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A Sustainable Framework for the Optimization of Retrofit Strategies of Existing Buildings

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ABSTRACT

The construction industry is one of the major causes of both the consumption of natural resources and environmental pollution. Buildings have a significant environmental impact during their life-cycle, consuming huge amounts of energy and natural assets and affecting the air and water quality in our cities.

The life-cycle of a building consists of two phases: design and facility management (FM). Raw materials such as steel, concrete, iron, wood and brick are used in the first stage, while natural resources like water, natural gas and energy are utilized throughout the entire life-cycle. In addition, environmental effects include an increase in greenhouse gas emissions, global warming and the depletion of the ozone layer. Several negative effects on the environment are also the consequence of deconstruction activities due to the intensive use of natural assets and the generation of solid and liquid waste.

As a consequence, all the stakeholders involved in the Architecture Engineering Construction (AEC) sector, such as architects, engineers, energy consultants, project managers, building users and local administrators, are working together to develop appropriate technologies. Indeed, the rising cost of energy, the overconsumption of natural resources, and all the environmental issues mentioned above have led to an increased demand for sustainable building structures with a low environmental impact, following eco-friendly principles.

This means that the construction sector is in a period where there is a need for two important elements. The first is a boost in terms of eco-efficiency, which is considered to be an integration of several environmental and economic aspects aimed at reducing waste and the use of resources, as well as the ecological impact. The second is the development of innovative and digital methodologies that are able to ensure coordination between stakeholders, with the aim being to achieve the cultural and social-economic sustainability of a building.

As a result, the role of sustainable design has assumed fundamental importance. The concept of sustainability associated with the construction industry provides an opportunity to create facilities with the same functionalities as those designed with a traditional approach, but with a low environmental impact and high energy efficiency.

The concept of sustainable building needs to be implemented in all the phases of a building’s life-cycle, from design to construction (including the consumption of raw materials and natural resources), and from the usage phase to the deconstruction of the building (including the management of solid and liquid waste).

A sustainable development model is based on three key concepts: good environmental management; social responsibility and cost-saving solutions. Consequently, it may be said that sustainability has three main components: environmental; economic; and social.

Within this context, demands made on the construction industry are moving in the direction of a transformation which is both rapid and radical (from a digital point of view), with the purpose being to place the management of the information flow at the centre of this “revolution” in order to increase the effectiveness of decision-making and sustainable design.

Over the last decade, there has been growing interest within the construction sector in using Building Information Models (BIMs), due to their numerous benefits and resource savings during the design, planning, construction and management stages of buildings.

A Building Information Model is a digital representation of the physical and functional characteristics of a facility and its related life-cycle information. The resulting model is a data rich, object-oriented, intelligent and parametric digital representation of a building, and serves as a shared repository of information for building owners and operators during its life-cycle. A BIM represents the shared resource of information that provides a reliable basis for decision-making from the design stage to deconstruction and throughout the building's life-cycle.

The BIM tool allows various types of information to be managed, such as the planning of resources, energy analyses, cost assessments and time schedules. This multi-disciplinary information can be synthesized within one model. A BIM system is a central scheme that involves different stakeholders at different phases of the life-cycle of a facility, enabling information in the BIM model to be inserted, extracted, updated or modified. This collaborative approach enables a focus on the design process of a building on environmental and economic issues, such as construction and maintenance costs and energy efficiency.

Building Information Models are a way of producing sustainable models and conducting performance analyses throughout a building's life-cycle. This is why BIM models are increasingly being used to support sustainable designs, construction, operations and the demolition of buildings. The BIM digital revolution will affect the entire construction industry, providing several benefits and generating buildings that operate more efficiently. It is important to note that the digital models produced also aim to mitigate risks (such as seismic risks), as well as increase efficiency and effectiveness. What is more, the "BIM-oriented" planning of buildings has extraordinary advantages: increased productivity, fewer errors, less downtime, lower

costs, greater inter-operability and the maximum sharing of information.

Refurbishment is carried out to improve the performance of a building and, sometimes, to meet the requirements of owners and building codes. These renovation measures include structural upgrades such as seismic and energy retrofits like improving electrical or plumbing systems or thermal insulation. These operations require a great deal of data about structural and non-structural components, as well as their materials and compositions, geometry and physical properties. Integration with BIM methodologies is fundamental to this phase of the life-cycle, because they are able to manage large amounts of data and improve the feasibility of the processes.

By exploring the relationship between BIMs and sustainability in the construction industry, the aim of this thesis is to demonstrate how sustainable design principles that focus on structural retrofits and the renovation of existing buildings may be implemented with the support of BIM methodologies. The approach of this research moves from the consideration that the management of the structural design process has a significant impact on the management of the sustainability of an entire building. A weakness in the performance of a structural system may affect the functionalities of building components, and this may in turn produce a weakness in the functionality of the whole system.

This research develops different applications of an integrated platform, where information converges from energy, economic and environmental elements. The final aim of this sustainable framework is to support researchers, designers and practitioners in the decision-making stage, thereby optimizing environmental aspects, structural retrofit strategies and energy retrofit solutions during the life-cycle of buildings that are prone to seismic risk.

Chapter 1 of this thesis contains a brief introduction to Building Information Modelling. It describes the advantages of a BIM-oriented design and the maturity levels of the methodology, and also investigates the application of BIMs in the life-cycle of buildings.

Chapter 2 sets out a procedure to assess the environmental impact of some seismic retrofit interventions on an existing reinforced concrete (RC) building. Once the structural requirements have been satisfied and the environmental effects of these retrofit solutions defined, the final aim is to identify the most environmentally sustainable retrofit strategy. The environmental impact of the structural retrofit options is assessed using a life-cycle assessment (LCA).

In Chapter 3, a simplified method based on a semi-probabilistic methodology is developed to evaluate the economic performance of a building prone to seismic risk. The proposed approach aims to identify the most cost-effective strengthening strategies and levels for existing structures during their structural lifetime. To this end, the method identifies: the optimal strengthening level, computing the costs of strengthening the structure at different performance levels for each strategy; and the expected seismic loss during its lifetime.

Chapter 4 develops the BIM-based approach to support the engineering analysis of RC structures and manage the large amount of data required for a detailed seismic analysis. In particular, a BIM is used in an economic seismic loss assessment procedure in order to improve the feasibility of the process and the accuracy of the analysis. The framework developed is able to assess the expected seismic and economic losses of an existing building and to optimize retrofit operations from an economic point of view.

Chapter 5 introduces a sustainability assessment framework for the retrofit process of existing buildings based on the integration of energy and structural aspects. Multi-stage energy optimization is carried out by implementing a genetic algorithm and a smart research strategy. As a consequence, cost-optimal energy retrofit solutions are identified and their influence on the expected economic losses due to seismic damage is assessed throughout a building's lifetime.

Chapter 6 sets out the methodological framework, which enables us to address the integration of the seismic and energy retrofitting of existing buildings from an economic point of view. The overall outcome of this integration is handled in terms of the global expected cost, which includes the economic indicators associated with adopted energy measures and economic loss quantifications related to the structural performance of the retrofitted building.

Keywords: *Building Information Modelling, sustainability, life-cycle, environmental impact, seismic retrofit, expected annual loss, strengthening optimization, energy retrofit.*

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CHAPTER 1

THE CHALLENGE OF SUSTAINABILITY

1.1 THE CONCEPT OF SUSTAINABILITY

Climate change, global warming, ozone layer depletion and the decrease in biodiversity are environmental issues of great importance and are a threat to urban and global development. These environmental issues are the results of an imbalance between production and consumption and an economic development models based on overconsumption of natural resources and raw materials, which affect social well-being and standards of living.

As a consequence, these environmental issues have induced modern societies to aim to manage urban and global development in a more sustainable way. A sustainable process is, in fact, a set of actions aimed at ensuring the well-being of both present and future generations.

Sustainability is an interdisciplinary issue and has its roots in both the physical and the social sciences. The need for sustainability is embedded in achieving a balance between economic activities and their associated ecological and social impact (Muhammad Asif, De Bruijn, Fisscher, & Steenhuis, 2008). Sustainability creates the conditions to minimize depletion of natural resources and to ensure that humans and nature can exist in productive harmony. In summary, sustainability looks to protecting the environment, human and ecological health, while driving innovation without reducing our quality of life.

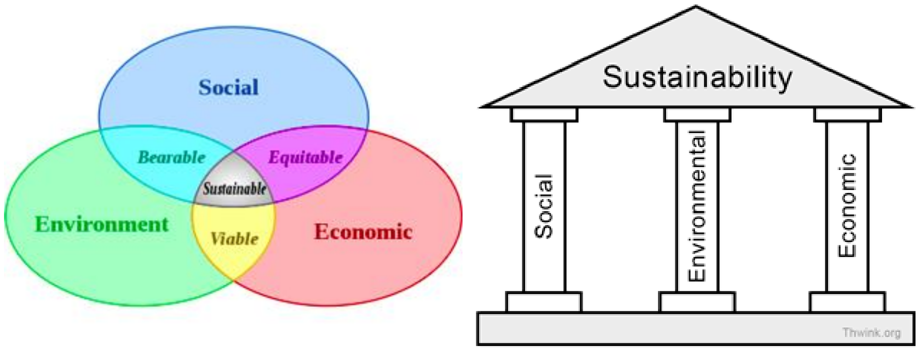
The word sustainability derives from the Latin *sustinere*. Sustain can mean “maintain", "support” (“Oxford English Dictionary”). Since the 1980s sustainability has been used more in the sense of human sustainability on planet Earth and this has resulted in the most widely quoted definition of sustainability as a part of the concept sustainable development, that of the Brundtland Commission of the United Nations on March 20, 1987: “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Assembly, 1987).

Teacher Centre, instead, assesses that "A sustainable future is one in which a healthy environment, economic prosperity and social justice are pursued simultaneously to ensure the well-being and quality of life of present and future generations. Education is crucial to attaining that future." (Teacher Center, 2009).

The concept that emerges from these definitions is that sustainability aims towards environmental management, social responsibility, and economic solutions by ceasing to be a consumer society (Yilmaz & Bakis, 2015). This means that sustainability has three main dimensions: environmental, economic, and societal that are known as “the three pillars”.

The social, economic and environmental impacts of sustainability have become well known as the ‘triple bottom line’ concept. It means that sustainability efforts need to be evaluated in terms of impacts on social, economic, and environmental aspects. This concept is also summarized by the “triple P (planet, people, and profit)” theory that implies that a company creates more value if it takes into consideration the environmental (planet), social (people), and financial issues (profit).

There are two popular ways to visualize the three dimensions/pillars of sustainability, as shown in Figure 1.1.



a) b)

Figure 1.1 Dimensions of sustainability. a) Venn diagram of sustainable development; b) three pillars of sustainability

The social pillar of sustainability ensures that people's health and wellness is strongly protected and focuses on balancing the needs of the individual with the needs of the group. Basically, social sustainability implies a system that mitigates poverty.

The environmental pillar of sustainability occurs when processes and activities reduce the environmental impact of products and operations. This implicates the decreasing of waste generation, the recycling of renewable resources and the limitation of the depletion of non-renewable resources.

The economic pillar of sustainability, instead, is the ability of a profitable business to support a defined level of economic production indefinitely. A sustainable economic model promotes the use of resources in an efficient way that provides long-term benefits to society.

The three pillars are interdependent but none can exist without the other.

At the World Summit on Sustainable Development in Johannesburg, 2002, the three pillars People, Profit, Planet (PPP or 3P) were modified into People, Planet, Prosperity. The change of Profit into Prosperity should reflect that the economic dimension covers more than company profit. (Heijungs, Huppes, & Guinée, 2010).

Agenda 21 (United Nations, 1992) is the 'Earth Summit' pact signed by 149 cities that addresses the 'sustainable development' of Economic, Social, and Environmental components. It proposes concrete planning measures and strategies to achieve the concept of sustainability that should guide planning for present and future generations. These include equity, entrepreneurship, transport reform, and urban renewal (Basiago, 1999). In particular, Agenda 21 supports low-cost building material programs to 'sustainable' urban living for the homeless and for the urban poor. Furthermore, Agenda 21 states that a future comprehensive framework will be based on the assumption that a sustainable building approach will include all factors that may affect the natural environment or human health.

1.1.1 A sustainable construction industry

With the rising cost of energy and growing environmental concerns, the demand for sustainable building facilities with minimal environmental impact is increasing. The construction industry has an enormous economic effect and a strong environmental and social impact, thus its relationship with sustainable development is very important.

The construction industry is a fundamental economic sector, which consists of establishments related to constructing, renovating, and demolishing buildings and other engineering structures, such as commercial centres, highways and airports. Thus, it is one of the major causes of both the consumption of natural resources and environmental pollution. In fact, buildings have a significant environmental impact during their life-cycle, consuming huge amounts of energy and natural assets and affecting the air and water quality in our cities.

According to 2010 data, buildings use 40% of world energy and 50% of water (IEA International Energy Agency, 2013). When environmental effects are considered; 23% of air pollution, 50% of greenhouse gas production, 40% of water pollution, and 40% of solid waste in cities are environmental problems caused by buildings (Willmott Dixon, 2010). Furthermore, the construction industry is responsible about 8~10% of global CO_2 emissions due to the production of concrete (approximately 1 kg of CO_2 for each kg of cement produced), and it is estimated that 2000 million tons a year of this material is to be consumed during this decade (Peris Mora, 2007; Suhendro, 2014). Ten countries, including China, the US, India, Russia, Japan, Germany, South Korea, Canada, Iran, and the UK, account for two-thirds of global CO_2 emissions (Nejat, Jomehzadeh, Taheri, Gohari, & Abd. Majid, 2015).

These levels of consumption in industrialized countries and their environmental impacts are unsustainable and cannot be continued in the future. These environmental problems may be substantially decreased with the integration of sustainability design concepts in the construction projects aimed at mitigating negative impacts. The goal of sustainable design is to produce green buildings that are eco-friendly, profitable and healthy places to live or work.

Nevertheless, in the last few decades the rate of new building construction has significantly decreased. This forces all the stakeholders involved to implement sustainable design concepts in all phases of the life-cycle of the buildings, especially in facility management. This may be achieved by minimizing energy requirements (installing, for example, solar panels or wind generators), reducing water consumption, reducing carbon footprint, using materials that have low environmental impact, reducing wastage, safeguarding human health and wellbeing (increasing, for example, the structural capacity of buildings) and optimizing economic resources. Moreover, it is important to highlight that a long-term view must be taken regarding sustainable design, because green alternatives do not present immediate positive economic effects.

As a consequence, all the stakeholders involved in the Architecture Engineering Construction (AEC) sector, such as architects, engineers, energy consultants, project managers, building users and local administrators, are working together to develop appropriate technologies to implement the three sustainability dimensions in the life-cycle of the buildings.

The first players are Owners/Developers (O/Ds) who develop and finance construction projects. These projects should incorporate improvements in design procedures, efficient and sustainable construction and equipment industry, changes in sustainable development practices in the materials, utilization of high performance materials and systems in the design and construction industry, and public and government policy actions for sustainable design and construction practices.

The second players are the Architects/Engineers (A/Es) who are involved in designing sustainable infrastructures. Sustainable design will improve economic, social and environmental impacts ensuring the well-being of present and future generations. These impacts will be evaluated through life-cycle design analyses over the whole phases of the facility. An indicator may be expressed by a value derived from a combination of different measurable parameters (variables). Indicators have to be defined in a clear, transparent and unambiguous way. They must address the issue of whether they relate to and evaluate several parameters (Bragança, Mateus, & Koukkari, 2010).

Finally, both contractors and governments are important players, in the regulatory stage and execution of projects (Majdalani, Ajam, & Mezher, 2006).

1.1.2 Sustainability assessment

Sustainability is considered as a guiding principle for both public policy and corporate strategies. However, the biggest challenge for most organizations remains the implementation of the sustainability concept. The core of the implementation challenge is the question, how sustainability performance can be measured, especially for products and processes (Finkbeiner, Schau, Lehmann, & Traverso, 2010).

A method to assess the sustainability performance of products is the Life-cycle Sustainability Assessment (LCSA). It assesses product performance considering the environmental, economic, and social dimensions over the whole life-cycle and can be used to compare different products supporting decision makers and stakeholders in making a more sustainable decision (Traverso, Finkbeiner, Jørgensen, & Schneider, 2012).

Klöpffer put the LCSA framework into the conceptual formula (Klöpffer, 2007), where the life-cycle sustainability assessment (LCSA) is a Life-cycle Assessment (LCA), a Life-cycle Costing (LCC) and a Social Life-cycle Analysis (SLCA), done in a consecutive way:

$$LCSA = LCA + LCC + SLCA$$

This means, that LCSA evaluates the potential environmental, economic and social impacts using the three complementary methodologies.

LCA is the methodology that assesses the environmental dimension of sustainability. It addresses “the environmental aspects and potential environmental impacts throughout a product’s life-cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal" ("ISO 14044:2006 - Environmental management -- Life-cycle assessment -- Requirements and guidelines"). LCA is the only technique already standardized with ISO 14040 ("ISO 14040:2006 - Environmental management -- Life-cycle assessment -- Principles and framework") and 14044.

The economic dimension of sustainability is evaluated with the Life-cycle Costing. LCC is an assessment of all relevant real money flows associated with the whole life-cycle of a product and with all the stakeholders in the product life-cycle. It is not yet standardized, but some suggested methodological guidelines exist (Swarr et al., 2011).

The social dimension of sustainability captures the impact of an organization, product or process on society. The social benefits can be estimated by analysing the effects of the organization on stakeholders at local, national and global levels (The GRI Board of Directors, 2002). SLCA methodology is still under constant development despite the publication of guidelines for social life-cycle assessment of products by the United Nations Environment Programme (UNEP-SETAC, 2009). A state of the art of SLCA has been published by Jørgensen et al. (Jørgensen, Finkbeiner, Jørgensen, & Hauschild, 2010; Jørgensen, Hauschild, Jørgensen, & Wangel, 2009; Jørgensen, Le Bocq, Nazarkina, & Hauschild, 2007).

The social, economic and environmental impacts are characterized by a set of impact categories and their respective performance indicators. The selection of impact categories is a crucial step in performing a sustainability assessment of available alternatives that can enhance real world systems (Souza, Rosenhead, Salhofer, Valle, & Lins, 2015).

In the Life-cycle Assessment the indicators must cover all relevant issues related to the analysed product/system (e.g. embodied energy,

global warming potential, human toxicity, ozone layer depletion, terrestrial eco-toxicity, acidification).
In the Life-cycle Cost the indicators are related to costs incurred by the actors during the whole life-cycle of the analysed product/system (e.g. manufacturing costs, waste disposal costs, finishing costs, electricity costs, equipment costs, raw material costs).
Regarding SLCA, Finkbeiner et al. (Finkbeiner et al., 2010) argue that the "selection of social criteria and their impacts is still one of the major challenges" because social indicators have not yet been established by the scientific community. There are several social issues that take place and are not easy to assess. The SLCA Guidelines (UNEP-SETAC, 2009) points out that the impact categories must be based on "social issues of interest to stakeholders and decision makers". Finkbeiner et al. (Finkbeiner et al., 2010) after a detailed study, suggest social indicators able to address several topics, such as politics, society, women's rights or health, that can be partitioned into individual needs (e.g., protection and improvement of human health, creating a balanced settlement structure, education and others) and societal goals (e.g., social responsibility in companies, examination of the size and distribution of population).
The issues related to LCSA are not limited to the difficulties in carrying out separate LCA, LCC and SLCA analyses. An assessment obtained from different life-cycle tools, with different purposes, involves three dimensions of sustainability and three different impact categories (Gundes, 2016). This means that the assessment and the interpretation of LCSA analyses results are a further challenge due to the diverse nature, the variety of stakeholder groups effected by them and the tendency for a greater change in time compared to environmental aspects (Grießhammer et al., 2006). Halog & Manik (Halog & Manik, 2011) proposed an advancing integrated systems

modelling framework for life-cycle sustainability assessment. Another well-known framework for the assessment of various multi-criteria approaches and ratios is the Life-cycle Sustainability Dashboard (LCSD) proposed by Traverso & Finkbeiner (Traverso et al., 2012) that evaluates alternatives based on scores and colours. Nevertheless, these frameworks do not fully integrate all the dimensions of the LCSA.

However, this is a critical issue in sustainability assessment, because the concept of sustainability stands on the three pillars and all the aspects related to the three dimensions should be considered together in the decision-making and not separately. In the future a framework that integrates the three analyses will be necessary to enhance a comprehensive life-cycle sustainability assessment of a product.

1.2 BUILDING INFORMATION MODELLING

Over the last decade, there has been a growing interest within the construction sector in using Building Information Models (BIMs), due to their numerous benefits and resource savings during the design, planning, construction and management stages of buildings. In fact, BIM is considered one of the most promising recent developments in the architecture, engineering, and construction (AEC) industry.

Building Information Modelling (BIM) is a positive collaborative method and is defined as the process of generating, storing, managing, exchanging and sharing building information in an inter-operable and reusable way (Vanlande, Nicolle, & Cruz, 2008). Indeed, BIM was introduced based on the concept of storing and managing various data produced throughout a building’s life-cycle in an integrated manner (Leszczyna, 2013). This is realized with object-oriented software and the BIM model is composed of parametric objects which represent a building’s components (Cerovsek, 2011; Lee, Sacks, & Eastman, 2006; Nicolle & Cruz, 2011). The aim of using parametric object modelling technology is to create relationships between objects within a virtual building model that include physical and functional characteristics as well as project life-cycle information. Furthermore, the scope of BIM directly and/or indirectly affects all the stakeholders involved in the processes.

As a consequence, the term “BIM” could be seen as a synonym of collaboration because BIM software generates rich models that may be shared amongst multiple parties, in a manner that supports decision-making from the design stage to the deconstruction phase.

Conceptually, BIM has been the object of much research since the 1970s (Eastman, Teicholz, Sacks, & Liston, 2011) but the first application of the BIM process was in pilot projects in the early 2000s (Penttila, Rajala, & Freese, 2007a), and aimed to support the building designs of architects and engineers. The implementation of BIM to both new and existing buildings induces profound changes to processes and information flows and, at the same time, has considerable advantages.

The use of BIM concentrates on preplanning, design, clash detection, quantification, costing and the construction of buildings and infrastructure. Recently, however, the focus of research has shifted from earlier life-cycle (LC) stages to maintenance, refurbishment, deconstruction and end-of-life considerations. Facility Management (FM) is the longest period in the life-cycle phase, and generally thus constitutes the main expense and includes all the operations that ensure that buildings continue to fulfil their functions. The application of BIM methodologies in the FM stage enables the highest level of life-cycle data management. The potential benefits of this integration are significant, and researchers and practitioners claim that BIMs may also be used to perform activities like producing as-built documentation, the maintenance of warranties and service information, quality control, energy and space management, refurbishment and deconstruction. In countries with a low number of new buildings, the activities of the construction sector are focused on building renovation, retrofit interventions and the deconstruction of existing buildings (Mill, Alt, & Liias, 2013; Penttila, Rajala, & Freese, 2007b).

As a result of the long life-cycles of constructions, maintenance interventions and deconstruction management become very important for coping with resource efficiency and enabling closed loop material cycles (Volk, Stengel, & Schultmann, 2014). However, the use of BIM is well-established for new buildings, while its implementation in existing structures is still limited.

The application of BIM to existing buildings also enables values such as energy consumption and waste water levels to be monitored. It also makes it possible to evaluate the recyclability or other end-of-life considerations of a component during a building's life-cycle (Volk et al., 2014). To achieve this, a BIM model requires a lot of time for data capturing, processing and the creation of the building model. Hence, it is often not applied to existing buildings.

When BIM is extended from design to construction, facility management and the maintenance of a building, new levels of inter-operability and collaboration may be achieved. The collaborative use of BIM reduces design mistakes and increases the productivity of the construction industry (Miettinen & Paavola, 2014; Succar, 2009).

New and existing buildings are very different due to how they are used (e.g. residential, commercial, infrastructural) and owned (private owner or public authorities). These various framework conditions influence the application of BIM, its level of detail (LoD) and its supporting functionalities, i.e. design, construction, maintenance and deconstruction processes (Volk et al., 2014).

