction sector and its related tools. Similarly, the LCEA methodology was analysed along with an overview on the BES tools mainly used to compute the operational energy of buildings through dynamic energy analyses. The **third category** groups the EU and non-EU sustainability rating systems based on indicators of different weight. These tools generally refer to the environmental dimension of the sustainability, neglecting or marginally reflecting economic and social aspects. Hence, it is not surprising that the majority of investigated sustainability rating systems include energy efficiency and CO_2 emissions as highly relevant indicators, but a seismic safety indicator is only implemented in a couple of them with a low weight. A valid attempt to overcome the extensive heterogeneity of the existing sustainability rating systems was carried out at European level with the development of a framework, denoted as Level(s), which was also briefly presented. However, quantitative integrated methods need to be considered for a proper combined seismic and energy retrofit assessment of existing buildings. Hence, the **fourth category** grouped the methodologies developed in the last years devoted to integrated life cycle based approaches, towards the development of holistic methods. Within this category, the SSD methodology was identified as one of the most relevant approaches to carry out a combined retrofit assessment by including energy and environmental performances in structural design/retrofit in a life cycle perspective in order to obtain a single global parameter in economic terms facilitating the decision-making process. Thus, the SSD methodology was considered as a point of reference to develop a new simplified method for the combined retrofit assessment.

Based on the review above, the second part of the report introduced a **simplified method** for the assessment of the combined effect of upgrading of existing buildings. A set of **requirements** was first identified and classified according to three main levels: (i) general principles, related to both sustainable development principles and life cycle thinking in the construction sector, (ii) technological characteristics, devoted to guarantee an effective technological integration of energy and seismic retrofit measures, and (iii) engineering computation requirements, aimed at addressing the computational stage of the novel assessment method and its related outcomes while avoiding complex analysis. Subsequently, the **framework of the proposed method** consisting of four interconnected steps was presented. The first step - *Input information* - aims at collecting the initial data and boundary conditions of an existing building needing retrofit. The second step - *Selection of techniques* – deals with the analysis of the physical and mechanical characteristics of the seismic and energy retrofit technologies to identify a set of potential compatible retrofit technologies. The third step - *Integrated retrofit design and evaluation* - represents the computational tool to assess the seismic, energy, and environmental performances of the combined retrofit in a life cycle perspective and expressed in equivalent costs. The equivalent economic performance of a retrofitted building is obtained by combining three main cost contributions associated with three different stages of its life cycle, i.e. initial time (time of the retrofit intervention), extended lifetime, and end-of-life time. The final economic result expresses the variation of the Total Life Cycle $Cost_{eq}$ over the lifetime of the building, and it can be represented by a cost vs time curve. The total initial cost (€/m^2) is the sum of the equivalent costs of the seismic and energy retrofit interventions, and the equivalent CO_2 costs for manufacturing the retrofit materials. As for the extended lifetime stage, the three performances are assessed on a yearly basis, expressed in economic terms and combined into a global 'integrated retrofitting performance parameter' (IRPP) (€/m^2year). The IRPP is defined as the sum of expected annual seismic losses, expected annual costs related to energy consumption, and equivalent CO_2 costs due to both seismic damage and energy consumption. The difference in IRPP before and after the retrofit (ΔIRPP) represents the total extended lifetime cost, which includes the economic savings due to retrofit. The total end-of-life cost (€/m_2) is the sum of the equivalent cost for dismantling the seismic and energy retrofit measures and the cost associated with the environmental impact of dismantling and recycle/reuse of retrofit materials/components. The fourth and last step - *Optimised solutions* – focuses on a comparative assessment of different combined retrofit solutions to identify the most effective one.

The third part of the study focussed on the identification of four **case studies**, representative of EU residential and non-residential buildings needing combined retrofit to apply both the selected standard method (i.e. SSD methodology) and the proposed simplified combined assessment method.