Most BIM design applications aspire to be more than a design tool. A *BIM tool* identifies a specific application that produces a specific outcome, such as model generation, drawing production, specification writing, cost estimation, clash and error detection, energy analysis, rendering, scheduling, and visualization. Currently, BIM design applications provide also a *BIM platform* that is an application that generates data for multiple uses. Most BIM platforms incorporate tool functionality and interfaces to multiple other tools with varied levels of integration. Moreover, there design applications integrate both tools and platforms providing a *BIM environment*. BIM environments supplies the opportunity to carry much wider forms of information and many other forms of information used in managing a project (Eastman et al., 2011).

1.2.1 Advancements in BIM technology

In the last few years, advancements in BIM technology have allowed for the synchronisation of spatial data between design and construction processes (David P. Welch, T.J. Sullivan 2014) and for the achievement of deeper level of BIM, called “maturity level”.

The “maturity level” of BIM in a particular organization will affect the understanding of it and its definition. Succar (Succar, 2010) defines “BIM Maturity” as: “the quality, repeatability and degree of excellence within a BIM Capability.” BIM capabilities are listed in terms of three stages: 1) object-based modelling; 2) model-based collaboration; and 3) network-based integration.

The functionalities and technique for the data capturing related to the level of detail influence all the phases of the BIM process (Cerovsek, 2011; Eastman et al., 2011). BIM standards identify four different levels of BIM maturity, as shown in the BIM maturity map (Figure 1.2) (Department of Business, 2011).

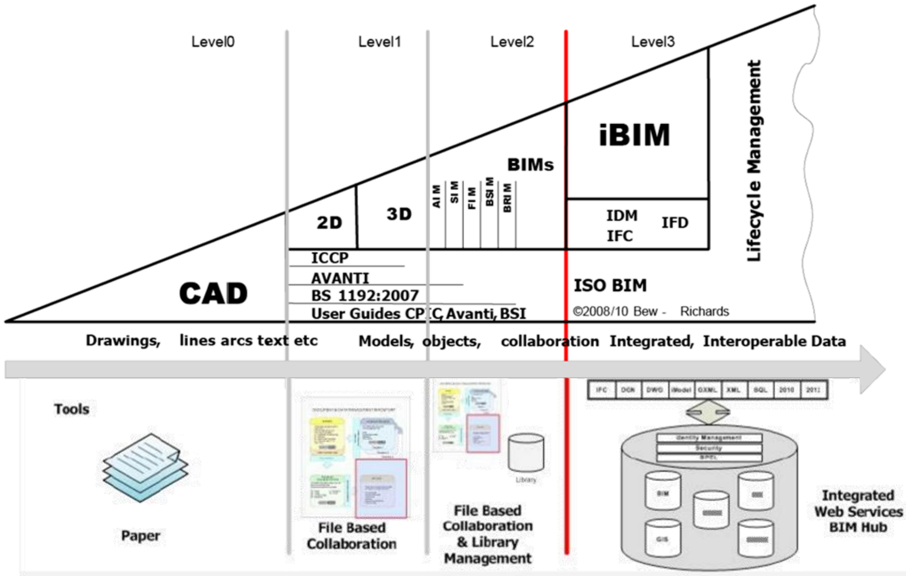


Figure 1.2 BIM maturity map (UK BIM Task Group)

These are as follows:

- Level 0 corresponds to the classical representation of 2D CAD, with drawings, lines, arcs, text, etc...
- Level 1 corresponds to a 2D model or a more developed 3D model, i.e. a spatial model with quantity take-off, with file based collaboration. The 3D model may be used for clash detection analyses that reduce issues and conflicts. Integration of all the information into one centralized model will improve the design efficiency.
- In level 2 the 3D model also contains any kind of information about the materials, the components and the systems, including the execution time of the works, with file-based collaboration and library management. BIM 3D models may be used to assist contractors in the programming and scheduling of BIM projects. The 4D model may then be used to assist contractors

and designers in improving and refining the schedule of the project.

- In level 3 the BIM model becomes an integrated-interoperable model that can be used by all the stakeholders involved in the project. In particular, it contains accurate information for the economic assessment of the work.
- In level 4 the "as built" model contains all possible information associated with the facility. 6D Models are useful for maintenance and management purposes ad are available to users as well. This means that all the information about details, manufacturer, performance criteria and cost may be available at the click of a button.

With regard to the flow of information, in the BIM model it is useful to focus on the benefits associated with the definition of the time needed for: completing the work (information 4D), conducting a cost assessment (information 5D), and having the opportunity to conduct an analysis of management (information 6D). This shows the BIM tool's potential and benefits. In fact, BIM tools could also be used to carryout analyses (structural, environmental, energy, etc.) and to calculate solutions and optimizations to improve project management, mitigate risks, limit costs and increase the duration of facility management.

The benefits of implementing BIM processes and technologies include: a simplified evaluation of building materials, reduction in construction costs and time, improved quality of design information, integration of project systems, data and teams, a reduced propensity for change orders, improved interoperability, increasing of efficiency and efficacy, risk mitigation and whole life-cycle asset management (Aranda-Mena, Crawford, Chevez, & Froese, 2009; Barlish & Sullivan, 2012; Howard & Bjö Rk, 2007; Love, Edwards, Sangwon, Han, & Goh, 2011; Love 2014, Matthews, Simpson, Hill, & Olatunji, 2014).

1.2.2 Interoperability

As described previously, one of the most important features of the Building Information Model is its inter-operability. Inter-operability is defined as the ability to pass data between applications, eliminating the need to manually copy data already generated in another application and improving the feasibility of complex issues, such as structural or energy analyses. The most common form of inter-operability is the platform-to-tool exchange, while the most prevalent shared neutral exchange format is the Industry Foundation Class (IFC).

The IFC has been designed to address all the data structures (geometry, relations and attributes), over the whole building life-cycle, from feasibility and planning, through to design (including analysis and simulation), construction, to occupancy and building operation (Khemlani, n.d.). These base entities are then composed to define Shared Objects. These Shared Objects are building elements such as generic walls, floors, structural elements, building service elements, process elements, management elements, and generic features. This implicates the need to define a further neutral exchange format for Shared Objects to be used from design to construction, and from construction to operation, such as the Construction Operations Building information exchange (COBie).

The COBie deals with all the information collected at the end of a construction project such as technical data sheets, warranties, spare parts, and puts them in an easy-to-implement manner. It collects data from designers (as they design the building) and then by contractors (as the building is constructed). This information is essential to the maintenance management and renovation of the facility

1.2.3 BIM for sustainable construction

Building Information Models are a way to produce sustainability models and conduct performance analyses throughout a building's life-cycle. This is why BIM models are increasingly being used to support sustainable designs, construction, operations and the demolition of buildings. The BIM digital revolution will affect the entire construction industry, providing several benefits and generating buildings that operate more efficiently.

Kriegel and Nies (Krygiel & Nies, 2008) indicates that BIM may aid in the aspects of sustainable design which are building orientation (which may reduce the cost of the project), building massing (to analyse building form and optimize the building envelope), day lighting analysis, water harvesting (reducing water needs in a building), energy modelling (reducing energy needs and analysing how renewable energy options can contribute to low energy costs), sustainable materials (reducing material needs and using recycled materials) and site and logistics management (to reduce waste and carbon footprints). Digital models produced also aim to mitigate risks (such as seismic risks), as well as increase efficiency and effectiveness.

The "BIM-oriented" planning of buildings has extraordinary advantages: more productivity, fewer errors, less downtime, lower costs, greater inter-operability and the maximum sharing of information. Figure 1.3 shows the typical information flow in BIM-based performance and/or sustainability analyses (Azhar & Brown, 2009).

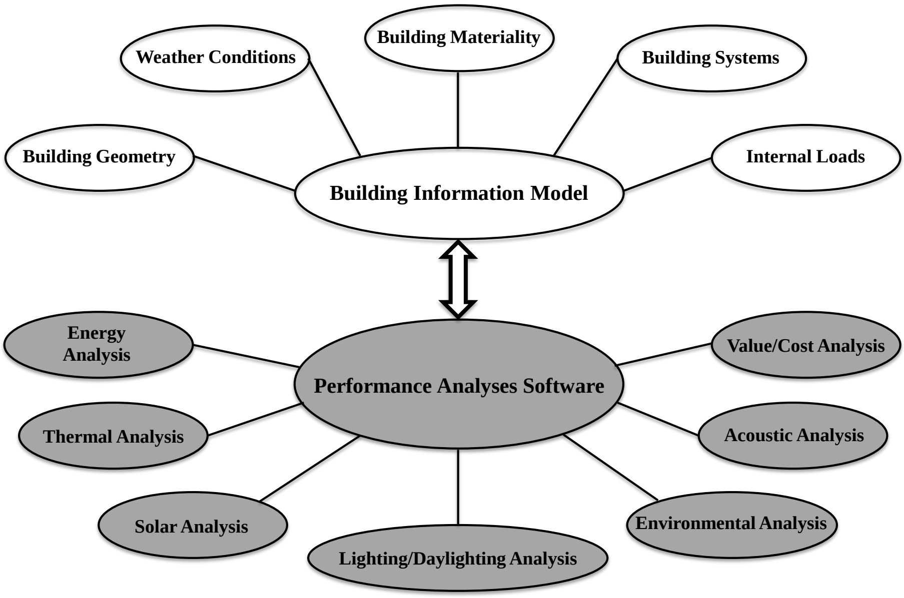


Figure 1.3 Typical information flow in BIM-based building performance (or sustainability) analyses (Azhar & Brown, 2009)

BIM-based model contribute to each dimension of sustainability.

Indeed, the BIM contributes to the economic pillar of sustainability by the process of cost estimating, because a BIM model represents both the graphical and non-graphical aspects of a building (Eastman et al., 2011), and offers a database which represents "the truth" in a reliable manner at any given moment in time This process reduces cost and risks over the whole life-cycle, especially in a 4D model where stakeholders incorporate time in their analyses.

Next, benefits on an environmental level are achieved through sustainability analyses and simulations that play a key role in decreasing industry wastes and environmental effects. By using a building information model, designers can analyse how a building will perform in the very early stages of design, evaluating energy and material consumption, and based on that, they can quickly assess design alternatives to arrive at a better decision based on the best green design (Azhar, Carlton, Olsen, & Ahmad, 2011). For example, some BIM software contain libraries of embodied energy and LCA information that may assist designers in making environmental and life-cycle comparisons between different materials.

The benefits of sustainability for social aspects are on the other hand, considered part of activities that result in promoting human well-being, comfort and health. The implementation of BIM in design processes also enhances collaboration and communication among those stakeholders involved. Finally, it is important to highlight that the decrease in project costs and the reducing of environmental impacts are further activities that positively influence the social pillar of sustainability.

1.3 PURPOSE OF THE STUDY

Facility Management is the longest period in the life-cycle phase, and generally thus constitutes the main expense and includes all the operations that ensure that buildings continue to fulfil their functions. Indeed, after several years, many constructions do not guarantee quality and safety, therefore interventions become necessary. Less than 15% of the total cost is incurred during design and construction, while approximately 60% of the total cost is incurred during the phase of facility management due to maintenance and refurbishment operations (Teicholz, 2004).

Refurbishment is carried out to improve the performance of a building and, sometimes, to meet the requirements of owners and building codes. These renovation measures include structural upgrades such as seismic and energy retrofits like improving electrical or plumbing systems or thermal insulation. These operations require a great deal of data about structural and non-structural components, as well as their materials and compositions, geometry and physical proprieties.

In the last few years, in industrialized countries, such as Italy, the attention of designers and constructors has shifted to maintenance and management of facility due to long building life-cycles and a low new construction rate. This way of thinking about the whole life-cycle of infrastructure is called Life-cycle Management (LCM) and should support the stakeholders in the decision-making process. A strategic approach to LCM contributes directly to the development of economic, social and environmental performance. Life-cycle Management is the way to manage costs and benefits, risks and opportunities over the whole life-cycle of the facility.

Within this context, the purpose of this study is to develop an integrated platform where refurbishment and renovation operations are integrated with energy, economic and environmental elements. In particular, the research focuses on reinforced concrete (RC) existing buildings prone to seismic risk. The approach of this research moves from the consideration that the structural design process has a significant impact on the management of the sustainability of an entire building. A weakness in the performance of a structural system may affect the functionalities of building components, and this may produce a weakness in the functionality of the whole system. Once the technical operations to refurbish the building and to increase the structural capacity against seismic actions are estimated, their long-term consequences will be evaluated. Thus, seismic retrofit strategies will be connected to environmental, economic and energy aspects.

The framework proposed in this thesis is synthetized in Figure 1.4.

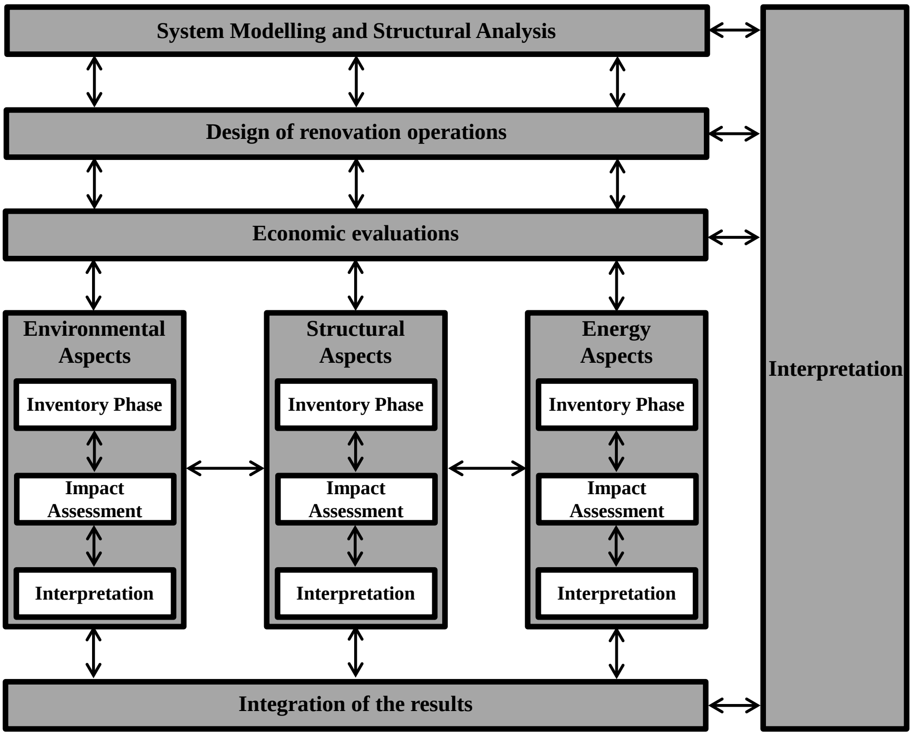


Figure 1.4 Integrated platform

This sustainable framework may support researchers, designers and practitioners in the decision-making stage, thereby optimizing environmental aspects, structural retrofit strategies and energy retrofit solutions during the life-cycle of buildings.

Finally, the aim of this thesis is also to demonstrate how BIM methodologies can be used to implement sustainable design principles that focus on structural retrofits and the renovation of existing buildings. The integration of sustainability principles with BIM enables the management of large amounts of data and improves the feasibility of the processes.

CHAPTER 2

LIFE-CYCLE ASSESSMENT OF SEISMIC RETROFIT STRATEGIES

In the last few years, the renovation and refurbishment of existing buildings have become the main activities of the construction industry. Many studies have recently focused on the mechanical and energy performances of existing retrofitted/refurbished facilities, while some research has addressed the environmental effects of such operations. The present chapter aims to assess the environmental impact of some retrofit interventions on an existing reinforced concrete (RC) building. Once the structural requirements have been satisfied and the environmental effects of these retrofit solutions defined, the final purpose of the procedure proposed is to identify the most environmentally sustainable retrofit strategy. The environmental impact of the structural retrofit options is assessed using an LCA analysis.

2.1 LCA METHODOLOGY

In the last few years, several studies have focused on the assessment of global environmental impacts in both developed and developing countries. As described previously, global warming, and its different potential effects on the planet, is a consequence of the long-term accumulation of greenhouse gases (CO_2, CH4, N2O, etc.) in the higher layer of the atmosphere (BSEE, 2011). Due to this phenomenon, it is important that future generations give priority to sustainable development in the execution of activities in all sectors, thus preventing damage to the environment.

To achieve the sustainability goal, it is necessary to adopt a multi-disciplinary approach covering a number of features such as: energy saving, better use of materials, reuse of materials and recycling, and control of emissions (M. Asif, Muneer, & Kelley, 2007).

The Life-cycle Assessment considers the entire life-cycle of a product, from raw material extraction and acquisition (through energy and material production and manufacturing) to use and end-of-life disposal ("ISO 14040:2006 - Environmental management -- Life-cycle assessment -- Principles and framework," n.d.). Through this systematic approach, the LCA has the opportunity to analyse the environmental impact of a product during the various life-cycle stages. This comprehensive view makes LCA unique in the suite of environmental management tools (Klöpffer, 2014).

This methodology was introduced in 1960s as an environmental tool (Selmes, 2005). The first company to adopt it was Coca-Cola that assessed the environmental effects of packaging from the resource extraction to the use and disposal phase (Hunt, Franklin, & Hunt, 1996). Nevertheless, at that time the methodology focused primarily on solid waste reduction, rather than on environmental emissions or energy use (Khasreen, Banfill, & Menzies, 2009).

The LCA is part of ISO 14040:2006 and ISO 14044:2006 ("ISO 14044:2006 - Environmental management -- Life-cycle assessment -- Requirements and guidelines," n.d.). The methodology is an iterative technique and consists of four main steps, as reported in Figure 2.1:

a) Goal and scope definition.
b) Inventory analysis or life-cycle inventory (LCI).
c) Impact assessment or life-cycle impact assessment (LCIA).
d) Interpretation of the results.

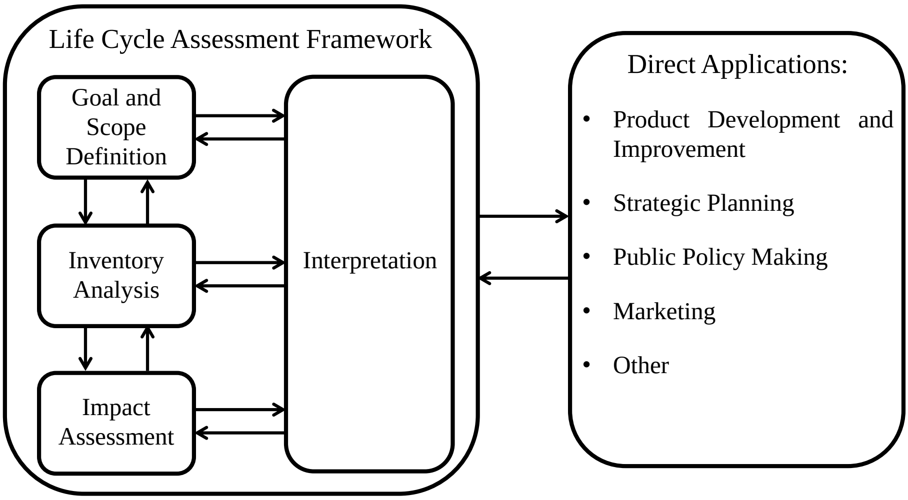


Figure 2.1 Phases and applications of an LCA (based on ISO 14040, 2006 (“ISO 14040:2006 - Environmental management -- Life-cycle assessment -- Principles and framework,” n.d.))

The goal and scope phase defines the purpose of the study, its application, the products to be used, the system boundaries and the functional unit. The functional unit is an important step that enables alternative products or services to be compared and analysed; it is not the mere quantification of materials.

The LCI phase is a detailed description of all the environmental inflows (e.g. materials, embodied energy) and outflows (e.g., air, water and solid emissions) at each stage of the life-cycle. Thus, the LCA practitioner assesses emissions and the consumption of resources in each phase of the product’s life-cycle (from “cradle to grave”). Usually in this phase, a work flow diagram of the product or process’s entire life-cycle is constructed.

The LCIA phase quantifies all the environmental effects and the resources used. The results of the previous phase are used in the LCIA to evaluate the corresponding environmental impact. According to ISO 14042 (“ISO 14042:2000 - Environmental management -- Life-cycle assessment -- Life-cycle impact assessment,” n.d.), LCI results are classified into impact categories (such as climate change, toxicological stress, noise, land use) and, in some cases, in an aggregated manner (such as years of human life lost due to climate change, carcinogenic effects, noise), each with a category indicator.

There are two assessment methods:

a) Classical impact assessment (e.g. CML (Guinée et al., 2001) and EDIP (WEnzel, Hauschild, & Alting, 2001)), which collects LCI results in so-called midpoint categories. These points are located somewhere in the cause-effect chain between LCI results and the endpoint and limit uncertainties.
b) Damage-oriented approaches such as Eco-indicator 99 (Goedkoop & Spriensma, 2001) or EPS (Centre for Environmental Assessment of Products and Material Systems, 1999), which collect LCI results in endpoint categories, sometimes with high uncertainties.

In the last step, namely the interpretation of the results, the life-cycle phases and the products with the greatest environmental impact are identified.

Overall, life-cycle interpretations occur at every stage in an LCA. A practitioner will thus be able to determine the best solution after the LCI phase if two product alternatives are compared.

The LCA is a relative approach, which depends on the functional unit chosen. Indeed, the functional unit influences all the inputs and outputs in the LCI stage and, consequently, the results of the LCIA.

The depth of detail and the amount of time required for an LCA may vary depending on the accuracy and goal and scope definition. Effectively, there is no single method for conducting an LCA. Indeed, there are several variants in which the LCA analyses can be performed that are:

- <u>Cradle-to-grave</u>: a variant of LCA that considers all the phases of the life-cycle, from resource extraction (cradle) to the use and disposal phase (grave).

- Cradle-to-gate: a partial life-cycle assessment because excludes the use and disposal phase. The analysis covers the phases from resource extraction to the factory gate.
- Cradle-to-cradle: a type of LCA analysis where the recycling process of products is considered. The aim of this variant is to minimize the environmental impact of products by employing sustainable production.
- Gate-to-gate: a partial LCA that takes into account only the processes in the entire production chain.
- Well-to-wheel: an LCA analysis used for transport fuels and vehicles. In particular, this variant is generally used to assess energy consumption, emission impact of motor vehicles and fuels used during the transport phases.

The quality of life-cycle assessment analyses is directly related to the quality of inventory data, its correctness and its concordance with the goal of the study. The source of data might be one or more of direct measurements, laboratory measurements, governmental and industrial documents, trade reports and databases, national databases, environmental inventories, consultancies, academic sources, and engineering judgments (Scientific Applications International Corporation (SAIC), 2006).

In conclusion, there is no single way to develop an LCA within the decision-making context. LCA practitioners thus have to decide, case by case, by considering several factors such as products, strategy, systems and available tools.

2.2 APPLICATION OF LCA TO THE CONSTRUCTION INDUSTRY

The construction industry has a significant global impact on the environment. In fact, in each country, this sector is one of the major users of energy and natural resources. This means that it is necessary to involve the construction industry when seeking to achieve sustainable development.

Some methodological frameworks analyse single or multiple aspects of environmental scenarios that are related to construction activities (Caruso, Menna, Asprone, Prota, & Manfredi, n.d.). These frameworks are contained in national/international standards and legislation, (e.g. ITACA Istituto per la Trasparenza, l'Aggiornamento e la Certificazione degli appalti from Italy, LEED Leadership in Energy and Environmental Design from USA, etc.) and can be mandatory or voluntary (Itaca, n.d.; USGBC U.S. Green Building Council, 2010).

The life-cycle assessment (LCA) is an extremely valuable decision-making support tool within the building sector, because it provides an account of the materials and energy used in a product and assesses the related environmental impact (Khasreen et al., 2009).

The LCA methodology is being increasingly applied to the construction industry in order to quantify the environmental effects of the use of energy, CO_2 emissions, the use of renewable and non-renewable resources, and the emission of organic and non-organic compounds into the air, water and soil. Furthermore, life-cycle assessment is also implemented to evaluate the best practical methodologies and to assist the field of engineering techniques of buildings.

Given these features, an environmental impact assessment in the construction industry using an LCA could be usefully adopted for:

1. The development of tools and databases related to the impact of products, technologies, systems and processes.
2. The selection of construction products.
3. The evaluation of construction systems and procedures (Caruso et al., n.d.).

Applications of an LCA to the construction industry started two decades ago (Gustavsson & Sathre, 2006; Mora, Bitsuamlak, & Horvat, 2011; Taborianski & Prado, 2004). Two alternative approaches have been adopted when applying an LCA to the building sector. These are (Erlandsson & Borg, 2003; Ortiz, Castells, & Sonnemann, 2009):

- An LCA for building materials and component combinations (bottom up).
- An LCA of the entire construction process (top down) (Menna, Asprone, Jalayer, Prota, & Manfredi, 2013).

Jönsson et al. (Jönsson, Tillman, & Svensson, 1997) compared the environmental impact of three flooring materials in Sweden using an LCA. Asif et al. (M. Asif et al., 2007) also conducted an LCA of materials used in residential constructions in Scotland, and found that concrete was responsible for over 60% of the total embodied energy. Ximenes and Grant (Ximenes & Grant, 2013), meanwhile, compared the advantages of wood and alternative building products in Australia, finding that greenhouse gas benefits occurred when the original floor and sub-floor products were replaced by timber. Wu et al. (Wu, Zhang, & Chen, 2005) conducted an LCA of several types of concrete and steel that are generally used in the Chinese building industry, adopting a "green tax-based weighting" approach in the course of their research. Esin (Esin, 2007) used a similar approach to evaluate the environmental effects generated during the production of various building materials in Turkey. Asdrubali (Asdrubali, 2009), meanwhile, investigated the environmental impact of the replacement of conventional thermal and sound insulating materials with sustainable versions. Their LCA showed significant benefits in terms of the environmental impact of all the various life-cycle phases of the building due to this substitution of materials (Cabeza, Rincon, Vilarino, Perez, & Castell, 2014).

Adalberth et al. (Adalberth, Almgren, & Petersen, 2001) performed an LCA in 1996 of four multi-family buildings built in Sweden. The goal of the research was to investigate the different life-cycle stages of the four buildings in order to identify the phase with the greatest environmental impact. The stages considered in the research were: manufacturing, transport, erection, use, renovation, demolition and removal (Cabeza et al., 2014). The authors discovered that the use phase accounted for about 70-90% of the total environmental impact of the buildings.

On the other hand, Xing et al. (S. Xing, Xu, & Jun, 2008) performed a comparative LCA involving a steel and RC office building with different floor areas. Pajchrowski et al. (Pajchrowski, Noskowiak, Lewandowska, & Strykowski, 2014) in turn assessed the environmental impact of four equivalent buildings made of two different building materials (wood and masonry) throughout their entire life-cycle. Guggemos and Horvath (Guggemos & Horvath, 2005), meanwhile, compared the environmental effects of the construction phase of steel- and concrete-framed office buildings using an LCA. The results showed that the concrete-framed building had higher emissions and energy consumption due to its longer installation process. Kofoworola and Gheewala (Kofoworola & Gheewala, 2008) conducted an LCA of an RC office building in Thailand. They found that steel and concrete were the materials with the greatest environmental impact, and their use-phase accounted for 52% of the energy consumption of the total life-cycle. Blengini (Blengini, 2009) performed an LCA of a building that was demolished by controlled blasting. The demolition phase and its recycling potential were both included in this study. The research showed that building waste recycling has a low environmental impact from an energy and environmental point of view, but is not profitable in economic terms. Pushkar (Pushkar & Svetlana, 2016) evaluated the environmental damage from three flat roof technologies typically used in Israel, which are: concrete, ribbed slab with concrete blocks, and ribbed slab with autoclaved aerated blocks.

Nevertheless, there are very few studies that evaluate the environmental impact of the retrofitting of buildings. Usually, retrofit studies have focused on the mechanical, functional and energy performances of retrofitted structures. Ardente et al. (Ardente, Beccali, Cellura, & Mistretta, 2011) presented a study in which they compared six public buildings located in different countries where retrofit actions had been implemented. The authors concluded that the replacement of lighting and glazing components had important energy benefits, but the most significant advantages in terms of energy savings and the reduction of CO_2 emissions were due to the improvement of thermal insulation. Strategies to reduce buildings' heating and cooling demands were also investigated by Asadi et al., Ascione et al., Biekšaa et al., Xing et al., and Užšilaitytea and Martinaitis (Asadi, da Silva, Antunes, & Dias, 2012; Ascione, De Rossi, & Vanoli, 2011; Biekša, Šiupšinskas, Martinaitis, & Jaraminienė, 2011; Užšilaityte & Martinaitis, 2010; Y. Xing, Hewitt, & Griffiths, 2011). The environmental impact of some strengthening solutions, such as the steel jacketing of structural members and the application of fibre-reinforced polymer (FRP) sheets, has been investigated by Moliner et al., Zhang et al., and Das (Das, 2011; Moliner Santisteve, Fabregat

Bastida, Cseh, & Vidal, 2013; Zhang, Lin, Abududdin, & Canning, 2011). Moreover, Rodrigues and Freire, Perini, and Allacker (Allacker, 2012; Perini, 2013; Rodrigues & Freire, 2014) performed LC analyses to evaluate the impact of different structural options such as flat roofs, wooden floor, and the integration of green roofs in existing buildings.

The decision-making process in a retrofit operation should be regarded as a multi-objective, multi-criteria optimization problem (Foxon et al., 2002; Menna et al., 2013; Sahely, Kennedy, & Adams, 2005; Waheed, Khan, & Veitch, 2009). Indeed, as reported in Juan et al. (Juan, Kim, Roper, & Castro-Lacouture, 2009), the best option should be chosen by considering several matters such as energy consumption, economics, technical and environmental factors, relevant regulations, and social effects, while the overall process of a building retrofit could be divided into three main steps. The first step consists of a structural analysis of a facility to assess capacity and identify the strengthening solution aimed at extending its lifetime. In the second step, these retrofit actions should be evaluated using appropriate criteria (quantitatively expressed by proper indicators), with consideration given to financial, environmental, social and structural factors. Finally, the third step consists of the identification of the optimal retrofit solution. If this approach is adopted, both sustainability and structural requirements are implemented in the design stage of the retrofit.

Generally, designers take only some parameters into account in the decision-making process. These are:

- Costs.
- Structural performance.
- Speed of the installation process.
- Suspension time.
- Feasibility of the maintenance processes.

Designers very rarely consider environmental effects in the decision-making process due to the difficulty of assessing some factors.
Within this context, and according to the approach of Juan et al. and Menna et al. (Juan et al., 2009; Menna et al., 2013), the purpose of this part of the research is to evaluate different strengthening solutions applied to an RC building located in Italy. In particular, the study analyses and compares the environmental performances of four retrofit strategies, all of which have an equivalent strengthening effect. The environmental impact of the retrofit options is examined using an LCA, according to ISO:14040 2006 and ISO:14044 2006 ("ISO 14040:2006 - Environmental management - Life-cycle assessment - Principles and framework" "ISO 14044:2006 - Environmental management - Life-cycle assessment - Requirements and guidelines").

2.3 RETROFIT SRATEGIES

In a highly seismic territory such as Italy, the attention of designers in the last few decades has principally been focused on seismic effects, with the aim being to guarantee an adequate structural performance with the purpose of safeguarding human life. In fact, most existing structures have been designed and built with reference to old building codes, with limited or without seismic provision. Accordingly, strengthening interventions are necessary to improve the structural capacity of structures in the face of seismic events. Generally, retrofit actions are based on four main strategies: (a) an increase in structural strength and stiffness; (b) an increase in the global energy dissipation capacity; (c) an increase in both structural strength and deformation capacity; and (d) a reduction in the seismic demand.
The selection criteria for strengthening interventions are mainly based on their effectiveness, application time and cost; the environmental impact of the interventions is still a secondary criterion in the final

decision. In this section, the LCA methodology described is implemented in a case study of the sustainability of four retrofit options in an existing RC building.

These strengthening solutions are: the application of FRP sheets to the surface of the structural elements; the RC jacketing of columns and the application of FRP sheets to the surface of beams and joints; the installation of RC shear walls; and the base isolation of the building.

The application of LCA to the building sector has become an activity of great importance in the engineering field. This is not only due to the complexity of buildings but also due to several factors which combine, that are:

- Long lifetimes of buildings. This implicates great difficulty in the prediction of the whole life-cycle, especially from cradle to grave.
- Change in use during lifetime. Buildings or components can change and these changes may be significant.
- There are many stakeholders involved in the construction industry (Khasreen et al., 2009).

Consequently, the aim of this research is to compare the environmental impact of materials and processes related to the four options set out above, with a cradle-to-gate system boundary. This system boundary allows a partial assessment that takes into account environmental impacts from the resource extraction to the installation phase.

2.3.1 Design of the seismic strengthening interventions

A building that is assumed to be located in the city of Naples has been chosen as the case study for implementing the procedure illustrated in the previous sections of this paper. The building is an academic example of a typical Italian facility built in the 70’s with the old building code and with no seismic prevision. The building has an approximate rectangular shape in terms of the plane configuration and three storeys. The structure is made up of RC frames in two directions and two staircases. The floor plan of the building has dimensions of 48.10 m in one direction and 18.10 m in the other, with a total area of about 870 m^2 (Figure 2.2). The foundation system is composed of RC footings and connection beams framed in two orthogonal directions. The total height of the building is 10.1 m and it consists of three floors with a storey height of 3.2 m, except for the first floor, which is 3.7 m. The following mechanical properties have been assumed for the materials: the concrete compressive strength f_{cm} = 15 MPa; and the steel tensile strength f_{ym} = 220 MPa. The cast-in-situ RC slabs are 24 cm high and the joist beams are oriented in one direction.

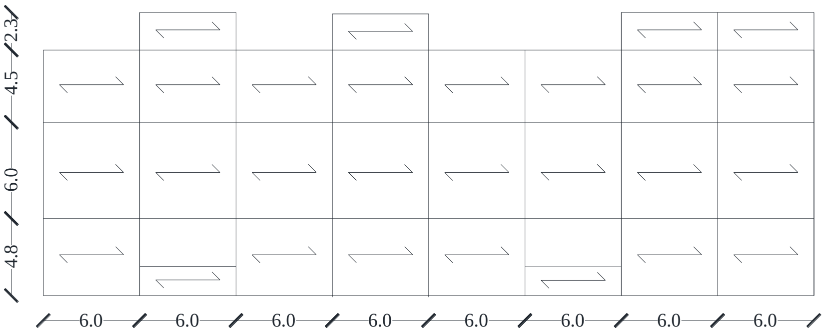


Figure 2.2 Plan view of a generic floor

The geometrical proprieties of the elements are listed in Table 2.1.

	Columns	Beams in Y direction	Beams in X direction
First storey	0.50x0.30, LR: 4Ø14, TR: Ø8/25 cm	0.60x0.30, LR: 4Ø22, TR: Ø8/25 cm	0.35x0.24, LR: 4Ø14, TR: Ø8/25 cm
Second storey	0.50x0.30, LR: 4Ø14, TR: Ø8/25 cm	0.60x0.30, LR: 4Ø22, TR: Ø8/25 cm	0.35x0.24, LR: 4Ø14, TR: Ø8/25 cm
Third storey	0.50x0.30, LR: 4Ø14, TR: Ø8/25 cm	0.60x0.30, LR: 4Ø22, TR: Ø8/25 cm	0.35x0.24, LR: 4Ø14, TR: Ø8/25 cm

LR: longitudinal reinforcement; TR: transverse reinforcement

Table 2.1 Longitudinal and transverse reinforcement details

Table 2.2 lists the first three vibration modes of the structure and the participating mass of each mode.

Mode	Period	UX	UY	RZ
Unitless	Sec	Unitless	Unitless	Unitless
1	1.317	83.50%	0.01%	0.10%
2	0.651	0.02%	18.57%	68.98%
3	0.614	0.00%	69.60%	18.25%

Table 2.2 Vibration modes of the structure

The non-linear building response was simulated with finite element software SAP2000 (Computer and Structurers, n.d.) using lumped plasticity models of the beams and columns (four hinges for each structural member: top and bottom for both directions). The column and beam plastic hinge models are calculated according to the European Code UNI-EN 1998-3: 2005 (E. Standard, 2005), as shown in Figure 2.3.

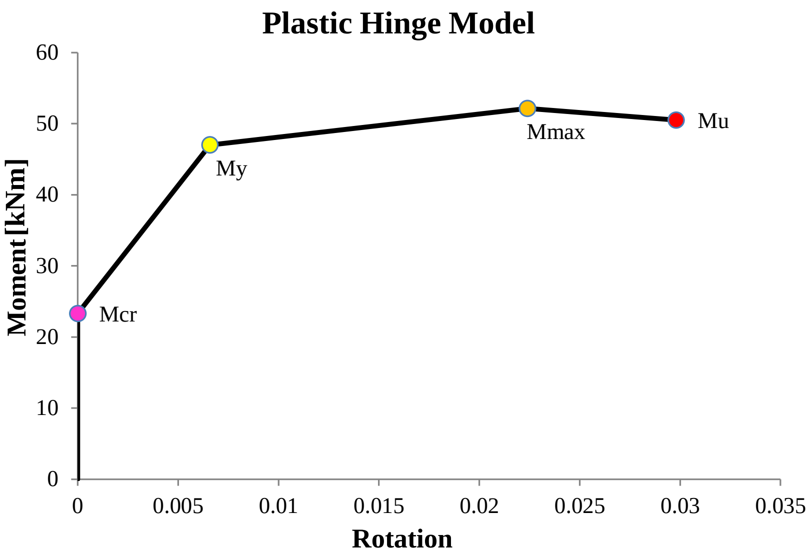


Figure 2.3 Plastic hinge model for the structural elements elements (M_{cr} is the bending moment in correspondence of the first crack, M_y is the bending moment in correspondence of the yelding of the steel bars, M_{max} is the highest flexural capacity, and M_u is the moment in correspondence of the ultimate rotation)

Non-linear static analyses have been carried out for the two plan directions of the structure (x and y directions) up to its global mechanism. A bi-linearization procedure has been performed according to the N2 approach for each step of the pushover curve (Fajfar, 1999).

	Direction X+e+		Direction X+e-	
	Mass	Mode	Mass	Mode
Γ	1,29		1,29	
F*y [kN]	815,6	709,1	815,5	709,0
d*y [m]	0,040	0,043	0,040	0,043
k*[kN/m]	20600,2	16661,7	20615,5	16673,0
m*[kNs2/m]	1702,5	1702,5	1702,5	1702,5
T* [sec]	1,8	2,0	1,8	2,0

	Direction X-e-		Direction X-e+	
	Mass	Mode	Mass	Mode
Γ	1,29		1,29	
F*y [kN]	786,9	688,1	769,5	688,1
d*y [m]	0,038	0,041	0,038	0,041
k*[kN/m]	20914,3	16850,8	20067,7	16802,3
m*[kNs2/m]	1702,5	1702,5	1702,5	1702,5
T* [sec]	1,8	2,0	1,8	2,0

	Direction Y+e+		Direction Y+e-	
	Mass	Mode	Mass	Mode
Γ	1,26		1,26	
F*y [kN]	1836,3	1754,5	1991,4	1891,6
d*y [m]	0,022	0,027	0,025	0,030
k*[kN/m]	83339,8	65074,5	79868,6	62733,3
m*[kNs2/m]	1830,7	1830,7	1830,7	1830,7
T* [sec]	0,9	1,1	1,0	1,1

	Direction Y-e-		Direction Y-e+	
	Mass	Mode	Mass	Mode
Γ	1,26		1,26	
F*y [kN]	2067,6	2014,4	1910,8	1855,3
d*y [m]	0,021	0,027	0,018	0,023
k*[kN/m]	98227,5	74772,1	107080,5	81577,6
m*[kNs2/m]	1830,7	1830,7	1830,7	1830,7
T* [sec]	0,9	1,0	0,8	0,9

Table 2.3 SDOF parameters

A severe earthquake with a return period of 475 years has been assumed to be the structural demand, according to the Italian National Building Code (Ministero delle Infrastrutture, 2008). The PGA demand value depends on the site hazard and in the case study is 0.168g.

	Direction X+e+		Direction X+e-	
	Mass	Mode	Mass	Mode
T* [sec]	1,805	2,007	1,805	2,007
Sde (T*) [m]	0,010	0,012	0,010	0,012
d*max [m]	0,103	0,114	0,103	0,114
dmax [m]	0,133	0,147	0,133	0,147

	Direction X-e-		Direction X-e+	
	Mass	Mode	Mass	Mode
T* [sec]	1,792	1,996	1,829	1,999
Sde (T*) [m]	0,010	0,012	0,011	0,012
d*max [m]	0,102	0,114	0,104	0,114
dmax [m]	0,132	0,147	0,134	0,147

	Direction Y+e+		Direction Y+e-	
	Mass	Mode	Mass	Mode
T* [sec]	0,931	1,053	0,951	1,073
Sde (T*) [m]	0,005	0,006	0,006	0,006
d*max [m]	0,051	0,060	0,054	0,061
dmax [m]	0,065	0,076	0,068	0,077

	Direction Y-e-		Direction Y-e+	
	Mass	Mode	Mass	Mode
T* [sec]	0,857	0,983	0,821	0,941
Sde (T*) [m]	0,005	0,006	0,005	0,005
d*max [m]	0,053	0,056	0,047	0,054
dmax [m]	0,067	0,070	0,059	0,067

Table 2.4 Displacement demands

The achievement of the first failure mechanism due to stress of a structural member identifies the PGA capacity of the structure (equal to 0.051g), and the ratio between the capacity and the demand in terms of the PGA has been defined as the safety level. The demand has been evaluated according to the Italian National Building Code (Ministero delle Infrastrutture, 2008) and the Eurocode (E. Standard, 2005). In the case study, the non-linear static analyses have shown a very low value of the ratio between seismic capacity and seismic demand for the structure in the original configuration, and retrofit interventions are indispensable (Table 2.5).

	Columns Shear Failure EC8	Columns Shear Failure NTC08	Beams Shear Failure EC8	Beam-Column-Joints Shear Failure
Po y-_e-_mass	31%	<28%	<28%	<28%
Po y-_e+_mass	35%	<28%	30%	<28%
Po y+_e-_mass	42%	<28%	<28%	<28%
Po y+_e+_mass	42%	<28%	33%	<28%
Po y-_e-_mode	33%	<28%	<28%	<28%
Po y-_e+_mode	40%	<28%	<28%	<28%
Po y+_e-_mode	36%	<28%	<28%	<28%
Po y+_e+_mode	36%	<28%	31%	<28%
Po x-_e-_mass	>100%	56%	>100%	<28%
Po x-_e+_mass	>100%	60%	>100%	<28%
Po x+_e-_mass	>100%	60%	>100%	<28%
Po x+_e+_mass	>100%	60%	>100%	<28%
Po x-_e-_modo	>100%	76%	>100%	<28%
Po x-_e+_modo	>100%	76%	>100%	<28%
Po x+_e-_modo	>100%	68%	>100%	<28%
Po x+_e+_modo	>100%	68%	>100%	<28%

Table 2.5 Safety levels of the pushover analyses

The aim of these interventions is to increase the seismic capacity of the structural members in order to have the first failure mechanism in correspondence to a PGA value higher than the PGA demand.

In order to carry out an analysis of the environmental impact of several strengthening strategies, the performance of the building is improved with the different retrofit options at the same safety level, meaning that the seismic capacity of the structure after the retrofit is almost equal to the seismic demand imposed by the Italian National Building Code.

The strengthening strategies aim to either increase the ductility, stiffness and strength, or all of them, of the structural elements or to reduce the seismic demand. According to these goals, the following strengthening techniques have been adopted in this case study:

- FRP-based strengthening solution (i.e. shear strengthening of the beam-column joints, columns and beams using FRP sheets to prevent brittle failure mechanisms, and the confinement of columns at the ends by means of FRP wrapping to increase the structural global ductility); this strategy aims to increase the ductility and strength of the structure. This solution is applied to 40 columns, 36 beams and 17 beam-column joints.
- FRP – RC jacketing-based strengthening solution (i.e. RC jacketing of columns to increase the flexural and shear capacity of the members and the shear strengthening of the beam-column joints and beams using FRP sheets. This allows a slight increase in the building's global stiffness that is to be balanced with the local increase in shear capacity in order to prevent brittle failure mechanisms).
- Insertions of RC shear wall-based strengthening solution (i.e. insertion of two shear walls in the Y direction to sustain the seismic action); this strategy aims to increase the strength and stiffness of the structure.
- Base isolation (i.e. inserting a horizontally flexible and dissipative interface on the first floor of the building, thus significantly reducing the demand rather than increasing the structural capacity).

The first method consists of the application of one or more quadriaxial FRP sheets to the surface of the beam-column joint panels and uniaxial FRP sheets onto the beams and columns as shear strengthening.

The second intervention strategy aims to improve the seismic performance of the individual elements, with RC jacketing of columns with a thickness of at least 5 cm and the application of FRP sheets on beams as described above against shear failures. The structure increases its capacity in terms of both stiffness and ductility with these intervention strategies.

The third strategy aims to increase the stiffness of the structure by the insertion of two internal RC shear walls with a thickness of 30 cm in the Y direction due to the results of numerical analyses. Nevertheless, the insertion of the shear walls does not avoid all the brittle crises of the structural members. Some quadriaxial and uniaxial FRP sheets are applied to increase the shear capacity of the joints and beams.

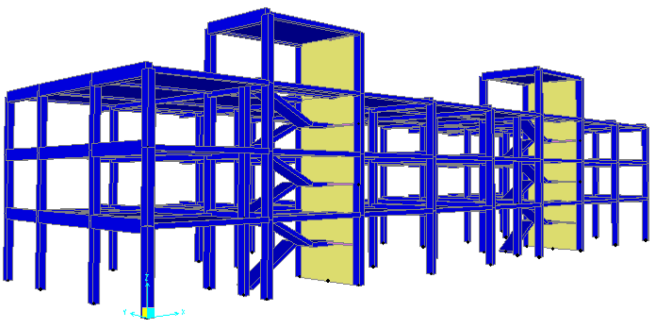


Figure 2.4 Shear walls strengthening solution

The fourth strategy consists of the insertion of rubber bearings and friction isolators between the first and second floors. The structure rests on these devices, which provide sufficient energy dissipation and allow significant relative displacements. In this way, the building' movement is decoupled from the soil movement, producing an increase in the structural vibration period. The building must achieve a target period (higher than in the as-built configuration) that corresponds to the target spectral acceleration in the inelastic spectra demand. The target spectral acceleration depends on the step of the pushover curve where the first ductile failure occurs. However, the insertion of the isolation devices could not prevent all the brittle failures of the structural members, and limited FRP shear strengthening of the single elements is therefore necessary.

2.4 LIFE-CYCLE ASSESSMENT OF THE STRENGTHENING STRATEGIES

The proposed approach, based on the LCA scheme reported in Figure 2.1, aims to contribute to the sustainable design of retrofit interventions in the construction sector.

It is important to highlight, that the main hypothesis for this LCA comparative study of the retrofit options is that the different strengthening solutions are designed to achieve the same structural performance in terms of seismic capacity. In fact, as described above, the retrofit strategies applied to the existing structures are designed to increase the structural capacity in order to achieve the same seismic safety level.

The LCA is conducted for each investigated solution, with a cradle-to-gate system boundary, and includes the following phases: extraction and processing of raw materials, manufacturing, and installation of the strengthening system. The other life-cycle phases such as use, maintenance, end of life and transportation are not included in this application case.

It is important so clarify that a “full” LCA study is always a cradle-to-grave study because building materials have the greatest environmental impact during their use phase. Indeed, assumptions made about the disposal of materials from buildings after they are demolished can have a significant effect on their whole lifecycle environmental impacts (Steelconstruction.info, 2017). For example, an LCA of concrete construction products may take into account that only 20% of these are reused or recycled and 75% of these end up in landfill where they decompose and emit CO2; while an LCA of steel construction products may take into account that 96% are reused or recycled (Figure 2.5). Studies with a cradle-to-gate system boundary make no differentiation between these two very different scenarios and do not take into account benefits provided by the recycling of materials.