The selection of the four case studies was carried out according to a three-step approach. First, a detailed analysis of the recurrent construction technologies of the EU existing building stock along with the most common EU structural systems, and vertical and horizontal elements of building envelope was first carried out to identify the **case studies categories**. It was pointed out that RC and masonry buildings represent the predominant construction technologies in the EU-27, mainly spread as RC framed structures, and rubble or brick stone masonry constructions. Specifically, the following categories of case studies were considered: (i) a cultural monumental rubble masonry building with pitched timber roof, and steel beam and hollow clay flat block floors, (ii) a residential brick masonry building with pitched timber roof, and cast-in-place RC beam and hollow clay block floors, (iii) a residential RC building, and (iv) a public RC building, both with cast-in-place RC beam and hollow clay block roofs and floors, and hollow brick infill walls. Second, a six-column seismic hazard-climatic matrix was defined in order to identify the **location of case studies** to be representative of all the possible European seismic scenarios from both climatic exposure and seismic hazard points of view. Specifically, the average value of the PGA range defining a moderate seismic hazard zone (i.e. $0.1g \le PGA \le 0.25g$) in the ESHM20 was considered to identify two macro-seismic hazard areas. Based on the EU 2019 HDD data, three climatic zones were defined. Italy was considered suitable for locating the case studies, as it includes all possible scenarios of the matrix. Based on both categories and location of case studies, four representative buildings needing combined retrofit were selected in Italy. **Case study 1** is a residential RC building in Toscolano Maderno, retrofitted with steel exoskeletons, external expanded polystyrene cladding, and heating system replacement. **Case study 2** is a residential brick masonry building in Dalmine, retrofitted with prefabricated steel shear walls, and the application of roof insulation, new heating system and windows. **Case study 3** is the Santini RC primary school, retrofitted with an exoskeleton of concentric steel x-braced frames and a double-skin envelope. **Case study 4** is a rubble masonry building hosting the city hall of Barisciano. Various local strengthening interventions and the replacement of the heating system and windows were considered.

The **SSD methodology** was first applied to the four case studies before and after the seismic and energy retrofit. Retrofit interventions provided an effective seismic and energy improvement in all four buildings in terms of total cost (i.e. the sum of energy, environmental, and structural costs represented by the global assessment parameter in the fourth step of the SSD methodology). Specifically, total cost reductions of approximately 42 %, 41 %, 31 %, and 47 % for the case study 1, 2, 3, and 4 were achieved, respectively, compared to the non-retrofitted buildings. Subsequently, the **proposed simplified combined assessment method** was applied to the four case studies. Attention was particularly deserved to the third step of the proposed method, i.e. the computational step, leading to the creation of the total life cycle cost over time curves that express the final economic result for the four case studies. Specifically, these curves showed the initial costs for the combined interventions, the recovery of the investment over time up to the payback time, and the potential credits achievable at the end of life stage due to the recycle/reuse of materials/components. A focus on the simplified assessment of the IRPP before and after the retrofit is deserved. Indeed, the simplicity of the method in calculating the expected annual seismic losses and costs related to energy consumption at the extended lifetime stage was ensured by using generalised seismic (i.e. fragility curve) and energy (i.e. thermal energy demand vs HDD curve) performance results. They are based on simulation procedures (i.e. nonlinear static and energy dynamic analyses, respectively) for the combination of different representative building classes (RBCs) and retrofit techniques. The ΔIRPP, calculated for the four case studies, confirmed the economic savings found by applying the SSD methodology (although with a moderate discrepancy of results due to simplified assumptions to overcome the lack of some input information) and consequently the effectiveness of the retrofit interventions. Specifically, cost reductions between the pre-and post-retrofit scenarios result equal to 71 %, 55 %, 61 %, 39 %, with the highest discrepancy of results between the SSD methodology and the proposed simplified method referring to the case study 1 and 3. Furthermore, the payback time for the four case studies, considering a service life of 50 years, resulted equal to approximately 16, 17, 18, and 20 years, respectively. These results can be reduced, if fiscal incentives are considered (e.g. Sisma Bonus and Eco Bonus mechanism in Italy).

The combination of many different data within the quantitative assessment methods for an integrated retrofit of existing buildings remains an ambitious challenge. Hence, within the proposed simplified assessment method further research is needed to enrich the catalogue of generalised seismic and energy performance curves and extend the application of the proposed simplified combined assessment method to a larger number of RBCs in Europe.

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List of abbreviations and definitions

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers

ATC Applied Technology Council

BEAM Building Environmental Assessment Method

BES Building energy simulation

BEST-D Building Energy Software Tool Directory

BPIE Building Performance Institute Europe

BREEAM Building Research Establishment Environmental Assessment Method

BS_E Building Site – climatic zone

BS_S Building Site – seismic hazard

BSL BEAM Society Limited

CASBEE Comprehensive Assessment System for Built Environment Efficiency

CED Cumulative Energy Demand

CEN European Committee for Standardisation

CF Confidence Factor

CF_{CO2} CO_2 emission conversion factor (expressed as tCO_2eq/kWh)

$CF_{CO2,M}$ Monetary conversion factor, indicating the unitary carbon price (expressed as €/tCO_2eq)

CFD Computational fluid dynamic

CHS Circular hollow section

CO_2 Carbon dioxide

DGNB Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)