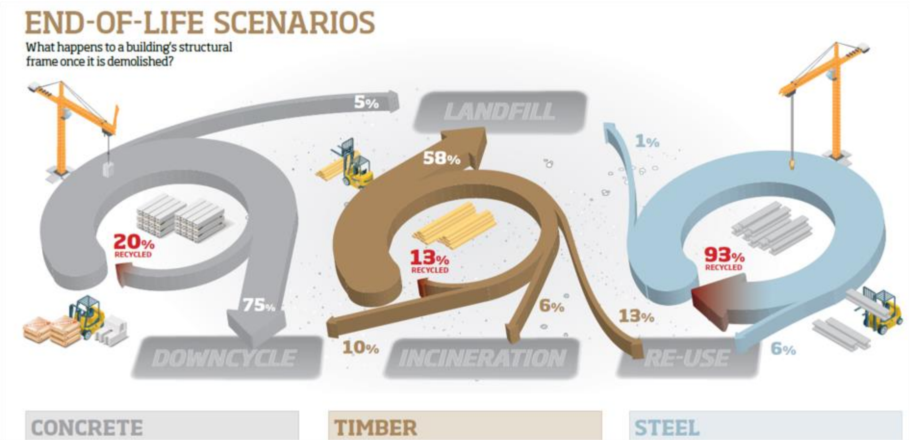


Figure 2.5 Current end-of-life scenarios for three common construction materials

Recycling of materials may be described with two models that reflects the change in inherent properties of the materials:

- Open loop recycling involves the conversion of material from one product life cycle into another product life cycle which should be treated as one system.
- Closed loop recycling describes the recycling of a product into an identical product without any change in the inherent material properties.

2.4.1 Goal and scope definition

The goals and scope of this study are to separately assess the environmental impact of the structural retrofit options that are usually applied to existing RC structures. In detail, four strengthening solutions have been taken into account in order to define which strategy is more sustainable and is characterized by the lowest environmental impact.

Following the scheme of the LCA, the strengthening of the entire building, which allows that the PGA capacity is equal to the PGA related to an earthquake of 475 years, has been assumed as the functional unit for the assessment. Finally, the system boundary adopted in this study includes the following three phases:

- Materials production phase (extraction and production of the materials and construction phases).
- Preparation phase (building demolition, material disposal and transport).
- Installation phase (application of the technique).

For the demolition operations needed for the installation of the systems, it is assumed that the waste materials are sent to a landfill site and/or an incinerator, and that the demolition of the partitions is carried out using manual operations and electrical equipment in order to avoid both further brick damage and compromising the integrity of the wall. All the processes and materials included in the three phases in the system boundary are explained in detail in Table 2.3.

Strengthening Strategies	**Cradle-to-gate system boundary**		
	Materials production phase	**Preparation phase**	**Installation phase**
FRP Solution	▪ Carbon fibre. ▪ Weaving process. ▪ Epoxy resin.	▪ Brick removal. ▪ Plaster removal. ▪ Cover removal. ▪ Longitudinal steel reinforcement treatments. ▪ Concrete cover reconstruction. ▪ Transport of ruins to landfill or incinerator.	▪ Primer application. ▪ Epoxy resin application. ▪ Carbon sheet application. ▪ Brick reconstruction. ▪ Transport of construction materials.
RC Jacketing Solution	▪ Concrete. ▪ Longitudinal and transverse steel reinforcement .	▪ Partial demolition of slab. ▪ Brick removal. ▪ Plaster removal. ▪ Concrete cover removal. ▪ Concrete surface treatments. ▪ Transport of ruins to landfill or incinerator.	▪ Concrete cast in place. ▪ Steel reinforcement placement. ▪ Slab reconstruction. ▪ Transport of construction materials.

RC Shear Walls Solution	▪ Concrete. ▪ Longitudinal and transverse steel reinforcement.	▪ Partial demolition of slab. ▪ Brick removal. ▪ Excavation for foundation strengthening. ▪ Transport of ruins to landfill or incinerator.	▪ Foundations steel reinforcement placement. ▪ Concrete cast in place. ▪ Steel reinforcement placement in shear walls. ▪ Slab reconstruction. ▪ Transport of construction materials.
Base-Isolation Solution	▪ Steel for friction isolators. ▪ Steel for rubber-bearing isolators. ▪ Natural rubber for rubber-bearing isolators. ▪ Vulcanization process.	▪ Transport of isolation devices from the factory to the construction site. ▪ Cutting of columns with a diamond saw. ▪ Application of the hydraulic jack. ▪ Infill walls removal. ▪ Transport of ruins to landfill or incinerator.	▪ Infill walls reconstruction with bricks and mortar. ▪ Infill walls painting. ▪ Transport of construction materials.

Table 2.6 Processes and materials included in the three phases

2.4.2 Inventory analysis (LCI)

In this phase, primary data have been used to model the production of carbon FRP sheets and rubber-bearing isolators while secondary data have been retrieved from databases available in the SimaPro 7.3 LCA software package. SimaPro is an efficient tool (also used for the LCIA phase) that is useful for collecting sustainability data and analysing and monitoring the sustainability performance of products/services. In the application case, secondary data taken from the Ecoinvent 2.2 database (Hedemann, König, Cuche, & Egli, 2007) have been used to assess the environmental impacts of building materials, the use of building equipment, transport operations and electricity. This is a broad environmental database that includes compositions, production processes, the disposal scenarios for most of the existing materials, industrial processes and construction materials.

The design of the retrofit interventions have been carried out according the structural requirements reported in Italian building codes, thus the amount of data related to the material and the processes involved in each strengthening option (including equipment/machinery use) are based on the design process (Consiglio Nazionale delle Ricerche, 2004).

Furthermore, some assumptions have been made regarding the transport phase:

- The distance between the construction and landfill sites is assumed to be 20 km.
- The material-supplying site is located 5 km from the construction site.
- The transport of the building materials from/to the construction site is assumed to be carried out by a lorry (EURO3).

2.4.3 Impact assessment (LCIA)

The LCIA assesses the environmental impact of the strengthening strategies. This phase has been carried out using the Impact 2002+ approach.

The IMPACT 2002+ LCIA methodology is a combined approach that links midpoints and damage categories, as shown in Figure 2.6 (Jolliet et al., 2003).

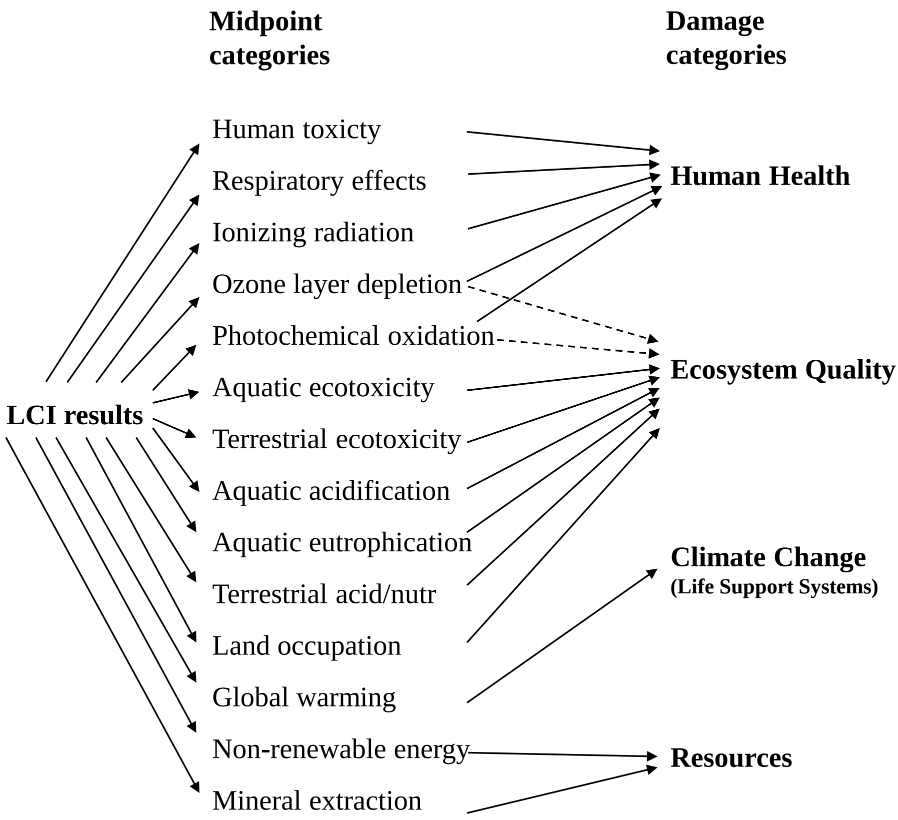


Figure 2.6 Impact 2002+ methodology (Jolliet et al., 2003)

In particular, it links life-cycle inventory result to four damage categories via 14 midpoint categories (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction). These four categories are described as follows:

- Climate change (CC): this evaluates substances that contribute to global warming.
- Human health (HH): this evaluates the consequences of the release of substances that affect human beings.

- Ecosystem quality (EQ): this evaluates the potential consequences for the health of an ecosystem.
- Resource depletion (RD): this measures the depletion due to mineral extraction and the consumption of resources (renewable and non-renewable).

All the midpoint scores are expressed in units of a reference substance and related to the four damage categories, as listed in Table 2.7.

The assessed environmental effects are shown in terms of the damage categories for each life-cycle phase of the four strengthening strategies. The four damage categories have different damage units (as reported in Table 2.7) and need to be normalized in order to analyse the respective share of each impact to the overall damage. The impact values are divided by the maximum value achieved among the four options for each category and are plotted in percentages in order to effectively illustrate the building's environmental performance comparison.

Midpoint category	**Midpoint reference substance**	**Damage category**	**Damage unit**
Human toxicity (carcinogens + non-carcinogen)	kg_{eq} chloroethylene into air	Human health	DALY
Respiratory (inorganics)	kg_{eq} PM2.5 into air	Human health	
Ionizing radiations	Bq_{eq} carbon-14 into air	Human health	
Ozone layer depletion	kg_{eq} CFC-11 into air	Human health	
Photochemical oxidation	kg_{eq} ethylene glycol into air	Human health	
		Ecosystem quality	$PDF*m^2*yr$
Aquatic ecotoxicity	kg_{eq} triethylene glycol into water	Ecosystem quality	
Terrestrial ecotoxicity	kg_{eq} triethylene glycol into water	Ecosystem quality	
Terrestrial acidification/nutrification	kg_{eq} SO_2 into air	Ecosystem quality	
Aquatic acidification	kg_{eq} SO_2 into air	Ecosystem quality	
Aquatic eutrophication	kg_{eq} PO_4^{3-} into water	Ecosystem quality	
Land occupation	m^2_{eq} organic arable land year	Ecosystem quality	
Global warming	kg_{eq} CO_2 into air	Climate change	$kg_{eq}CO_2$ into air
Non-renewable energy	MJ Total primary non – renewable or kgeq crude oil ($860kg/m^3$)	Resources	MJ
Mineral extraction	MJ additional energy or kg_{eq} iron (in ore)	Resources	

Table 2.7 Midpoint categories, reference substances and damage units used in Impact 2002+ (Jolliet et al., 2003)

The first set of Figures report for each strategy the contribution of different phases to that strategy. Figure 2.7 shows the LCIA of the carbon FRP solution. The preparation phase makes the highest contribution to ecosystem quality, while the materials and production phase has the greatest impact on human health, climate change and resources.

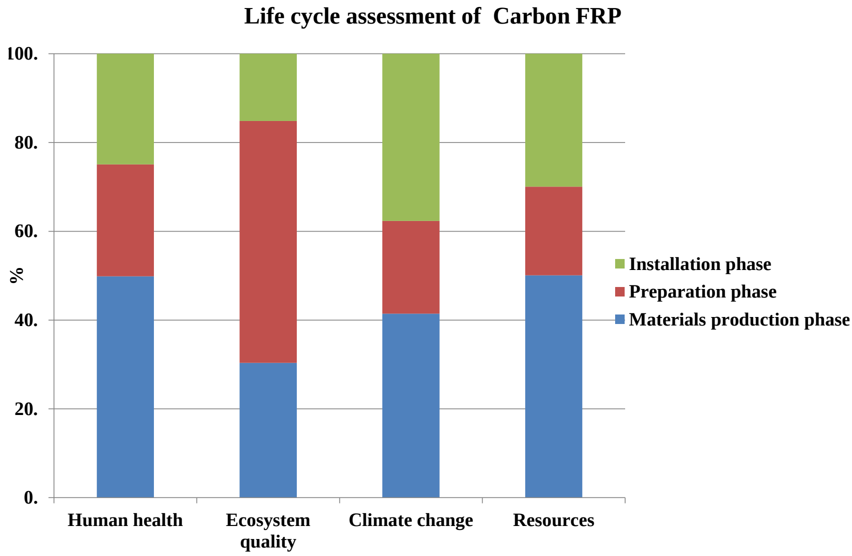


Figure 2.7 Life-cycle assessment of FRP

The environmental results following the RC jacketing of the columns are reported in Figure 2.8. The material and production phase has the greatest environmental impact, accounting for almost 50% of the total burden in almost all the damage categories.

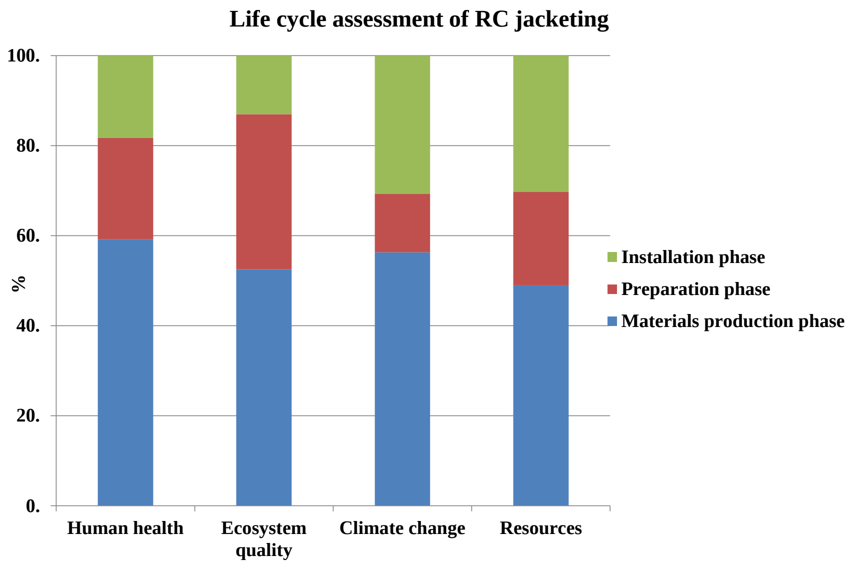


Figure 2.8 Life-cycle assessment of RC column jacketing

Figure 2.9 shows the LCIA related to the construction of two internal shear walls to be inserted as new structural elements in the existing building obtained with the strengthening of selective bays of the frame. For this strengthening technique, the environmental results reveal that the material and production phase ranges between 90 and 95% of the total impact. These environmental effects are due to the amount of concrete and longitudinal steel reinforcement carried out.

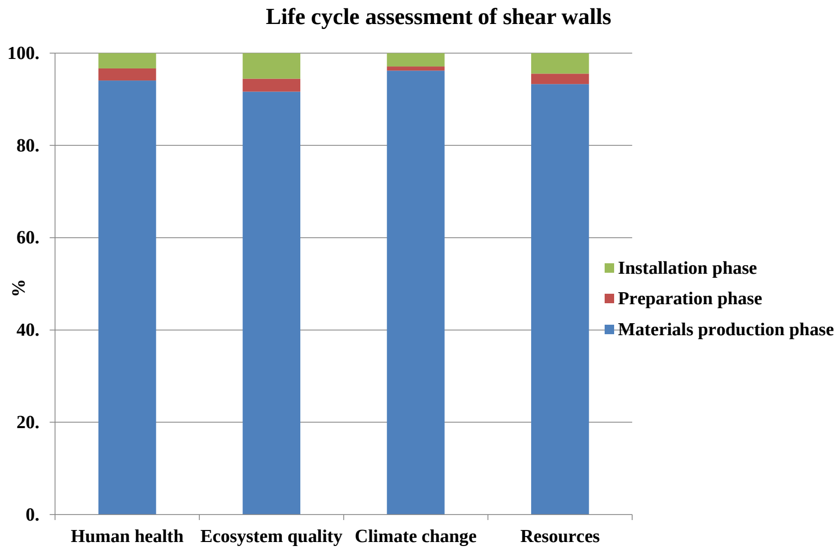


Figure 2.9 Life-cycle assessment of a shear wall

Figure 2.10 displays the environmental results related to the isolation strategy. Isolators are applied to the pillars of the first floor. The strengthening of foundation base has not been taken into account. In this strengthening solution, the greatest contribution to ecosystem quality is made by the material production phase, while the installation phase has the most impact on human health, climate change and resources.

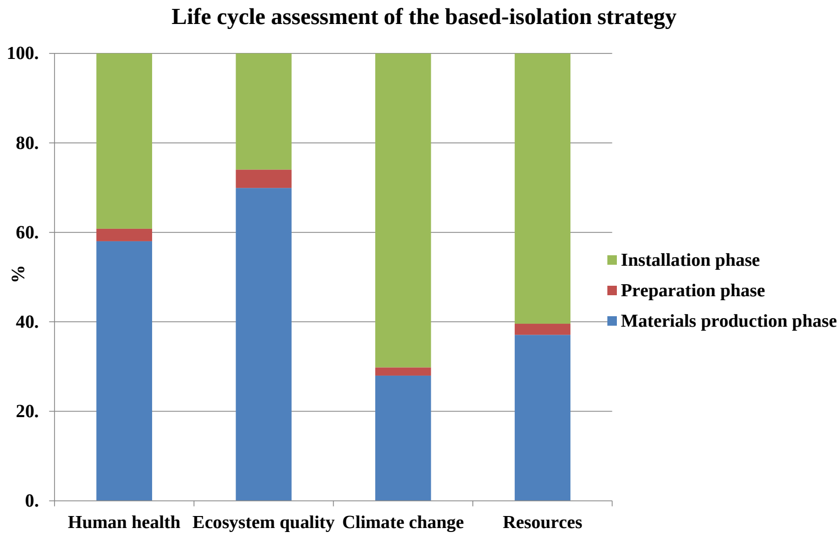
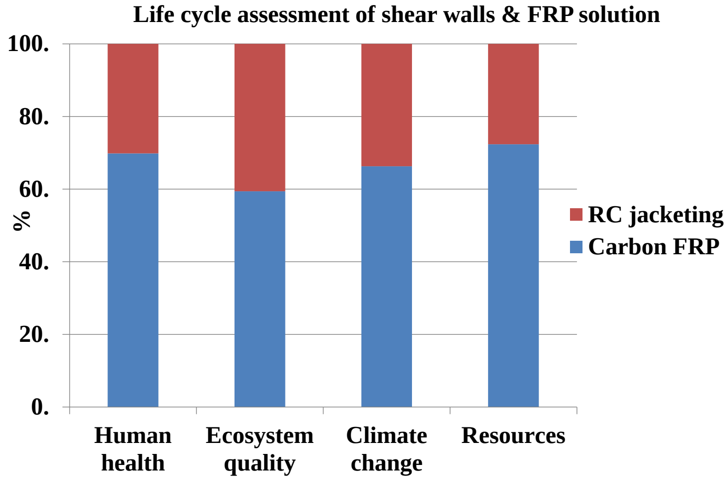


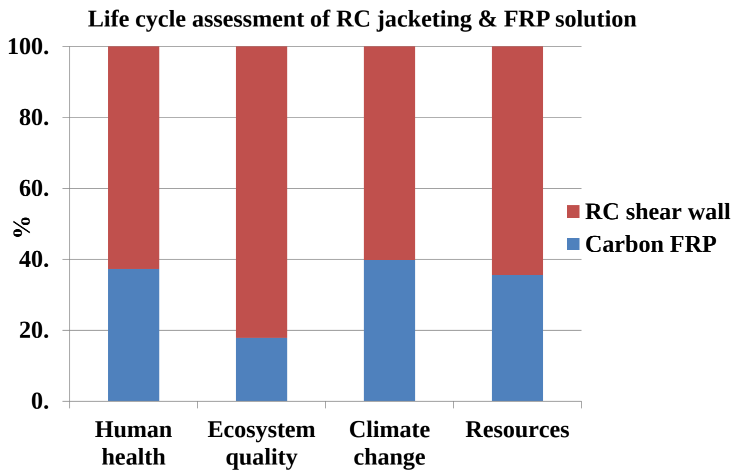
Figure 2.10 Life-cycle assessment of the isolation strategy

For the second and third strategies, where two different techniques are applied, Figure 2.11 shows the contribution of each system to that strategy.

The results show that in the second retrofit strategy, the carbon FRP has the greatest impact in all the damage categories, while in the third strengthening solution the shear walls are responsible for the highest environmental impact.



(a)



(b)

Figure 2.11 Life-cycle assessment of the second (a) and third (b) strengthening solutions

2.4.4 Discussion

A comparative LCA has been conducted to assess the environmental performance of the four retrofit strategies, which are designed to improve the performance of the building at the same level. Figure 2.12

sets out the aggregated results of the LCA over all the phases in terms of the damage categories.

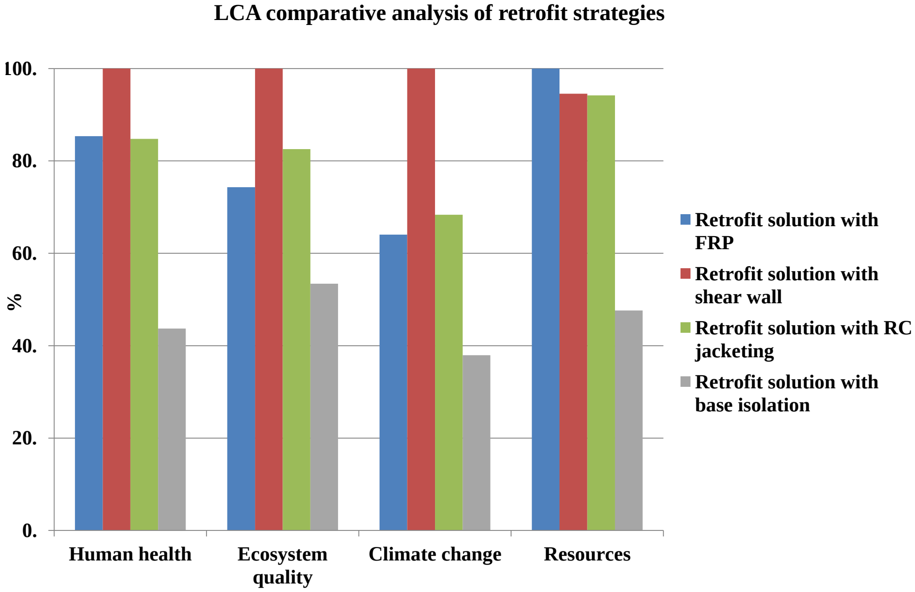


Figure 2.12 LCA comparative analysis of the retrofit strategies

It can be seen that the major environmental load is related to the shear wall strengthening solution. In particular, the shear wall strategy has the highest environmental burden in terms of human health, ecosystem quality and climate change. The FRP solution has the greatest impact in the resources category; this is related to the amount of resources involved in the extraction of carbon fiber and epoxy resin.

Finally, the isolation strategy has the lowest impact on all the damage categories.

Data obtained from these environmental analyses are related to this case study alone and cannot be extended to other scenarios. In fact, the environmental impact depends on several factors such as the vulnerability of the facility, the seismic hazard of the building site and the databases used (Umberto Vitiello, Salzano, Asprone, Di Ludovico, & Prota, 2016).

2.5 ADDITIONAL DEVELOPMENTS OF LCA

The procedure adopted in this chapter assesses the environmental sustainability of materials and processes related to seismic retrofit strategies for existing structures.

The results obtained raise the awareness of designers with respect to what is the most environmentally sustainable retrofit strategy. An LCA is an essential tool for assessing, evaluating, comparing and improving materials and processes in terms of their potential environmental impact. Nevertheless, one of the most important limitations in the application of LCA is the limited inclusion of cost and social impacts. In the decision-making process concerning the strengthening interventions, these indicators have to be taken into account. This means that the best solution from an environmental point of view may not be the retrofit strategy adopted by practitioners. This topic will be developed in the next chapters.

Furthermore, as highlighted previously, the environmental outcomes depend on the databases that practitioners use, the accuracy of the LCA and the system boundary. Even though life cycle assessment is a powerful method to evaluate and compare alternatives from an environmental point of view, it requires a large number of measures in the whole life cycle. Usually, LCA practitioners use 2D drawings and enter data about building and materials manually. However, manual re-entry of the project data into the LCA tool is generally one of the main drawbacks.

A way to overcome this issue is the integration of LCA procedures or tools in BIM models. The use of BIM helps to avoid unnecessary waste of time and resources caused by inefficient data management. The easiest way to implement BIM is to support quantity take-off and estimation for the tasks that involve counting, such as doors, windows, and plumbing fixtures (Eastman et al., 2011). Indeed, building information models provide data that can more readily integrate with LCA tools during the whole life-cycle, from conceptual design to construction and then to facility operation and management. In addition, BIM also helps stakeholders in the decision-making process related to energy issues that have a significant impact on the building life-cycle. In fact, integrated tools have the ability to provide practitioners with the opportunity to explore different energy saving alternatives avoiding the time-consuming process of re-entering all the building geometry.

In the last few years there has been a growing interest in the integration of LCA analyses in BIM models. Integrated tools have been developed for several applications, such as the assessment of the embodied energy of building components (Jalaei & Jrade, 2014) or the embodied carbon footprint of a building throughout the life-cycle of a construction project (Pierucci, Dell'Osso, & Cavalliere, 2015). Overall, even though the application of BIM methodologies is being increasingly applied, there is still much scope for using the potential of BIM in LCA analyses.

CHAPTER 3

LIFE-CYCLE COST OPTIMIZATION OF SEISMIC RETROFIT STRATEGIES

The life-cycle cost (LCC) analysis of buildings prone to seismic risk is a critical issue in structural engineering. Expected loss, including damage and repair costs, is an important parameter for structural design. In this chapter, a simplified method based on a semi-probabilistic methodology is developed to evaluate the economic performance of a building prone to seismic risk. The proposed approach also aims to identify the most cost-effective strengthening strategies and strengthening levels for existing structures during their structural lifetime.

3.1 INTRODUCTION

The second pillar of sustainability is the profitability/prosperity aspect. As described in the previous chapter, Life-cycle costing (LCC) is a sustainability tool that focuses on the evaluation of all costs associated with the life-cycle of a product that are directly covered by one or more of the stakeholders involved in the product life-cycle. LCC may be defined as “the cost of acquisition, ownership, and disposal of a product over a defined period of its life-cycle” (International Standard, 2004; Rausand & Høyland, 2004). The assessment of these costs is fundamental for both present and future decisions. Nevertheless, in many cases it may not be necessary to carry out a complete LCC analysis, because it may be also applied to estimate the differences between the alternatives for the major cost elements (N. Standard, 1996).

The first application of LCC was carried out by the US Department of Defense for the acquisition of high-cost military equipment (Sherif & Kolarik, 1981). In Europe, on the other hand, the methodology has been used since the '70s to make policy and business decisions (UNEP-SETAC, 2009).

Typically, LCC assessments are applied to compare durable products where the purchase price is only a small part of the life-cycle cost. Other costs over the lifetime of the product need to be discounted to current values in order to be put into a common basis or the purpose of a decision (Asiedu & Gu, 1998; Gluch & Baumann, 2004; Hoogmartens, Van Passel, Van Acker, & Dubois, 2014; Kloepffer, 2008). The application of discount rates is often controversial: from an economic point of view, high discount rates are preferred to show higher weight of financial flows, while, from a societal and environmental point of view, low discount rates are preferred to avoid the fact that current activities impose high costs on future generations (Azar & Sterner, 1996; Rabl, 1996; Sáez & Requena, 2007; Weitzman, 1994).

The construction sector is the industry where LCC is most widely applied. In this field, LCC involves evaluation of all future costs related to design, construction and/or production, distribution, operation, maintenance and support, retirement, and material disposal; that means all of the phases in the system life-cycle (Fabrycky & Blanchard, 1991). Indeed, life-cycle costs are defined as the “cost of an asset or its parts throughout its life-cycle, while fulfilling the performance requirements” and life-cycle costing is defined as the methodology for the assessment of these costs. (Technical Committee ISO/TC 59/SC 14 Design life, n.d.).

LCC may be used to compare alternative design strategies and to evaluate the cost effectiveness of them, by considering the initial and operational costs that are incurred over the lifetime. More specifically, LCC can be used to support decision-making in a number of ways:

- to assess total cost of an asset, considering the complete life-cycle (from cradle to gate) or a selected intermediate period;
- to select choices between different means of achieving the same objectives;
- to achieve a balance between initial costs and future benefits;
- to identify cost-effective alternative solution during sustainability analyses (e.g. HVAC, Heating Ventilation and Air Conditioning, systems with high-energy efficiency);
- to assess options in relation to component replacements and/or refurbishment (for example the selection of component with long service life or reduced maintenance requirements);
- to plan maintenance, repair and replacement work;
- to identify alternative uses of the facility;
- to identify end-of-life considerations such as strategies for disposal, options for demolition and strategies for recycling (Langdon, 2007).

During their life-cycle, facilities have economic losses of two sources: ordinary maintenance operations and unpredicTable events that impact structural systems and require economic resources to restore the functionality of the facility. Homeowners often put aside assets for the costs of management and maintenance during the lifetime of a facility. Nevertheless, they are unable to estimate, and thus to save, assets for the cost of unplanned maintenance. Typically, for this reason, there is some uncertainty when an exceptional event happens and the functionality of a building needs to be restored. Knowing the expected economic losses and structural performance of a facility may support the planning of retrofit strategies aimed at preventing, or at least limiting, the damage caused to a structure. This can be achieved through a life-cycle cost procedure by defining seismic retrofits for a building to increase its structural capacity. Indeed, decision-making with respect to structural and non-structural systems situated in seismic areas requires consideration of the damage and other costs resulting from possible earthquakes during the lifetime of a structure. Accordingly, the life-cycle cost assessment procedure is an essential component of the design process (Lagaros, 2010).

In a highly seismic country such as Italy, it is evident how attention has focused in recent years on seismic design of strengthening interventions, with the purpose of guaranteeing an adequate structural performance of facilities and of safeguarding human life. Moreover, developments in relation to the April 6 2009 earthquake in Abruzzo have also shown that the economic losses suffered by buildings linked to the earthquake are issues of great importance (Di Ludovico, Prota, Moroni, Manfredi, & Dolce, 2017a, 2017b). Expected cost estimation methodologies will be described in greater detail in the next section.

3.2 LIFE-CYCLE COST PROCEDURES

One of the first building loss estimation methodologies was advanced by Scholl et al. (Scholl, Kustu, Perry, & Zanetti, 1982), who developed and suggested improvements to both empirical and theoretical loss estimation procedures. Part of the theoretical research included an in-depth study of developing damage functions for a variety of building components based on experimental test data. This proposed breaking down a building into various components and predicting the damage caused to each of them as a function of seismic intensity. The purpose of the study was to calculate the damage factor, which was defined as the ratio between the cost of the damage caused by an earthquake and the cost of replacing a building.

The method proposed by Scholl et al. required component damage functions to estimate damage to a building component. In conjunction with the Scholl et al. study, Kutsu et al. (Kustu, Miller, & Brokken, 1982) collected laboratory test data to estimate damage to various building components in order to implement the proposed component-based methodology. The components evaluated included both structural members (beams, columns, and shear walls) and non-structural components (masonry walls, drywall partitions, and glazing). Using these laboratory tests, it was possible to derive a relationship between the intensity of an earthquake and the damage to each component, and thus the cost of the construction. This type of assessment was, however, carried out with an elastic analysis, and cannot therefore represent the real state of damage to a structure when it is affected by the plasticization phenomena.

A more detailed loss estimation methodology was introduced by Gunturi and Shah (Gunturi & Shah, 1992). Structural behaviour was evaluated with a non-linear analysis, with different ground-motion records applied to a building's foundations. The building was divided into structural and non-structural elements, and the damage was calculated by obtaining structural response parameters for each non-linear time history analysis.

The variability in ground motion as it relates to assessing economic losses for buildings was addressed in a study by Singhal and Kiremidjian (Singhal, A. & Kiremidjian, 1996). A systematic approach to developing motion-damage relationships was proposed by subjecting a structure to a suite of simulated ground motions, and obtaining its probabilistic response using a Monte Carlo simulation.

Porter and Kiremidjian (K. A. Porter & Kiremidjian, 2001) introduced an assembly-based probabilistic loss estimation methodology that accounted for more sources of uncertainty than previous studies. The study also incorporated the uncertainty of estimating the damage to each component and the ambiguity associated with estimating repair costs as a function of this damage. A Monte Carlo simulation was used in this framework to predict building-specific relationships between expected loss and seismic intensity. To predict losses for an application case, techniques for developing fragility models for common buildings were presented.

As members of the Pacific Earthquake Engineering Research (PEER) centre, Aslani and Miranda (Hesameddin Aslani & Miranda, 2005) developed a methodology that incorporated the influence of collapse on monetary loss by estimating the probability of collapse at different levels of ground motion intensity. However, losses due to building demolition were not included in the evaluation of expected seismic losses. This component-based methodology also proposed approaches for disaggregating buildings into components in order to estimate which were the most significant in terms of influencing total losses.

Zareian and Krawinkler (Zareian & Krawinkler, 2006) proposed a simplified version of the Aslani and Miranda framework. This approach used a semi-geographical method to evaluate the economic loss component. In particular, the approach evaluated economic losses by grouping components into subsystems (at either the storey or building level). Components of the same subsystem were then represented by a single engineering demand parameter.

LCC has been implemented also for the assessment of the European seismic design codes and in particular EC2 and EC8 with respect to the recommended behaviour factor q. The assessment is performed on a multi-storey RC building which was optimally designed (Lagaros, 2010).

Recently, several studies have focused on the assessment of building reparability via the estimation of expected performance losses and associated costs of repair and, if necessary, the cost of strengthening existing RC buildings. In this case, it is necessary to establish if it is more convenient to repair and retrofit or to demolish and rebuild (Di Ludovico, Polese, Gaetani, Prota, & Manfredi, 2013; Holmes, 1994; Polese, Di Ludovico, Marcolini, Prota, & Manfredi, 2015; Polese, Di Ludovico, Prota, & Manfredi, 2013). Life-cycle cost assessment procedure can be considered fundamental for the design process in order to control the initial and the future cost of building ownership.

Padgett et al. (Padgett, Dennemann, & Ghosh, 2010) proposed also a method for evaluating the best retrofits for non-seismically designed bridges based on seismic life-cycle costs and cost–benefit analysis.

Kappos and Dimitrakopoulos (Kappos & Dimitrakopoulos, 2008) implemented decision-making tools, namely cost-benefit and life-cycle cost analyses, in order to evaluate if a pre-earthquake strengthening of a large, heterogeneous building stock is feasible or not, and what the optimal retrofit level for mitigating the seismic risk is. In addition a cost-benefit and life-cycle cost analysis has been carried out by Chrysostomou et al. (Chrysostomou et al., 2015) to evaluate the effectiveness of a strengthening programme adopted in Cyprus and to evaluate the optimum retrofit levels for each building type examined. Moreover, their aim was to provide a guide for any future strengthening programme of important buildings characterised by unacceptable levels of earthquake risk. Also Liel and Deierlein evaluated mitigation alternatives for older concrete frame building through a cost-benefit assessment (Liel & Deierlein, 2013).

In this thesis a simplified methodology is developed to assess the most cost-effective intervention strategy for existing structures through a life-cycle cost procedure by means of an economic and seismic capacity performance evaluation in a structure’s life-time.

3.3 PROPOSED METHODOLOGY

This section describes the methodology for performing a seismic capacity assessment of a structure in its original and strengthened configuration, and for evaluating the economic performance during its life-time. The methodology proposed herein is based on the PEER’s approach, but this section also points out the differences between the two methods.

3.3.1 PEER approach

Performance-based earthquake engineering (PBEE) consists of the evaluation, design, and construction of structures prone to seismic risk. Different measures of seismic performance can be selected in a PBEE framework, such as economic loss, death, and the time a facility is unavailable. The most commonly used PBEE approach for the assessment of a life-cycle cost analysis is the "PEER methodology" developed by the Pacific Earthquake Engineering Research body (Keith Alan Porter, 2003).

The main advantage of this approach is that it also incorporates the uncertainty resulting from the estimation of damage to a construction and the associated repair costs. This methodology is wholly probabilistic and consists of the numerical integration of all the conditional probabilities propagating the uncertainties from one level of analysis to the next (Goulet et al., 2007).

Figure 1 schematically shows the PEER methodology, which works in four stages: hazard analysis, structural analysis, damage analysis, and loss analysis. Their outputs are, respectively, the intensity measure

(IM), the engineering demand parameters (EDPs), the damage measure (DM), and the decision variable (DV). The expression p[X|Y] refers to the probability density of X conditioned on knowledge of Y, and g[X|Y] refers to the occurrence frequency of X given Y (Keith Alan Porter, 2003).

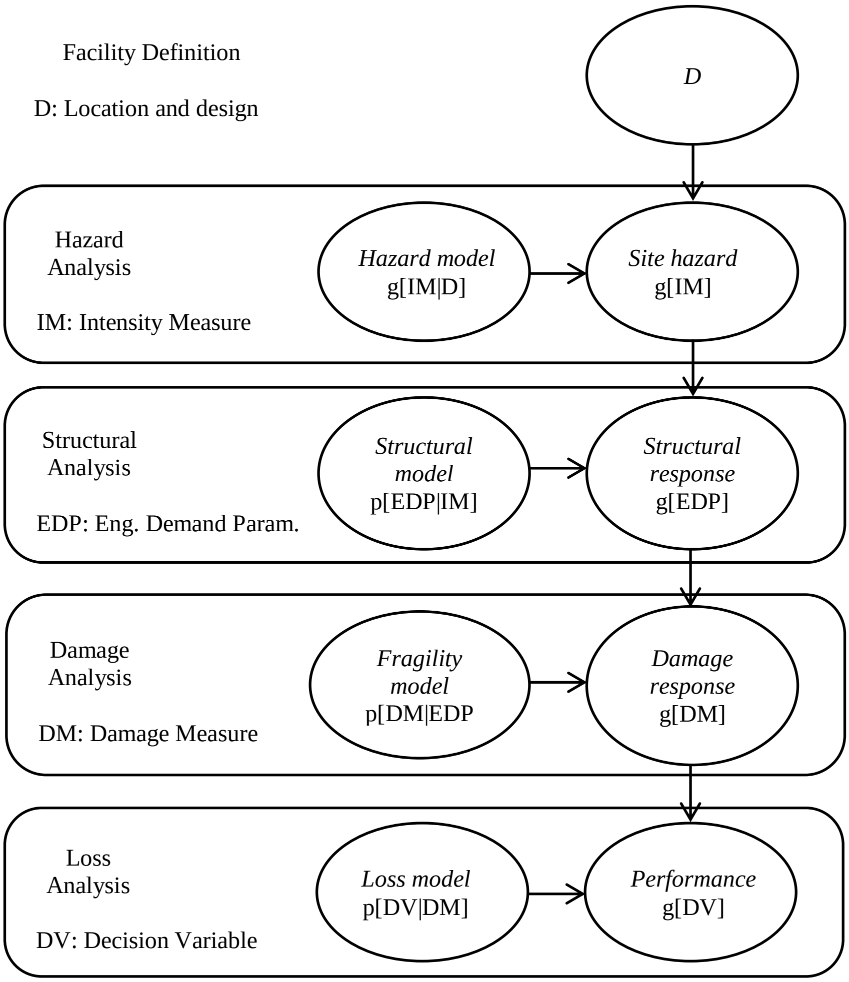


Figure 3.1 PEER analysis methodology

Consequently, the PEER framework equation is:

$$g\left[DV \mid D\right] = \int\int\int p\left[DV \mid DM\right] p\left[DM \mid EDP, D\right] \\ p\left[EDP \mid IM, D\right] g\left[IM \mid D\right] dIMdEDPdDM \tag{1}$$

where g[DV|D] is the mean annual probability that the DV exceeds a specific value given a facility, p[DV|DM] is the conditional probability that the DV exceeds a specific value of the DM, p[DM|EDP,D] is the derivative (with respect to the DM) of the conditional probability that the DM exceeds a limit value given a value of the EDP, p[EDP|IM,D] is the derivative of the conditional probability that the EDP exceeds a limit value given a value of the earthquake IM, and g[IM|D] is the derivative of the seismic hazard curve given a site location.

In the hazard analysis, the mean annual rate of exceedance of a particular ground-motion IM at the facility site is evaluated, assuming Poisson distribution model of earthquake occurrence.

In the structural analysis phase, an Incremental Dynamic Analysis (IDA) (Vamvatsikos & Allin Cornell, 2002) is performed to evaluate the response of the facility to the ground motion of a given IM in terms of inter-storey drift, peak floor acceleration, peak plastic hinge rotation or other EDPs. Each ground motion is scaled in increasing intensity until the onset of structural collapse. The IDA study is implemented through the following steps:

(i) define the nonlinear Finite Element model required for performing nonlinear dynamic analyses;

(ii) select a suit of natural records;

(iii) select a proper intensity measure and an engineering demand parameter;

(iv) employ an appropriate algorithm for selecting the record scaling factor in order to obtain the IDA curve performing the least required nonlinear dynamic analyses and

(v) employ a summarization technique for exploiting the multiple records results (Lagaros, 2010). Selecting IM and EDP is one of the most important steps of the IDA study. The EDPs are classified into four categories: engineering demand parameters based on maximum deformation, engineering demand parameters based on cumulative damage, engineering demand parameters accounting for maximum deformation and cumulative damage, global engineering demand parameters.

The third phase, the damage analysis, uses the EDPs with component fragility curves to estimate the probability that a component is in, or exceeds, a particular damage state. Once the damage state of a component has been estimated, it is possible to evaluate the repair efforts needed to restore the component, the relevant repair costs, operability, and the repair duration. These measures of performance are used in the fourth step to establish the probabilistic losses.

It is important to highlight that the methodology can be applied both to new and existing buildings, and can be used to:

(1) assess the probable performance of a building;

(2) design new buildings able to provide desired performance;

(3) design seismic retrofit interventions for existing buildings to improve their performance.

Moreover, the methodology can be applied to assess three different type of performance of a facility that are: intensity-based, scenario-based, and time-based assessments. Intensity-based assessments evaluate the probable performance of a building assuming that it is subjected to a specified earthquake shaking intensity. Scenario-based assessments evaluate the probable performance of a building assuming that it is subjected to an earthquake scenario consisting of a specific magnitude earthquake occurring at a specific location relative to the building site. Time-based assessments evaluate the probable performance of a building over a specified period of time (e.g., 1 year, 30 years, or 50 years) considering all earthquakes that might occur in that time period, and the probability of occurrence associated with each earthquake (Federal Emergency Management Agency, 2012).

The first to implement the method for evaluating the seismic damage to a building were Miranda and Aslani (H. Aslani & Miranda, 2004). Their study, in agreement with PEER methodology, assessed the economic performance of a building, taking into account the inter-storey drift and the acceleration of the top of the building as a parameter of the structural response.

This procedure may, however, be complicated, because of the type and amount of the required computations. This is why subsequent studies have been directed towards a simplification of PEER methodology in order to reduce the amount of information required or the time involved in performance estimations. This idea was backed up by the work of Ramirez and Miranda (Ramirez & Miranda, 2009), who tried to develop a more simplified process than their predecessors. In their study, they proposed an approach which, starting from the same basic principles of PEER methodology, reduced the amount of data that a designer must consider during the computations. This may be possible by introducing the functions which relate response simulation data directly to economic losses (EDP-DV functions).

The EDP-DV functions were also developed to estimate the damage to a component that does not have an appropriate fragility model using generic fragility functions based on empirical data.

3.3.2 Assessment of economic losses according to the proposed approach

In this study, a simplified semi-probabilistic methodology is proposed to easily assess the economic performance of a building prone to seismic risk. The approach developed consists of the same steps as the PEER methodology.

The first step is site hazard characterization, which is developed fully in a probabilistic way. Ground motion hazard characterization involves the quantification of an earthquake's IM. The probability of exceeding the intensity of a given earthquake can be evaluated in a simplified manner that is equal to the inverse of the return periods, T_R. In fact, the Italian code contains nine return periods for each site, and the nine data can be assumed to be the range of eight observation time intervals. Each interval is represented by the probability of the occurrence of a generic earthquake with a return period between two consecutive return periods set out in the code. The following formulation can be used to quantify the probability of occurrence of an earthquake *k* with an intensity belonging to a certain range of return periods:

$$p_{r,k}\left(T_{R,i} < T_{R,k} < T_{R,i+1}\right) \simeq \frac{1}{T_{R,i}} - \frac{1}{T_{R,i+1}} \quad (2)$$

where the subscripts *i* and *i + 1* define two consecutive return periods of the nine return periods of the building code, and $p_{r,k}$ is the probability of occurrence of an earthquake with a return period $T_{R,k}$ between $T_{R,i}$ and $T_{R,i+1}$.

The structural analysis step in the PEER methodology is simplified here by means of a static non-linear analysis instead of a non-linear time-history structural analysis, as also suggested by others to reduce the complexity of the process (Cardone, Sullivan, Gesualdi, & Perrone, 2017; Deierlein, 2004; Welch, Sullivan, & Calvi, 2014). Furthermore, also the FEMA P-58 guidelines suggest that, in certain conditions and with given limitations, simplified analysis method can be used as an alternative to non-linear time-history analyses providing the tool PACT (Performance Assessment Calculation Tool) for the assessment of Expected Annual Loss (EAL) (Federal Emergency Management Agency, 2012). The tool uses the empirical relationship of IDA curves with static pushover curves to estimate non-linear dynamic response, as proposed by Vamvatsikos & Cornell with the open source software, *Static Pushover 2 Incremental Dynamic Analysis* (SPO2IDA) (Vamvatsikos & Cornell, 2006). SPO2IDA is capable of recreating the seismic behaviour of oscillator with complex quadrilinear backbones. The software is an Excel workbook application designed to convert static pushover curves into approximate incremental dynamic analysis results.

The use of a non-linear static analysis improves the feasibility of the methodology making it suitable for common applications. Furthermore, such an analysis is commonly carried out by practitioners to assess the seismic capacity of existing structures and design strengthening interventions. This choice results in an average evaluation of the structural response given the intensity of the seismic event. Therefore, formally, in Equation (1), the term p[EDP|IM,D] is not introduced, since the structural response is not evaluated for different strong-motion input but is obtained from the intensity of the seismic event given the site hazard characterization. To do this, static non-linear analyses are carried out on the structure up to a maximum displacement corresponding to its global mechanism. In the simplified procedure proposed, the bi-linearization procedure is performed according to the N2 approach for each step of the pushover curve (Fajfar, 1999), instead of a quadrilinear backbone oscillator. Accordingly, a PGA value is derived for each step of the pushover curve as the demand intensity that would induce that particular structural response. It is possible to assume an average structural response for each hazard intensity, defined in terms of the PGA. The simplification of the approach is reflected in the fact that, given each deformation pattern of the structure during the different push-over steps, a set of average values for the EDPs is obtained. In other words, given the displacement value that controls the push-over curve associated with each hazard intensity (in terms of the PGA), average values for all the EDPs of interest are derived (e.g. inter-storey drift, IDR, and the spectral acceleration, SA, at each floor). Furthermore, it is possible to identify a PGA value corresponding to the maximum displacement of the curve. According to this approach, this value is assumed to be the hazard intensity that would induce the structural failure by activating the collapse mechanism. For each hazard intensity value equal to or greater than this, the occurrence of the structural collapse is assumed on average. In this case, there is no need to pass through the fragility models of each component for the derivation of the damage, and the economic loss is assumed to be equal to the overall reconstruction costs.

The basic assumption in pushover-based method is that structures are assumed to have independent translation response in the two horizontal axes (X and Y) and the structure vibrates predominantly in a single mode, thus separated analyses are carried out along these axis. This assumption is good for building with a regular shape, while for plan-asymmetric buildings some corrections factors can be adopted, based on the results of the elastic modal analysis to account for higher modes effects (Kreslin & Fajfar, 2012).

In the third step, to assess the damage to the building components, a set of fragility models are used providing, through the parameters of the structural response, the probability of occurrence of a certain level of damage. The building is divided into various components, both structural and non-structural, and for each of these a set of fragility curves is assigned that is representative of a certain intensity of damage. Therefore, more than one fragility curve can be assigned for each component, corresponding to a level of damage that is gradually greater. In detail, the EDPs that control the damage to each component are derived from the output of the structural analysis, and are used as an input to the fragility models in order to estimate the occurrence probability of each damage state.

Hence, in order to convert the damage to a component into a contribution to the economic losses of the building, it is necessary to compute the cost of each repair/recover intervention from the damage level or substitution. In fact, for each fragility curve, the damage state corresponds to the economic layout needed to restore the component to an undamaged state. This allows us to assess the economic losses of the entire building as the sum of the repair/recovery costs of each component multiplied by the probability of occurrence. A further difference with the classical PEER approach holds in the computation of the repair costs; here only the average values are considered and the randomness parameters for the cost distributions are not used.