DHW Domestic Hot Water

DM Damage Measure

DS_i i-th Damage State

DV Decision Variable

EAC_{EI} Expected Annual Costs for the Environmental Impact at the extended lifetime (t_{ext})

$EAC_{EI,E}$ Expected Annual Costs for the Environmental Impact due to Energy consumption at the extended lifetime (t_{ext})

$EAC_{EI,S}$ Expected Annual Costs for the Environmental Impact due to Seismic damage at the extended lifetime (t_{ext})

$EAEI_E$ Expected Annual Environmental Impact due to Energy consumption at the extended lifetime (t_{ext})

$EAEI_S$ Expected Annual Environmental Impact due to Seismic damage at the extended lifetime (t_{ext})

EAL_S Expected Annual Losses for Seismic damages

EDP Engineering Demand Parameter

E_E Embodied energy

EEX European Energy Exchange

EF Environmental Footprint

E_O Operational energy

$E_{O,a}$ Annual operational energy (expressed in KWh/m^2year – electricity, and KWh/m^2year or m^3/m^2year – natural gas)

$EOLC_E$	End-of-life Cost for dismantling the Energy retrofit intervention at the end-of-life time (t_{end})
$EOLC_{EI}$	End-of-life Cost for the Environmental Impact at the end-of-life time (t_{end})
$EOLC_S$	End-of-life Cost for dismantling the Seismic retrofit intervention at the end-of-life time (t_{end})
EPD	Environmental Product Declaration
EPLCA	European Platform on Life Cycle Assessment
EPS	Expanded polystryrene insulation
ERT	Energy Retrofit Technology
ESHM	European Seismic Hazard Model
ESR	Effort Sharing Regulation
EU	European Union
EU ETS	European Union Emission Trading System
FEMA	Federal Emergency Management Agency
GHG	Greenhouse gas
GIS	Geographic Information System
GP_E	Energy Generalised Performance
GP_S	Seismic Generalised Performance
GUI	Graphical User Interface
GWP	Global Warming Potential
HAZUS	Hazard US
HDD	Heating Degree Days
HK-BEAM	Hong Kong-Building Environmental Assessment Method
HKGBC	Hong Kong Green Building Council
HQE	Haute Qualité Environnementale
HVAC	Heating, ventilation, and air conditioning system
I – O	Input – output analysis
IC_E	Initial Cost of Energy retrofit intervention at the initial time (t_0)
IC_{EI}	Initial Cost of the Environmental Impact at the initial time (t_0)
IC_S	Initial Cost of Seismic retrofit intervention at the initial time (t_0)
IDR	Inter-storey drift ratio
IIR	Intensity of the Integrated Retrofit
iiSBE	International Initiative for a Sustainable Built Environment
ILCD	International Reference Life Cycle Data
IM	Intensity measure
IPCC	Intergovernmental Panel on Climate Change
IRPP	Integrated Retrofit Performance Parameter
$IRPP_0$	Integrated Retrofit Performance Parameter before retrofit
$IRPP_R$	Integrated Retrofit Performance Parameter after retrofit
ISO	International Organisation for Standardisation
ITACA	Istituto per l'innovazione e Trasparenza degli Appalti e la Compatibilità Ambientale (Institute for Innovation and Transparency of Procurements and Environmental Compatibility)

JSBC	Japan Sustainable Building Consortium
KL	Knowledge Level
L_b	Lifespan of a building (expressed in years)
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCEA	Life Cycle Energy Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LCT	Life Cycle Thinking
LEED	Leadership in Energy and Environmental Design
MRF	Moment resisting frame
NREL	National Renewable Energy Laboratory
NUTS	Nomenclature of Territorial Units for Statistics
OEF	Organisation Environmental Footprint
PACT	Performance Assessment Calculation Tool
PBEE	Performance-Based Earthquake Engineering
PEC	Primary Energy Consumption
PEF	Product Environmental Footprint
PEF_{nren}	Non-renewable primary energy factor
PEER	Pacific Earthquake Engineering Research Center
PGA	Peak Ground Acceleration
PP_E	Energy Performance Parameter
PP_S	Seismic Performance Parameter
PSHA	Probabilistic Seismic Hazard Analysis
RBC	Representative Building Class
RC	Reinforced concrete
R_{SSD}	Global assessment parameter of the Sustainable Structural Design methodology (expressed as €)
S-LCA	Social-Life cycle Assessment
SBTool	Sustainable Building Tool
SEAOC	Structural Engineers Association of California
SETAC	Society of Environmental Toxicology and Chemistry
SDG	Sustainable Development Goal
SPT_i	i-th Sustainability Performance Target
$SPT_{i,j}$	Incremental Sustainability Performance Target, with j equal to the j-th intervention overtime
SRT	Seismic retrofit technology
SSD	Sustainable Structural Design methodology
$Step_{(S)}$	Generic step related to the Seismic performance assessment at the extended lifetime (t_{ext})
$Step_{(E)}$	Generic step related to the Energy performance assessment at the extended lifetime (t_{ext})
$Step_{(EI)}$	Generic step related to the Environmental performance assessment at the extended lifetime (t_{ext})