In other words, the expected annual loss of the building can be computed as:

$$EAL = \sum_{i=1}^{n} \sum_{DS_j} \overline{C}_{i,DS_j} \int p\left[DS_j \mid \overline{EDP_j}(IM)\right] g\left[IM \mid D\right] dIM \qquad (3)$$

where:

- n is the number of the building components;
- DS_j is the j-th damage state of the fragility model of a component;
- $C_{i,SDj}$ is the cost to restore the component i due to the damage state DS_j;

- $\int p\left[DS_j \mid \overline{EDP_j}(IM)\right] g\left[IM \mid D\right] dIM$ is the probability of occurrence of the damage state DS_J for the i-th component given depending on an average set of EDPs and the intensity measure.

The difference with Eq. (1) is in the absence of the derivative of the conditional probability that the EDP exceeds a limit value given a value of the earthquake's IM. Finally, the economic loss calculated according to Equation (3) is computed over the life-time of the building and multiplied by the discount rate in order to actualize the total losses. Present-value discounting accounts for the time-value of money, recognizing that money paid or earned today is valued more than the same amount in the future. The discount rate is determined from interest rates and adjusted for inflation, and traditionally ranges from 2% to 6% (Nuti & Vanzi, 2003). This can be calculated using the following equation:

$$D_r = \sum_{i=1}^{V_n} \left(\frac{1}{1+d} \right)^i \qquad (4)$$

where d is the value of the yearly discount rate and V_n is the life-time of the structure.

For further clarification it is necessary to point out that this approach is significantly different from Vamvatsikos and Cornell (Vamvatsikos & Allin Cornell, 2002) in which the structural model is transformed into a SDOF system and subjected to one (o more) ground motion record(s), scaled to multiple levels of intensity, thus producing one (or more) curve(s) of response parametrized versus intensity level. There is no doubt that IDA analysis provides the most accurate estimation of the seismic behaviour of the structures among all analysis method but it is very time consuming.

The proposed approach is much similar to the Incremental N2 (IN2) method proposed by Dolsek and Fajfar (Dolšek & Fajfar, 2004). This method is a simple tool and can be employed for the determination of the approximate summarized IDA curves. The seismic demand is determined for multiple levels of seismic intensity using the N2 method (Fajfar, 1999) (based on pushover analysis and inelastic response spectrum) by means of oscillator with complex quadrilinear backbones. The quantities used to represent the intensity measure and the engineering demand parameter are the spectral acceleration at the natural period of the equivalent single-degree-of-freedom (SDOF) model and the top displacement. An IDA curve is determined with nonlinear dynamic analyses, while each point of an IN2 curve (approximate IDA curve), which corresponds to a given seismic intensity, is predicted with the N2 method.

The IN2 curve can substitute the IDA curve in the probabilistic framework for seismic design and assessment of structures. A reasonable accuracy of the IN2 curve is shown in comparison with the IDA curve for the examples adopted (Dolšek & Fajfar, 2007). The dispersion measures for randomness parameters βi cannot be determined from the results of the IN2 analysis and are predetermined.

On the contrary, in the approach here proposed the randomness parameters for the structural response βi have not been introduced since the final scope of the procedure is the evaluation of the expected annual loss. Thus, both for the structural response, given the intensity measure, and for the replacement costs of the components, given the damage limit state, only the average values have been used. This approach can be interpreted as a further simplification of the IN2 method where the PGA is used as intensity measure instead of the Spectral Acceleration. Moreover, SDOF models have not been used to perform dynamic analysis, but to assess damage levels on building components and the expected economic loss.

3.3.3 Optimization of strengthening interventions

The proposed methodology aims to identify the most cost-effective strengthening strategies and strengthening levels (i.e. strengthening intervention associated with a given safety level) for existing structures over their life-cycle. Indeed, the structural analysis could show a very low safety level for the structure in the original configuration and a strengthening intervention could be necessary. The safety level, expressed as a percentage, represents the ratio between the capacity of the structure, the PGA capacity, and the demand of the quake, namely the PGA demand. Analysing the pushover curve step-by-step, a PGA value can be associated with each step. The PGA associated with a failure is defined as the PGA capacity. A safety level of 100% means that, once strengthened, the building has achieved a safety level equal to that required of a new building designed according to current seismic code provisions.

In order to determine the most cost-effective strengthening solution, it is necessary, once the intervention strategy is identified, to calculate on the one hand the costs of strengthening the structure and, on the other, the expected seismic losses in the structural life-time at different performance levels (i.e. safety levels). In particular, each performance level corresponds to a level of strengthening intervention and relevant costs. Therefore, the cost of strengthening the building for various safety levels is obtained. The result will be a curve of costs that increase with the increase of the strengthening actions.

Both interventions that increase structural stiffness (and thus limit displacements), and those that increase ductility, generate a potential level of damage to the structure in its life-time that is lower than that which would occur to the structure if it were not strengthened. The goals are to assess whether the cost of the strengthening is beneficial enough to justify the intervention in the structural life-time of the building, and to identify the optimal strengthening level. For each safety level, the sum of the costs of the strengthening interventions and the economic loss associated with such a safety level is called the "expected total cost" for the building. The maximum safety level corresponding to the lowest value of the expected total cost will represent the most cost-effective solution, as set out in Figure 3.2. This Figure reports three curves: 1) the "economic loss" curve, which represents the economic losses related to several safety levels (the first point of the curve is the economic loss if no strengthening interventions are made; for the sake of simplicity in Figure 3.2, this point is related to a very low safety level, as commonly found in existing structures); 2) the "cost of the strengthening intervention" curve, which reports the costs required to attain a given safety level; and 3) the "expected total cost" curve, which is the sum of the costs reported in the previous curves associated with each safety level.

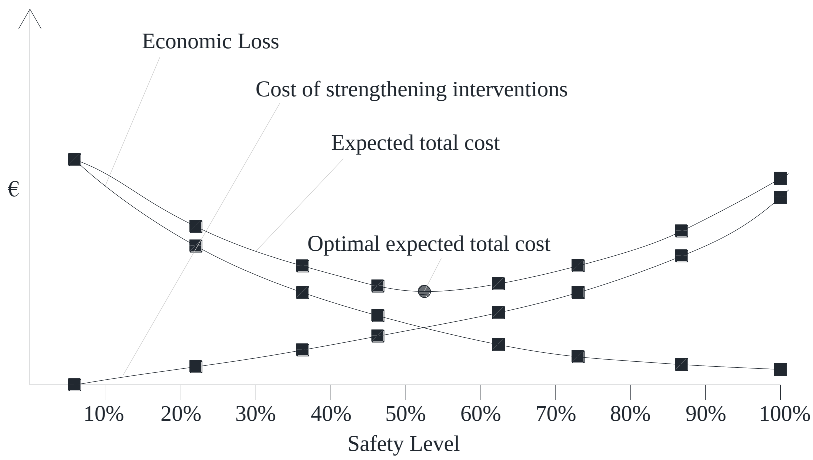


Figure 3.2 Procedure for the strengthening optimization

The curves are a schematic representation of the methodology. Generally, lines have a piecewise linear trend that depends from the number of cases related to the safety level analysed.

It is worth nothing that the curves may be determined for different strengthening strategies involving different strengthening techniques in order to identify the most cost-effective strengthening solution. The cost-effectiveness of retrofitting is highly dependent on the cost of the retrofit, the level of strengthening, the seismicity of the region, and the time horizon considered (Liel & Deierlein, 2013).

Using this procedure, it is possible to provide practitioners with an additional tool to quickly evaluate what is the best decision to make concerning an existing building from an economic point of view. It should be noted that the best choice from an economic point of view may not reach an adequate safety level, meaning that the safety level required may also be selected according to code provisions and as a balance between the reduction of expected seismic loss in the structural safety life-time and a proper safety level selected according to social factors.

As a summary, Figure 3.3 shows the scheme of the proposed methodology divided into seven simple steps. The first and second steps involve a suite of static non-linear analyses of the strengthened structure using several strategies aimed at achieving target security levels (risk indices). The fourth, fifth, and sixth steps concern the cost of the strengthening interventions, the total expected cost, and, thus, the most cost-effective level of strengthening for each strategy. Finally, the seventh step identifies the most cost-effective intervention strategy.

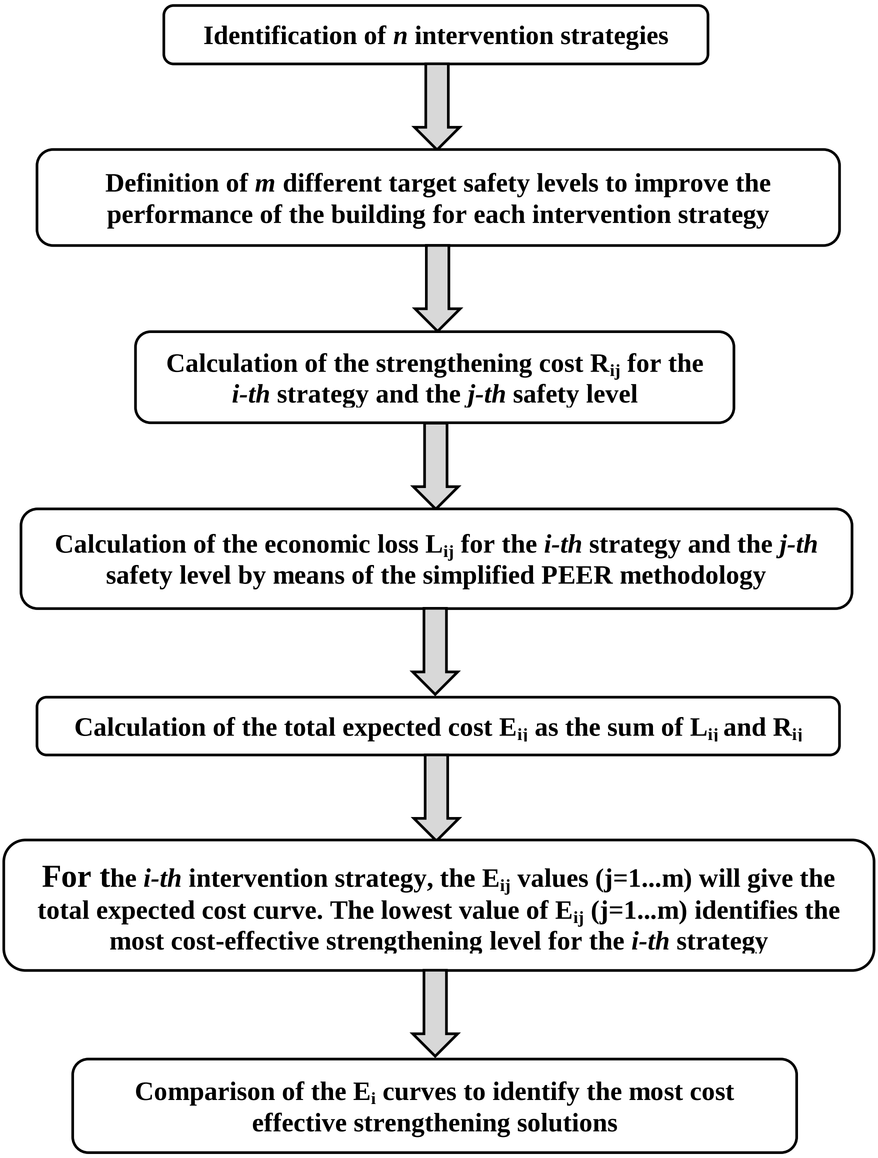


Figure 3.3 Schematic of the proposed methodology

3.4 IMPLEMENTATION OF THE PROCEDURE

A building located in the city of L'Aquila has been chosen as a case study for implementing the procedure described in the previous sections. The building has an approximate L shape in the plane configuration and five storeys. The structure is made up of reinforced concrete frames in two directions that are connected by secondary beams. The geometry and the details of the main elements have been derived from the original design drawings.

The floor plan of the building has dimensions of 32.0 m in one direction and 27.0 m in the other, with a total area of about 368 m^2 (Figure 3.4). The length of the beams is extremely variable, even within the same frame. The total height of the building is 20 m. It consists of five floors with a storey height of 3.3 m, except for the first floor, which is 3.5 m. The first floor is used as a garage and the other floors for residential purposes.

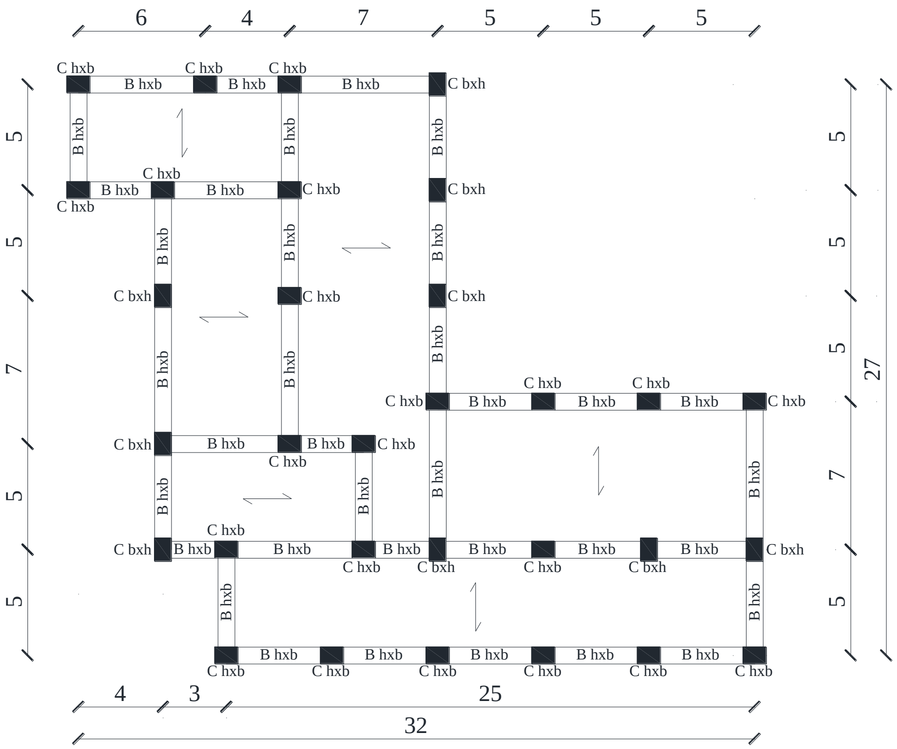


Figure 3.4 Floor plan of the building (Lengths are in meters)

The overall cast-in-situ RC one-way slabs thickness is 24 cm with a deck of about 4 cm which ensure the rigid diaphragm effect for each floor.

Geometrical proprieties of the elements are listed in the Table 3.1.

	Columns	Beams
First Storey	0.55x0.40, LR: 10Ø16, TR: Ø6/25 cm	0.50x0.40, LR: 9Ø12, TR: Ø6/25 cm
Second Storey	0.50x0.40, LR: 10Ø16, TR: Ø6/25 cm	0.50x0.40, LR: 9Ø12, TR: Ø6/25 cm
Third Storey	0.50x0.35, LR: 8Ø16, TR: Ø6/25 cm	0.50x0.35, LR: 7Ø12, TR: Ø6/25 cm
Fourth Storey	0.45x0.35, LR: 6Ø16, TR: Ø6/25 cm	0.50x0.30, LR: 7Ø12, TR: Ø6/25 cm
Fifth Storey	0.45x0.35, LR: 6Ø16, TR: Ø6/25 cm	0.50x0.30, LR: 7Ø12, TR: Ø6/25 cm

LR Longitudinal Reinforcement; TR Transverse Reinforcement

Table 3.1 Longitudinal and transverse reinforcement details

The longitudinal reinforcement represents the total rebar amount of the beams. The beams reinforcement is not symmetric. Two rebars are in the corners of the compressive zone while the other rebar are located in the tensile zone (equally distanced from each other).

In addition to the original design drawings, several destructive and non-destructive tests were carried out on the building to investigate the material mechanical properties. These tests found that the building consists of structural elements reinforced with smooth bars.

It was possible to determine the following mechanical properties from the destructive and non-destructive tests: the concrete compressive strength f_{cm} = 12.5 MPa; and the steel tensile strength f_{ym} = 279.1 MPa.

As reported previously, the first step of the procedure is the site hazard characterization. The probability of exceeding the intensity of a given earthquake is evaluated as the inverse of the return period. Indeed, in the application case, the vulnerability curve is divided into a discrete number of points that are the eight intervals of observation obtained by the nine return periods of the site.

Nonlinear building response was simulated, as in chapter 2, with finite element software (SAP2000) (Computer and Structurers, n.d.), using lumped plasticity models of beams and columns (4 hinges for each structural member: top and bottom for both directions). Column and beam plastic hinge models are calculated according to the European Code UNI-EN 1998-3: 2005 (E. Standard, 2005) as shown in §2.3.1.

In this application case, the EDP assumed is the relative displacement between the various floors, defined as IDR (inter-storey drift). This parameter is the most representative of the structural damage of almost all the components, and is the most simple to assess. Nevertheless, to derive other EDPs, different approaches can be followed as reported in FEMA P-58 with empirical relationships depending on the peak ground acceleration at each step of the pushover curve (Federal Emergency Management Agency, 2012).

All the floor displacements, and then all the relative displacements, are known from the structural analysis. This means that in the application case for the structural and non-structural elements belonging to the same storey, only one EDP, which is the relative inter-storey drift, has been assumed. Once the hazard and EDP have been defined, it is possible to identify the state of the damage to each structural component according to suitable fragility curves. In the application case, if the shear action is higher than the shear strength of an element it has been considered the failure of the element as damage state. Accordingly, in case of shear failure the cost of the damage is equal to the cost of replacement of the RC member. It is then also possible to obtain the economic losses relating to each step of the pushover curve. At this stage, it is necessary to calculate the value of the discount rate in the structure's life-time. The discount rate is largely dependent on two factors, which appear to be closely related: the inflation and interest rates of the central bank. It is very difficult to predict economic performance over a period of several years, and so it is necessary to assume a value of the average discount rate that may realistically occur in the time window. In this application, an annual rate equal to 2% has been assumed.

The nominal life-time of the structure has been chosen to be equal to 50 years, which is the period usually attributed to buildings without any strategic importance. The economic loss of the building may be computed by a simplified equation that multiplies the cost of the economic damage of the pushover step (corresponding to the demand related to several return periods) for the probability of occurrence:

$$EAL = D_r \times \sum_i \left(C_i \times p_{r,i} \right) \qquad (5)$$

where C_i is the cost of a generic step, the subscript i represents the eight time slots considered by the Italian Code, and D_r is the total discount rate.

3.4.1 Fragility curves

First, it is important to assign an economic value to each component of the building under investigation using a document that allows the components to be associated with a relative economic value. The price list of the Abruzzo region has been used in support of this assessment. This was produced in 2009 after the earthquake of 6 April of that year.

Furthermore, in this application case, the structure is divided into four components (both structural and non-structural): beam-column joints, beams and columns, drywall partition, and MEP systems (mechanical, electrical and plumbing systems).

Fragility curves adopted in this work have been chosen from the fragility models available in literature, after in-depth research.

- Beam-column joints

A study by Pagni and Lowes (Pagni & Lowes, 2006) was used to define the beam-column joint fragility curves. This defines four damage states (DS):

DS1: First opening of cracks.

DS2: Concrete spalling of at least 30% of the surface of the joint panel.

DS3: Concrete spalling of at least 80% of the surface of the joint panel.

DS4: Collapse of the joint.

Table 3.2 shows the mean and standard deviation for each DS.

Joints	IDR	
	Mean [%]	Standard deviation
DS1	1.40	0.57
DS2	2.60	0.50
DS3	3.10	0.45
DS4	3.70	0.26

Table 3.2 Joint fragility curves (Pagni & Lowes, 2006)

Table 3.3 provides the repair cost of each DS.

Joints		
Damage State	**Repair Efforts**	**Unit Cost**
DS1	House painting	15€/m^2
DS2	Cleaning of the concrete surfaces	10€/m^2
	Resin injection	179€/m^2
DS3	Removing of the damaged concrete surfaces	10€/m^2
	Cleaning of the concrete surfaces	10€/m^2
	Resin injection	179€/m^2
	Adjustment of steel reinforcement	131€/m^2
DS4	Removing of the damaged concrete surfaces	10€/m^2
	Cleaning of the concrete surfaces	10€/m^2
	Resin injection	179€/m^2
	Adjustment of steel reinforcement	131€/m^2
	Re-arrangement of the steel bars	50€/m^2

Table 3.3 Repair Cost of each damage State

- Beams and columns

The estimation of the probability of exceeding a certain level of damage to the beams and columns with a low amount of reinforcement was determined according to the work of Aslani and Miranda (Hesameddin Aslani & Miranda, 2005). For these elements, the following DS are identified:

DS1: light cracking.

DS2: severe cracking.

DS3: member shear failure.

The mean and standard deviation values depend on the geometrical properties of the elements. For this reason, fragility curves have been calculated for the elements belonging to each floor of the building under investigation in the present study. Table 3.4 shows the mean and standard deviation values obtained for the structural elements of the first floor.

Beams and columns	IDR	
	Mean [%]	Standard deviation
DS1	0.35	0.37
DS2	0.75	0.44
DS3	1.00	0.58

Table 3.4 Beam and column fragility curves (Hesameddin Aslani & Miranda, 2005)

Table 3.5 provides the repair cost of each DS.

Beams and Columns		
Damage State	**Repair Efforts-**	**Unit Costs**
DS1	House painting	15€/m^2
DS2	Cleaning of the concrete surfaces Resin injection	10€/m^2 179€/m^2
DS3	Cleaning of the concrete surfaces Resin injection Adjustment of steel reinforcement Re-arrangement of the steel bars	10€/m^2 179€/m^2 131€/m^2 50€/n°

Table 3.5 Repair Cost of each damage State

- Drywall partitions

A study by Ruiz-Garcia and Negrete (Ruiz-García & Negrete, 2009) was used to define fragility curves related to internal and external partitions. This contains a database of experimental tests carried out on various types of partition element, some of them compatible with Italian ones. For the definition of fragility curves for drywall partitions, it is common to only use two DS:

DS1: formation of cracks on the member surface no larger than 0.1 mm.

DS2: formation of X-shaped cracks on the member surface of about 5 mm and relevant concrete spalling in the beam-column joint panel.

The parameters related to the fragility curves are shown in Table 3.6.

Partitions	IDR	
	Mean [%]	Standard deviation
DS1	0.10	0.73
DS2	0.35	0.57

Table 3.6 Partition fragility curves (Ruiz-García & Negrete, 2009)

Table 3.7 provides the repair cost of each DS.

Partitions		
Damage State	**Repair Efforts**	**Unit Costs**
DS1	House painting Plaster	15€/m^2 25€/m^2
DS2	Demolition Reconstruction	80€/m^3 501€/m^3

Table 3.7 Repair Cost of each damage State

- MEP Systems

In implementing the procedure, it has been assumed that the mechanical, electrical, and plumbing systems need to be replaced if they are within very damaged partitions (i.e. the partition has to be demolished). Accordingly, the fragility curve of their only DS is perfectly equal to DS2 of the drywall partitions. This means that if the

partitions achieve DS1 as the damage state, the systems do not need to be replaced.
Nevertheless, ASCE/SEI 41-13 assesses that (American Society of Civil Engineers, 2014) seismic interactions between non-structural components and systems may have a profound influence on the performance of these systems. In particular, the designer should consider the essential post-earthquake functions of the building in order to identify the mechanical, electrical, and plumbing components that must operate for the building to function. For the sake of simplicity, this aspect has not been considered.

3.4.2 Economic loss

The economic loss is given as the sum of the repair costs of the damaged components at each ground-motion IM (i.e. PGA or drift) and the cost related to the unavailability time of the facility, named the cost of building unavailability in the following.

- Component repair costs

Each DS corresponds with one or more repair processes. The sum of the repair processes' costs provides the actual economic loss associated with a component (structural or non-structural). The economic loss is expressed as the ratio between the repair and reconstruction costs of the component. It is worth noting that, for a severe DS, the cost of repair could largely exceed the reconstruction cost (i.e. the economic loss in this case is greater than 1).

- Casualty and injury costs

The framework proposed may be improved with the addition of losses related to injuries and casualties as a number of references may be used to quantify the cost of human life (e.g. Coburn and Spence

(Coburn & Spence, 2003)). Introduction of costs related to human life could increase the benefit/cost ratios in some cases up to 8 times, thus shifting the outcome of the analysis towards the feasibility of retrofit (Kappos & Dimitrakopoulos, 2008). Nevertheless, this aspect is out of the scope of the application case even if the framework may be improved by including it.

- Cost of building unavailability

In order to determine the economic losses, it is also necessary to evaluate the costs related to the unavailability of the building due to a destructive earthquake. In particular, in the case of seismic actions that produce a certain level of structural damage, the building may not be usable. As a consequence, additional costs should be computed by accounting for the payment of alternative accommodation for those who lived in the building. This sum, of course, depends on how long the building is unavailable. The unavailability cost for each person has been evaluated in the present application taking into account the fact that each inhabitant of the building must be hosted in a comfortable hotel for the entire period the building is unavailable. In the case study, the average daily cost of staying in a hotel was estimated to be about € 17,00 per person. According to National Statistics Institute (ISTAT) data (http://www.tuttitalia.it/abruzzo/provincia-dell-aquila/statistiche/ popolazione-andamentodemografico/), in L'Aquila there is an average density of three persons per dwelling. Accordingly, in total, the daily cost of unavailability in the case study has been computed as follows:

$$C_{in} = n_{ap} \times d_{ab} \times C_{pers} \qquad (6)$$

where n_{ap} is the number of dwellings in the building, d_{ab} is the average density for each dwelling, and C_{pers} is the daily cost of a hotel stay for

each resident. In this application case, n_{ap} is 8 and thus the daily total cost of the unavailability of the building is approximately € 408,00.
The usability disruption is very complicated to predict, due the variability of many factors. In this study, an unavailability time as a function of the level of the structural damage has been established. This time has been assumed to be in a range between 6 and 18 months, and has been evaluated as the ratio between the loss due to structural damage and the cost of unavailability for six months. This ratio is assumed to be at least one and no more than three. For partial or total collapse, or for very severe structural damage (i.e. if demolition is needed), an unavailability time of 36 months has been assumed.
So, at this stage, the expected economic loss of the building over its structural life-time can be computed according to Eq. 5. In this study, Eq. 5 provides the following loss in Euros:

$$L_{V_n} = T_S \times \begin{bmatrix} C_{30-50} \times p_{r,30-50} + C_{50-72} \times p_{r,50-72} + C_{72-101} \times p_{r,72-101} + \\ C_{101-140} \times p_{r,101-140} + C_{140-201} \times p_{r,140-201} + C_{201-475} \times p_{r,201-475} + \\ C_{475-975} \times p_{r,475-975} + C_{975-2475} \times p_{r,975-2475} \end{bmatrix} \approx$$

$$\approx 1350 k€$$

This economic loss corresponds to the original building’s structural capacity (i.e. the safety level of the building if no strengthening interventions are made). If the capacity of the building needs to be increased, as commonly happens in existing structures, several strengthening strategies and relevant techniques may be selected. Each strategy implies an intervention cost as a function of the target safety level. In the present study, several strengthening techniques have been investigated and relevant costs have been determined in order to define the total expected cost curves. According to these curves, it is possible to select the strengthening strategy that minimizes the total expected costs with a maximum safety security level.

3.5 STRENGTHENING INTERVENTION STRATEGIES

As stated in the previous chapter, strengthening strategies aiming at increasing ductility, stiffness, and strength, or all of them, have been selected, as is common practice. In this chapter the strengthening techniques investigated are the same as in chapter 2 with the addition of RC jacketing-based strengthening solution. This solution consists of the RC jacketing of beams and columns to increase the flexural and shear capacity of members, as well as ductility, and to increase the global structural stiffness.

Shear walls-based strengthening solution consists in the insertion of two internal shear walls in both the plan directions of the building.

In order to carry out an analysis of the economic viability of a strengthening strategy, it has been assumed that the performance of the building at different strengthening levels is improved. The strengthening levels have been related to the safety levels, which are computed as the ratios between the structural capacity and the seismic demand in terms of the PGA. The safety level of 100% corresponds to strengthening interventions providing a structural capacity equal to the structural demand related to a severe earthquake with a return period of 475 years (i.e. the safety level currently required for new ordinary buildings designed according to current seismic code provisions).

Two non-linear static analyses have been performed for the two plan directions of the structure independent from each other (x-x and y-y directions). Accordingly, the most unfavourable from an economic point of view has been chosen (y direction). The horizontal load pattern assumed in the analysis is a first mode force pattern and has been defined according to the European Building code (European Standard, 2004). This horizontal load pattern is obtained from the displacement distribution of the modal analysis. The pushover curve

has been divided into different points, and each of them corresponds to a safety level. For each safety level, a structural analysis has been performed to identify all the brittle failures (shear failure on beams, columns, or beam-column joint panels). This allows us to determine a list of elements that needs to be strengthened (i.e. capacity lower than the demand). A price is associated with each action necessary for the strengthening of the element, the sum of the cost of the materials, and the manual workers required. Note that if the strengthening intervention modifies the structural stiffness, the pushover curve has to again be determined at each step of the analysis (i.e. the effective structural period changes and so does the displacement demand).
With the progress of the pushover curve (i.e. by increasing the top displacement), there is an increase in the failures that may occur in the elements. Increasing the number of failures, obviously, also increases the cost of achieving a given safety level for the structure.
The result is a cost curve that gradually increases with the increase of the safety level of the building, as shown in Figure 3.5 for each selected strengthening strategy. The curves have been computed up to a safety level of 100%. Table 3.8 provides also a breakdown of prices of each retrofit scheme.

Strengthening Strategies	Unit Costs
FRP*	370€/m^2/(n° of layer)
SHEAR WALLS**	3830€/m^3
BASE ISOLATION***	9822€/(n° of device)
RC JACKETING****	9960€/m^3
RC JACKETING & FRP****	9960€/m^3

Table 3.8 Breakdown of prices of each retrofit solution

* Crack injections, sand blasting, primer, putty, saturant, demolition and reconstruction of partitions and partition paintings are included;

** Rebars arrangement, formwork, concrete casting, foundation strengthening, demolition and reconstruction of partitions, partition paintings and check or restoration of all the systems (water supply, electric installation, etc.);

*** Retrofit procedures, installation and maintenance of devices, execution tests and steel plate for the foundations are included;
**** Rebars arrangement, formwork, concrete casting, demolition and reconstruction of partitions, partition paintings and check or restoration of all the systems (water supply, electric installation, etc.);
***** All the operations computed for * and **** are included.

The cost of strengthening works have been obtained from the price list of the Abruzzo region (Regione Abruzzo, n.d.).
For RC Jacketing and RC Jacketing & FRP the unit costs are average values, because the influence of demolition and reconstruction of non-structural elements on the unit costs depend on the strengthening target that one wants to achieve. The unit costs reported are evaluated considering as unit measure the amount of concrete casting necessary for the strengthening of the rc elements.

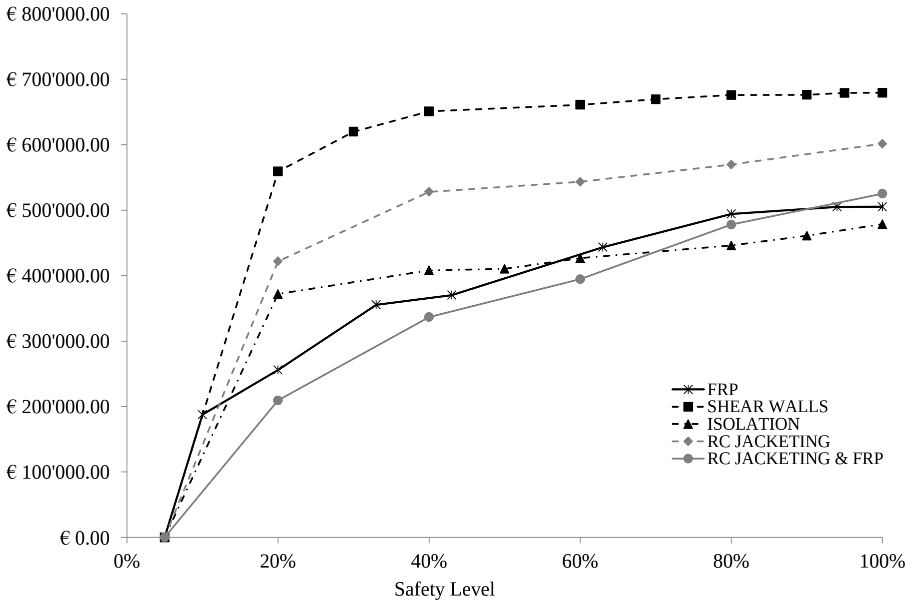


Figure 3.5 Cost of the strengthening interventions

In Figure 3.5, the dashed line represents the cost trends, which have been determined only for selected points. The safety increase may imply one or more strengthening interventions on different structural members depending on the retrofit strategy and technique; in the case of FRP based strategy a selective strengthening strategy is possible, the costs gradually increase by slightly increasing the structural safety level. For each failure corresponding to a given safety level, a localized strengthening solution may be designed with a slight but significant cost increase; this is possible because FRP does not imply stiffness variation. Accordingly, the curve may be obtained by connecting several points corresponding to different safety levels and strengthening costs. The curve related to the FRP-based strategy has an almost linear trend, except for the first branch. A similar trend can be also observed on the curve related to the FRP and/or RC jacketing strengthening strategy.

In the other cases (i.e. shear walls, base isolators, and RC jacketing), the curves show an initial strong increase in costs, even for a slight increase of safety levels. This because the stiffness or structural period is significantly changed in order to improve the structural seismic capacity or reduce the seismic demand. Then, with low additional costs, the safety level may be significantly increased by up to 100% (i.e. the curve has an almost constant trend). This is because these strategies imply a significant initial cost investment of applying the strengthening technique (e.g. the insertion of shear walls on each floor or the insertion of base isolators at the foundation level are clearly costly interventions), but then only few members may need to still be strengthened to avoid localized failures. Table 3.9 shows the number of structural elements strengthened for each safety level.

	Safety Level				
	20%	40%	60%	80%	100%
FRP	FSS to 44 Columns 37 Beams	FSS to 3 BCJ, 84 Columns, 42 Beams	FSS to 30 BCJ, 105 Columns, 50 Beams	FSS to 43 BCJ, 118 Columns, 59 Beams	FSS to 48 BCJ, 124 Columns, 68 Beams
SHEAR WALLS	RCSW; FSS to 63 BCJ, 31 Columns, 39 Beams	RCSW; FSS to 64 BCJ, 92 Columns, 39 Beams	RCSW; FSS to 65 BCJ, 94 Columns, 53 Beams	RCSW; FSS to 67 BCJ, 104 Columns, 66 Beams	RCSW; FSS to 68 BCJ, 105 Columns, 75 Beams
BASE ISOLATION	BID; FSS to 2 Columns	BID; FSS to 6 Columns	BID; FSS to 10 Columns	BID; FSS to 4 BCJ, 11 Columns, 8 Beams	BID; FSS to 12 BCJ, 11 Columns, 17 Beams
RC JACKETING	RCJ to 131 Columns, 84 Beams	RCJ to 165 Columns, 88 Beams	FSS to 5 BCJ; RCJ to 165 Columns, 152 Beams	FSS to 31 BCJ; RCJ to 165 Columns, 162 Beams	FSS to 61 BCJ; RCJ to 165 Columns, 166 Beams
FRP & RC JACKETING	FSS to 57 Columns, 49 Beams; RCJ to 35 Columns	FSS to 80 Columns, 61 Beams; RCJ to 70 Columns	FSS to 68 Columns, 77 Beams; RCJ to 95 Columns	FSS to 9 BCJ, 25 Columns, 104 Beams; RCJ to 140 Columns	FSS to 11 BCJ, 114 Beams; RCJ to 165 Columns

FSS = FRP Shear Strengthening; BCJ = Beam-Column Joints; RCSW = 4 RC Shear Walls (2 per direction); BID = Base Isolation Devices; RCJ = RC Jacketing

Table 3.9 Number of structural elements strengthened for each safety level

The next step consists of calculating the economic loss of the structure, according to the procedure described above. This assessment is made for the different safety levels for which the building is gradually strengthened. The economic loss trend related to each strengthening strategy is depicted in Figure 3.6. As expected, the curve trend is again almost linear for the FRP and the FRP and/or RC jacketing strategies, while an initial significant loss reduction is shown for the other strategies.

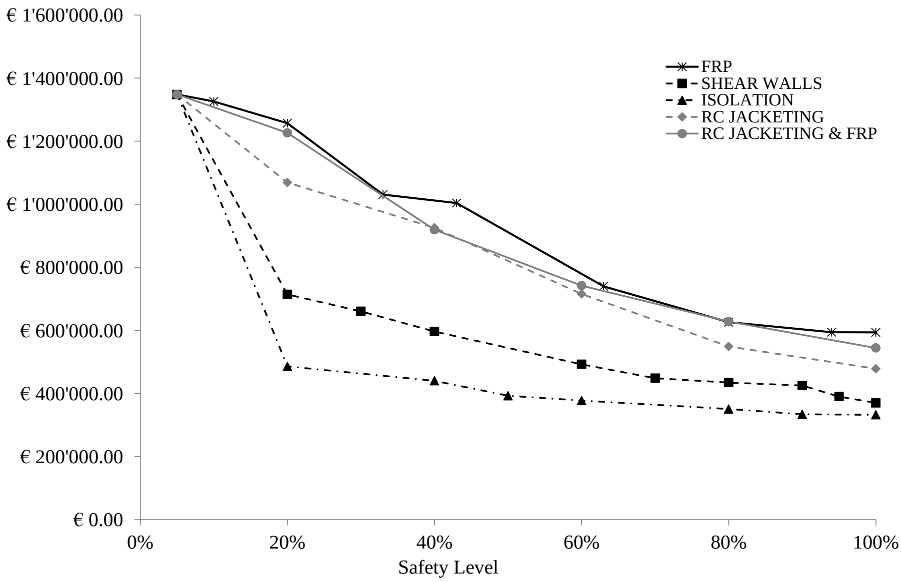


Figure 3.6 Expected economic losses

To check if a reinforcement intervention is cost effective for an owner, it is necessary to add the cost of the strengthening intervention and the loss of the structure for each safety level, thereby obtaining the total expected cost. This graph is shown in Figure 3.7. The graph shows that, for the case under investigation, the isolation strategy is the most cost-effective solution. The curve has a decreasing trend up to the optimal point, which corresponds to a safety level of 90%, with an expected total loss reduction of about 40% (i.e. 810,000 Euros/1,350,000 Euros) with respect to the no strengthening intervention case (for which the safety level is about 5%). In the other cases, the optimal point corresponds to 100% of the safety level, with an expected total loss reduction in the range of 28% - 32%. The strategy based on the insertion of RC walls also shows a strictly decreasing trend. The difference between these strategies and the other three is that the curves related to them have an initial increasing, and then a decreasing, trend. This means that, in order to define the most cost-effective intervention, in the case of the FRP-based or FRP and/or RC jacketing-based strategies, at least a certain minimum safety level should be attained to reduce the total expected losses with respect to the case of no strengthening: almost 40% for FRP combined with RC jacketing; and 50% and 55% for the FRP and RC jacketing strategies, respectively. If such safety levels are not attained, the strengthening solution, although it provides a benefit in terms of safety, is not economically viable. This confirms that the selection of the most effective strengthening strategy from both a structural and economical point of view is a challenging task. Furthermore, each strengthening strategy may imply a different minimum safety level to reduce losses in the structural life-time of the building.

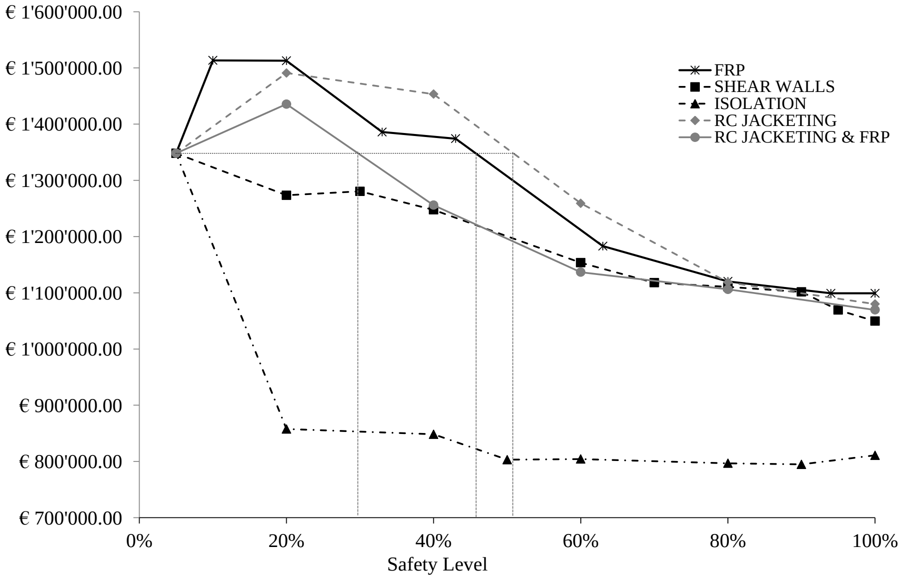


Figure 3.7 Total expected costs

Overall, the system boundary adopted for the LCC study is a kind of cradle-to-gate because the end of life phase has not been included in this application case. It is necessary to clarify, that assumptions about the disposal of materials from buildings after they are demolished may affect the results in terms of costs over the lifecycle

Finally, it may be interesting to underline that the building chosen as case of study was severely damaged by the 2009 L'Aquila earthquake. According to practitioners' calculations the repair and strengthening interventions were not economically viable. Therefore, the building was demolished and rebuilt with a total amount of 2,000,000 Euros which is significantly higher than optimal expected total cost.

3.6 MULTI-HAZARD ANALYSIS

The results of a life-cycle cost analysis, as shown, depend on different parameters. In fact, it is clear that the final results will be different when applying the same procedure, with the same fragility curves and the same strengthening strategies, to different structures or different building locations. For this reason, a multi-hazard analysis has been carried out to investigate the influence of the local seismic hazard on the most cost-effective solution. In the analysis, it is assumed that the building previously investigated is located in different sites with different PGA values belonging to four different seismic zones. In particular:

- Zone 1 – High seismicity [PGA higher than 0.25g.] (which is the case previously analysed).
- Zone 2 – Mean seismicity [PGA between 0.15 and 0.25g].
- Zone 3 - Low seismicity [PGA between 0.05 and 0.15g].
- Zone 4 – Very low seismicity [PGA lower than 0.05g].

The value of the economic loss of the building gradually decreases with the decreasing intensity of the PGA. Indeed, the probability of occurrence of the eight earthquakes is the same, but in each case the damage to the components changes. In Figures 3.8 3.9 and 3.10, the total expected loss curves are reported with reference to the mean, low, and very low seismicity zones (i.e. a PGA demand corresponding to a return period of 475 years has been assumed to be equal to 0.168g, 0.071g, and 0,049).

The Figures show that the isolation strategy is also the most cost-effective strengthening intervention for a PGA value belonging to the mean seismicity zone (see Figure 3.8). In this case, the FRP strategy is highly competitive, but a safety level of at least 50% has to be attained in order to define the most economically advantageous intervention. The other three strategies are definitely not effective from an economic point of view, because the total expected costs are greater than those related to the case where there is no strengthening intervention in the useful life-time of the structure, L_{Vn}.

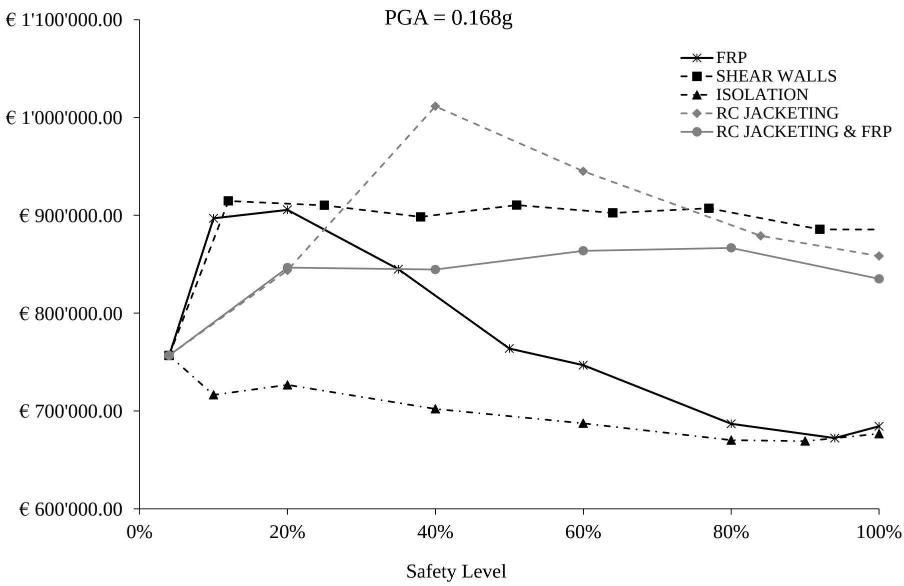


Figure 3.8 Total expected costs for PGA=0.168g

In the low and very low seismicity zones, the isolation strategy cannot be applied to the structure under investigation. In fact, the target period to achieve with this solution is lower than the fundamental period of the structure. This is not compatible with the concept of base isolation, in which the structural period of the vibration increases.

In these seismicity zones, Figures 3.9 and 3.10 show that the FRP-based strategy is the best and the only cost-effective strengthening intervention strategy. The optimal point is at a safety level of 100% and 60% for low and very low seismicity, respectively. The corresponding expected total loss reductions with respect to the case of the no strengthening intervention are about 84% and 75%, respectively. The other strategies are not economically viable.

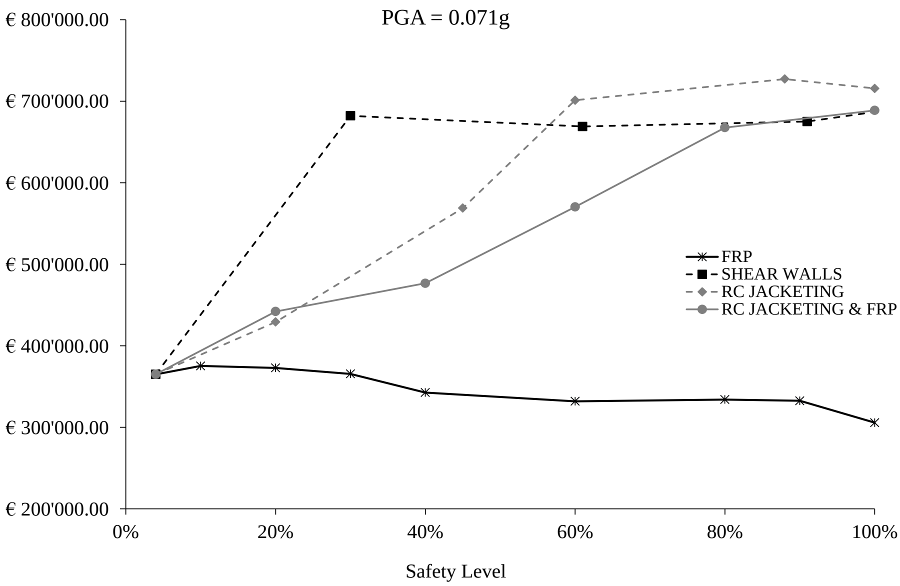


Figure 3.9 Total expected costs for PGA=0.071g

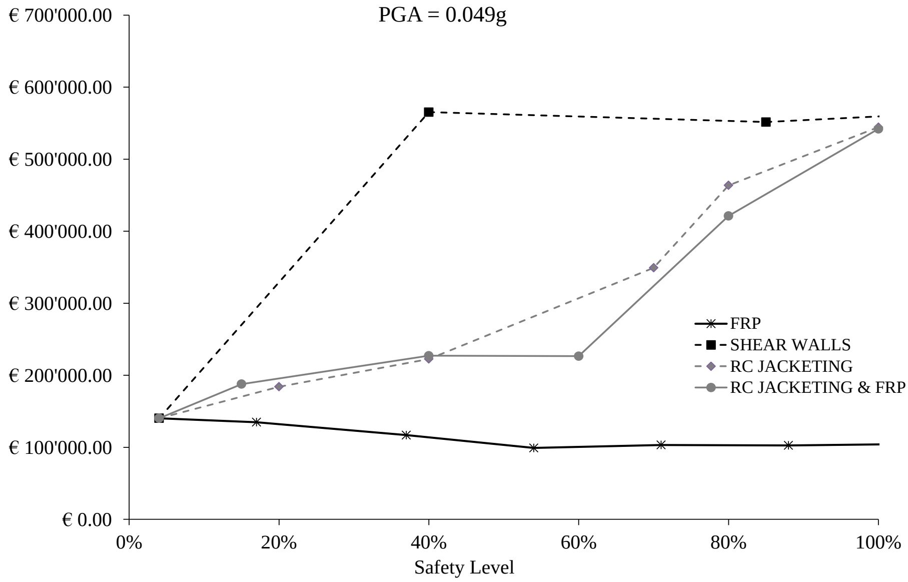


Figure 3.10 Total expected costs for PGA=0.049g

The application case clearly shows that the selection of the most effective strengthening strategy from a structural and economic point of view greatly depends on the hazard posed by the area where the building is located (U Vitiello, Asprone, Di Ludovico, & Prota, 2016). In the case study developed, the base isolation resulted in the most effective strengthening solution for the high PGA values, while the FRP-based strengthening solution was the most effective option for a lower seismic area.