TABULA	Typology Approach for BUiLding Stock Energy Assessment
TBL	Triple Bottom Line (of sustainable development)
TED_h	Thermal Energy Demand for space heating
TIM	Transparent Insulation Material
UN	United Nations
UN SDGs	United Nation Sustainable Development Goals
UNEP	United Nations Environmental Programme
UNI	Ente nazionale italiano di unificazione (Italian national standard body)
UNISDR	United Nations Office for Disaster Risk Reduction
US DOE	United States Department of Energy
USA	United States of America
U-value	Thermal transmittance (W/m^2K)
δ_y	Yielding displacement
δ_u	Ultimate displacement

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Annexes

Annex 1. Numerical inputs required by the EMAR tool

Input (i) No	Input description	Details/Measure unit
Geometry		
1	Number of floors	
2	Orientation	Angle between building north and true north
3	Gross area of each floor	[m^2]
4	S/V ratio (i.e. dispersing surface/volume)	[m^{-1}]
5	gross height of each floor	[m]
6	Window to wall ratio	South
7	Window to wall ratio	East
8	Window to wall ratio	North
9	Window to wall ratio	West
Envelope		
10	Solar absorptance of external vertical walls	
11	Solar absorptance of roof	
12	Thickness of (external) vertical walls' bricks (without insulation)	[m]
13	Equivalent thermal conductivity of vertical walls' bricks	
14	Equivalent density of vertical walls' bricks	[kg/m^3]
15	Thickness of (thermal) insulation of vertical walls	[m]
16	Thermal conductivity of insulation of vertical walls	[W/mK]
17	Equivalent density of insulation of vertical walls	[W/mK]
18	Position of insulation of vertical walls	
19	Thickness of roof block (without insulation)	[m]
20	Equivalent thermal conductivity of roof block	[W/mK]
21	Equivalent density of roof block	[kg/m^3]
22	Thickness of (thermal) insulation of roof	[m]
23	Thermal conductivity of insulation of roof	[W/mK]
24	Equivalent density of insulation of roof	[kg/m^3]
25	Position of insulation of roof	

26	Thickness of ground-floor block (without insulation)	[m]
27	Equivalent thermal conductivity of ground-floor block	[W/mK]
28	Equivalent density of ground-floor block	[kg/m^3]
29	Thickness of (thermal) insulation of ground-floor	[m]
30	Thermal conductivity of insulation of ground-floor	[W/mK]
31	Equivalent density of insulation of vertical walls	[W/mK]
32	Position of insulation of ground-floor	
33	Fraction of dwellings with single-glazed, aluminium framed windows	
34	Fraction of dwellings with single-glazed, wood framed windows	
35	Fraction of dwellings with double-glazed, aluminium framed windows	
36	Fraction of dwellings with double-glazed, wood framed windows	
37	Shading systems' type	South
38	Shading systems' type	East
39	Shading systems' type	North
40	Shading systems' type	West
41	Shading systems' position	South
42	Shading systems' position	East
43	Shading systems' position	North
44	Shading systems' position	West
45	Shading systems' radiation set-point	South - [W/m^2]
46	Shading systems' radiation set-point	East - [W/m^2]
47	Shading systems' radiation set-point	North - [W/m^2]
48	Shading systems' radiation set-point	West - [W/m^2]
49	Equivalent thickness of horizontal partitions	[m]
Heating, ventilating and air conditioning		
50	Heating set-point temperature	[°C] [vector]*
51	Cooling set-point temperature	[°C] [vector]*
52	Efficiency of heating distribution-emission-regulation system	[vector]*
53	Supply water temperature of heating terminals	[vector]*
54	Type of heating generation system	[vector]*

55	Efficiency of heating generation system	[vector]*
56	Type of cooling generation system	[vector]*
57	Energy efficiency ratio of cooling generation system	[vector]*
58	Ventilation set-point temperature	[vector]*
59	Natural ventilation - air change per hour (ACH)	[h^{-1}] [vector]*
	Photovoltaics	
60	Type of photovoltaic (PV) system	
61	Percentage of roof covered by the PV system	
62	Azimuth of PV panels	
63	Tilt of PV panels	

*HVAC input is defined through a vector that collects the value for each dwelling.

Source: Ascione et al., 2021.

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