Overall, we can assess that it is possible to obtain three different kinds of total expected cost versus safety level curve. In the first case, the curve presents a decreasing and then an increasing trend. In this case, the most-cost effective solution is simply identified by the lowest value of the curve. In the second case, there is an increasing trend followed by a decreasing trend. In this case, it is necessary to almost achieve a certain safety level to have expected costs that are lower than the economic losses. In the third case, the curve steadily increases with the safety levels, and so the best solution depends on the target safety level. In each case, the optimal choice of the strengthening intervention should be taken as a balance between the reduction of expected seismic loss in the structural safety life-time and a proper safety level selected according to social factors.

Designers and constructors must approach each project not only with the initial capital investment but with the entire life-cycle of the buildings as well. Refurbishment costs depend on the strategies adopted but they may be minimized if a strong preventive maintenance plan is put into action.

The methodology herein developed, is proposed for assessing the economic performance of a building prone to seismic risk and aims to: (i) assess economic losses for existing and new buildings; (ii) evaluate different retrofit scenarios of existing buildings; (iii) optimize the seismic strengthening of existing structures.

In conclusion, such a procedure can support owners to monitor the condition of a building during its life-cycle. Actually, loss assessment procedures are well established in the research community, but are too complicated to be applied. Indeed, practitioners rarely implement these procedures, due to the fact that they require the management of a great deal of data about a building and its components.

CHAPTER 4

INTEGRATION OF SEISMIC LOSS ASSESSMENT AND LCC PROCEDURES IN BIM MODELS

Accurate information about the building can improve the structural response, the assessment of seismic economic losses and the maintenance operations. Therefore, a Building Information Modelling (BIM) based approach is developed to support these procedures and to deal with the large amount of data needed in a detailed analysis. In fact, the BIM model can be considered a databank that may facilitate interoperability and the exchange of information throughout the life-cycle of a facility.

4.1 INTRODUCTION

During the life-cycle, facilities are prone to economic losses due to several events (both ordinary and exceptional). The assessment of these expected economic losses may support the asset management and the planning of retrofit interventions aimed at preventing, or at least limiting, the damage caused to a structure. A smart asset management consists of three main challenges:

1. Attainment of information. A transparent decision-making organization should be based on a complete set of information to oversee the technical condition of a facility, look beyond the life-cycle and select cost-effective choices.
2. Information management system. An information management system is required to store design information and data about

the condition and the performance of a facility. Moreover, this information system must be simple and allow information to be integrated on a continuous basis. This is in line with the concept of building information modelling.

3. Predictive models. A smart asset management requires economic assessment procedures in order to predict the future condition of a facility and its structural safety.

As stated previously, procedures for the assessment of economic losses are widespread in the research community, but practitioners very rarely implement them because they are complex to apply in practice. A BIM model can be effectively used as a record model for asset management purposes and LCC analysis once the level of information of BIM objects is correctly defined.

Within this context, the aim of the present chapter is to evaluate the possibility of integrating the simplified assessment procedure for economic losses due to a seismic event into a BIM based design approach. This is to improve the feasibility of these procedures and to deal with the large amount of data referred to the damage and cost analyses of the components that constitute a facility. In this way, the BIM model shows the economic condition of a building and becomes an updated database that can be constantly improved and queried at any time to obtain information on the structure and assess the costs of future interventions, including the expected economic losses caused by seismic events. This system data optimize the lifecycle of components, increase efficiency in the preventive maintenance, and provide accurate and electronic as-built documents. These aspects are at the core of BIM's fundamental promise to do away with the need for multiple data entry for different analysis applications, allowing the model to be analysed directly and within very short cycle times (Eastman et al., 2011).

Furthermore, this integration provides owners with a simple tool that can be used at different stages of the lifecycle of a facility. This tool may also be able to optimize the maintenance phases accounting for possible seismic retrofit operations and carrying out an LCC analysis.
On the one hand, BIM software is able to associate any kind of information with building components by way of parametric modelling. This capacity allows the integration of information and the processing of "complex" data. On the other hand, the simplified procedure for the assessment of a building's performance allows to evaluate the economic losses and the optimization of retrofit interventions of the structure through simple operations that can be implemented in BIM-based tools.
When completed, the BIM model contains accurate details about the geometry of the building, reinforcement details, material properties, construction activities and cost estimation, that reduce the data flow and help practitioners in the assessment of expected economic losses due to seismic events with rapid calculation (Akinade et al., 2015). This information can also improve the accuracy of seismic parameter assessment such as the seismic mass that influences the seismic risk estimation. (Dolsěk, 2011; Franchin, Pinto, & Rajeev, 2010; Lagaros & Mitropoulou, 2013).
To this end, the economic loss assessment procedure is integrated in a 5D model of a building, where time and costs are the fourth and the fifth dimension of the model. Finally, once the quantities and the properties of the components are estimated, , repair efforts, repair costs and repair duration are combined with the BIM model and the fragility models in order to determine the costs due to damages and the expected economic loss of the building.
BIM models are increasingly used to integrate energy optimization analysis, thermo-acoustic analysis, environmental analysis and

structural analysis while the integration of life cycle cost assessment procedures is still limited.

4.2 BIM SUPPORTING SEISMIC ENGINEERING

BIM is an innovative integrated design process involving the design, construction and management of digital representations of physical and functional characteristics of a facility (Georgiou, Christodoulou, & Vamvatsikos, 2014). In the last few years, Building information models are increasingly being applied throughout a building's life-cycle based on the as-built modelling of existing structures. In particular, the focus of research has shifted from earlier life-cycle (LC) stages to maintenance, refurbishment, deconstruction and end-of-life considerations. In fact, in many countries the main activities of the construction sector are focused on building renovation, retrofit interventions and the deconstruction of existing buildings (Mill, Alt, & Liias, 2013.; Penttila et al., 2007) and the structural safety of existing buildings is a critical issue.

In details, several aspects of seismic risk mitigation and assessment can be supported by BIM methodologies, e.g.:

1. building retrofit and renovation;
2. management of deconstruction-demolition;
3. emergency management and risk scenario planning in the aftermath of a major earthquake.

In case 1, the advantage is in the accurate evaluation of all the interventions, quantities and costs associated with the retrofit operations. The optimization of the building refurbishment can be carried out through an economic loss assessment procedure as described in the following sections. In order to estimate economic losses due to seismic events a PBEE procedure (Performance Based Earthquake Engineering) can be adopted. This procedure requires a large amount of data and detailed information about the structural and non-structural components of the building. The use of BIM in this case allows for a detailed cost estimation and supports the implementation of these data (U Vitiello, Salzano, Asprone, & Prota, 2016). Therefore, the use of BIM is expected to support the facility management by means of operational tools and methodologies to improve the efficiency of any planned maintenance and management operation. This efficiency depends on the parameterization and object-oriented modelling used by facility managers involved in the process. Akcamete et al. (Akcamete, Akinci B, & Garrett JH, 2010) point out that all the operations related to the renovation of a building, and the role of the facility manager, equates to 60% of the overall costs of the project. These renovation measures include structural upgrades such as seismic and energy retrofits like improving electrical or plumbing systems or thermal insulation. Some BIM models are used to achieve a considerable reduction in the energy consumption, to minimize the environmental impacts and to obtain high levels of human comfort.

These operations require a great deal of data about structural and non-structural components, as well as their materials and compositions, geometry and physical proprieties. Integration with BIM methodologies is fundamental to this phase of the life-cycle, because they are able to manage large amounts of data and improve the feasibility of the processes.

In case 2, the potential BIM functionalities are related to: deconstruction execution planning and process tracking, recycling and rubble management, secondary component and raw material auctions, recycling network logistics, and the monitoring of hazardous components or automated reporting to authorities (Volk et al., 2014). BIM model is applied to minimize demolition waste and to improve recycling of materials through deconstruction planning. As example, Akinade et al. (Akinade et al., 2015) developed a BIM-DAS score (Building Information Modelling based Deconstructability Assessment Score) to estimate the degree of building deconstructability. This phase may impact structural design and seismic risk mitigation actions.

Finally, in case 3, BIM models may be used to support post-earthquake assessment, such as search and rescue (S&R), repair and recovery. As-damaged models of the facilities may support S&R teams in the assessment of damages to building structures in the aftermath of an earthquake. As-damaged models can be useful both to plan efforts to reach survivors and also to assist structural engineers in the estimation of the degree of damage of the buildings (Zeibak-Shini, Sacks, Ma, & Filin, 2016). Ma et al. (Ma, Sacks, & Zeibak-Shini, 2015) proposed a rapid scanning to be compiled for post-earthquake assessment. The model was based on the specification of IFC (Industry Foundation Classes) objects to fully represent the as-damaged state. Burak et al. (Anil, Akinci, Kurc, & Garrett, 2016) proposed, instead, a different approach in which the different type of damages (such as cracking, crushing, spalling, etc.) were related to different classes in their framework. The cracks were represented using a series of entities. The CrackStation represented a point on a crack along with the width of the crack at that point. The CrackPath stored a list of CrackStations and represented a single continuous crack. The CrackPattern represented a collection of CrackPaths that needed to be processed together.

BIM in the life-cycle phase can be applied to buildings that have been designed using BIM methodologies or those that have been designed using a traditional approach. If a BIM model already exists as the result of a BIM-based design (the so called as-built model), the process of planning and performing renovations, refurbishment, maintenance, deconstructions and post-earthquake assessment may be carried out simply and rapidly. If a BIM model does not exist or is not available, the process starts with building auditing, documentation reviews and analyses of previous and current building properties (Penttila et al., 2007b), and it aims to provide an insightful basis for planning and cost estimations. The effort to set up a BIM model of an existing building has to be calibrated with the actual needs. Collection of data and information may generally be resource consuming and the level of details that is typically available in the as-built models, coming from BIM-based design processes, often cannot be achieved. In this case, information and data to collect have to be defined on the basis of the management operations that need to be implemented.

4.3 INTEGRATION OF THE LOSS ASSESSMENT PROCEDURE IN THE BIM APPROACH

4.3.1 Proposed framework

The development of the simplified loss assessment procedure linked to a BIM model provides a tool that increases the feasibility of economic loss assessment procedures due to seismic events. This tool reduces the uncertainties of the data and allows comprehensive seismic risk assessments. Indeed, the proposed framework may easily process data for structural elements, systems, non-structural components and building contents to provide all the necessary information for the economic loss assessment. This means that BIM may act a key role in the seismic assessment (David P. Welch, T. J. Sullivan, 2014).

The framework proposed in this work is synthesized in Figure 4.1.

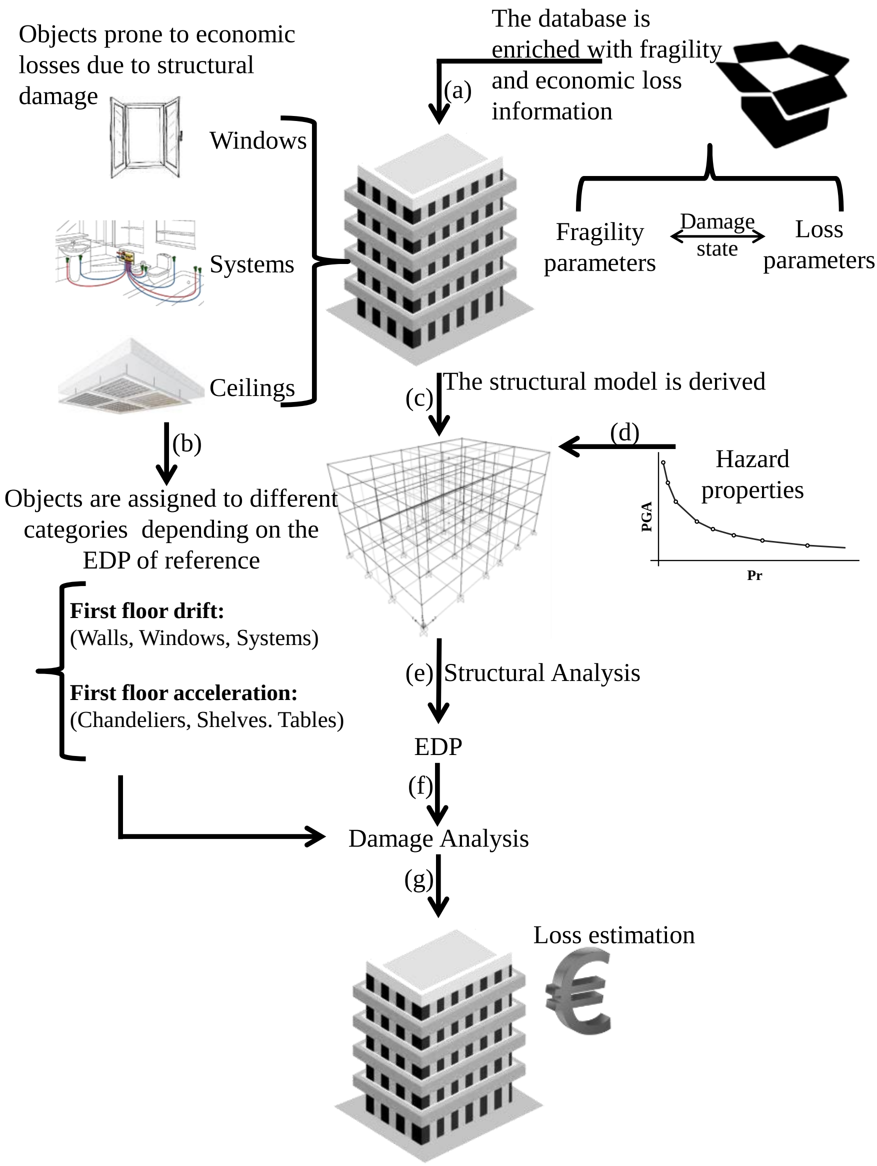


Figure 4.1 Scheme of the flow of information

Once the BIM model of the structure is realized, the framework consists of the following steps. In the first step (a) the database of the BIM model is enhanced with parameters obtained from fragility models. These fragility parameters depend on the state of damage and on various EDPs. Thus, in step (b) components prone to economic loss due to structural damage are assigned to different categories depending on the EDP of reference.

Each damage level of the components needs to be converted into an economic loss. To do this, it is necessary to implement fragility and cost parameters for each object. Fragility parameters to be inserted in the tool are average values and standard deviation values of the fragility curves, while cost parameters are the cost of replacing a component and restoration costs for each damage state of each component.

Accordingly, in step (b), objects prone to economic loss due to structural damage are assigned to different categories depending on the EDP of reference. For example, walls on the first floor may be assigned to the inter-storey drift of the first floor, since the damage they may experience is related to this EDP. Furthermore, each damage level of the components needs to be converted into an economic loss. The economic loss can be rapidly computed with a BIM model assigning to each object the following shared parameters, as shown in Figure 4.2:

- Average values of the fragility curves for each damage state (SD1, SD2, SD3).
- Standard deviation values of the fragility curves for each damage state (SD1, SD2, SD3).
- Cost of replacing a component.
- Restoration costs for each damage state (SD1, SD2, SD3).

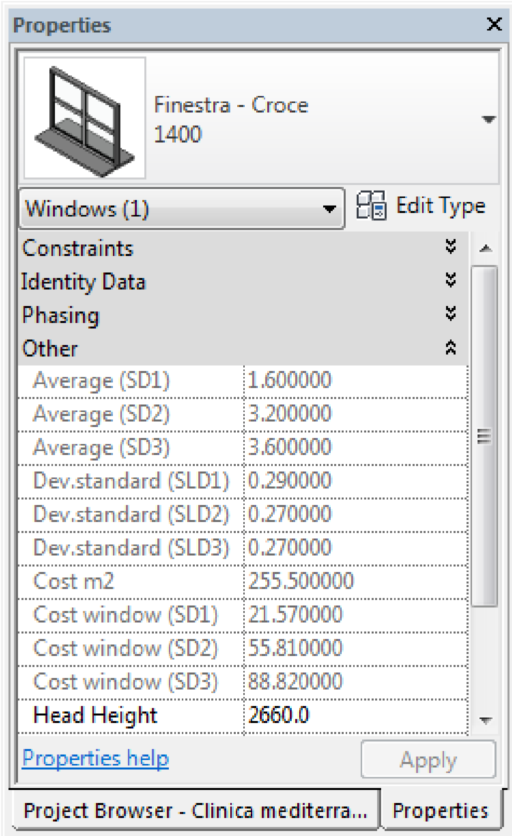


Figure 4.2 Shared parameters of a component

The average values and the standard deviation values are provided by their fragility curves, while the costs of replacing and the restoration costs for each damage state of a component are computed with a price list and used to generate the bill of quantities.

The use of shared parameters simplifies the calculation of the bill of quantities. In fact, one of the main issues is the computation of the costs, due to the amount of data needed. Moreover, the bill of quantities and the costs must be computed for each strengthening strategy and each retrofit level to identify the most cost-effective strengthening solution. Working in a BIM model makes it possible to calculate the geometric information and all the other information relevant for the quantification of each type of component. Accordingly, the cost parameters complete all the data necessary for assessing the economic value of each component category and the economic losses associated with all the damage levels considered.

Once the preliminary phases are completed, in step (c) a structural model is obtained from the BIM model to carry out a structural analysis. Previously, hazard proprieties of the building site had to be evaluated according the proposed procedure and implemented into the model.

The structural analysis carried out in the next phase (e) is a non-linear static analysis (push-over analysis) according to the simplified approach illustrated in the previous paragraphs. The outputs of the analysis are the values for the EDP parameters that are used in the next phase (f). For inter-storey drift-sensitive components, it is very easy to assess the drift ratio of each floor, based on the control displacement of each step of the pushover curve, while for acceleration-sensitive components the peak floor acceleration needs to be estimated.

The next step of the framework is the damage analysis. The damages to structural and non-structural components are evaluated through the fragility curve parameters. Thus, the expected cost of the restoration may be computed for each step of the push-over curve for each building component. Then, these costs may be summed up with the probability of overcoming a damage level to assess the expected economic losses of the building (g).

In the proposed framework, it is also possible to implement a seismic retrofit optimization phase, as shown in Figure 4.3. Practitioners may choose different strengthening solutions and different strengthening levels and assess the economic losses and retrofit costs for each of them. In this way, computing the economic loss and the strengthening cost of a strengthening strategy for various strengthening level, it is possible to evaluate the most cost-effective strengthening levels of the retrofit technique. Then, the cost-effective solution with the lowest value identifies the most cost-effective retrofit strategy. Nevertheless, if this solution cannot achieve a sufficient safety level, able to guarantee human safety or particular requirements of the reference building code, the reinforcement strengthening level can be selected as a balance between safety and costs. The advantage for designers of using this tool lies in the fact that there is clear awareness of the economic impact of their design choices.

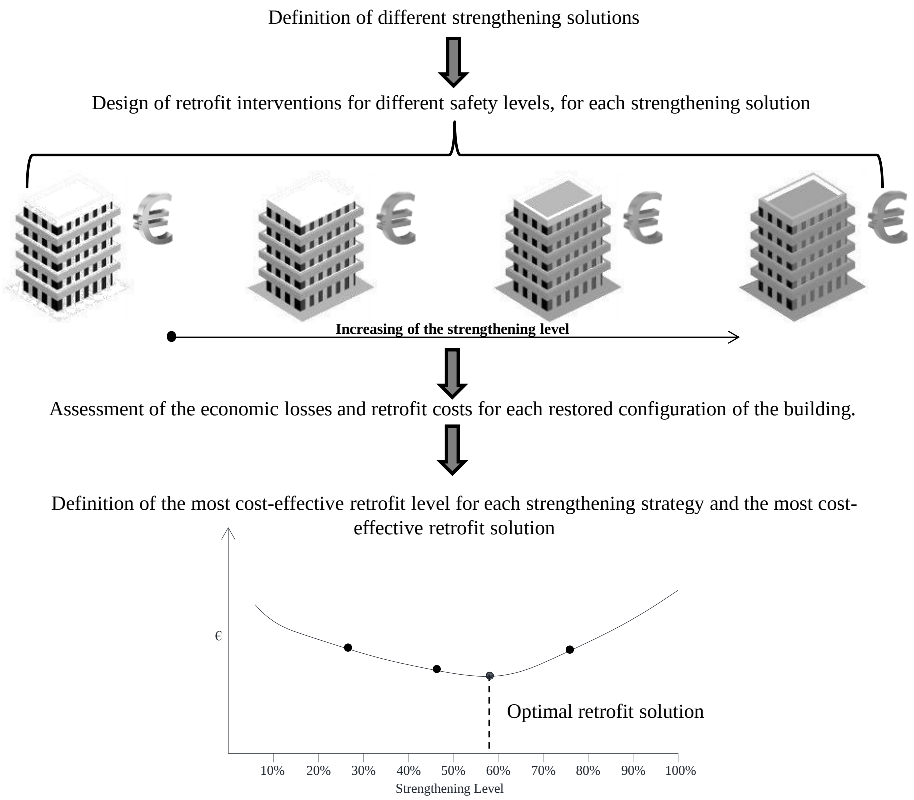


Figure 4.3 Definition of the optimal retrofit solution

To summarize the implementation of the economic loss assessment methodology into a BIM procedure, the following steps can be identified:

1. BIM model of the building. In this preliminary phase the BIM model of the building is defined.
2. Structural analysis of the building. The structural model of the building is obtained from the BIM model and a static non-linear analysis is carried out in order to assess the seismic capacity of the structure and to assess the EDPs of the components for each step of the pushover curve.
3. Enrichment of the database of the objects. In this phase, objects are divided into PGA-sensitive and drift-sensitive classes and for each of them the database is enriched by parameters which allow to assess the structural damage given an EDP and to compute the associated economic loss. These parameters are the average values and the standard deviation values of the fragility models, cost of replacing and/or cost of restoration for each damage state. Average values and standard deviation values are obtained from fragility models of the component typologies (there is a lot of data available for several building components), while the costs of replacing and restoration are computed according to a reference price list.
4. Implementation of the EDPs in the BIM model. In this step the EDPs obtained from the structural analysis for each step of the pushover curve are implemented into the BIM model. In this way, for each seismic level it is possible to assess the damage occurring to the components.
5. Damage assessment. In this step it is possible to compute the cost of replacement or restoration for each component. Accordingly, the BIM model returns the bill of quantities of these operations.
6. Economic loss assessment. Given different levels of seismic hazard, the economic loss of the building is computed, which

corresponds to a defined seismic capacity, based on the damage to the components and the bill of quantities of the restoration operations.

Definition of the most cost-effective solution. If the economic loss of the building corresponds to a very low seismic capacity, the framework may be applied in this phase to define the most cost-effective solution of strengthening the structure. Designers may identify retrofit solutions and different strengthening levels. For each of them, it is possible to evaluate the achieved seismic capacity and reiterate the BIM methodology in order to calculate the associated economic loss. The solution with the lowest value of expected cost (sum of economic loss and cost of strengthening operations) identifies the most cost-effective retrofit strategy.

4.3.2 Implementation of the procedure: case study

The proposed framework has been implemented in a BIM model containing both structural components (columns, beams and slabs) and non-structural components (partition walls, windows and doors) as shown in Figure 4.4 and Figure 4.5. Non-structural elements have been added in order to achieve the best building simulation and the best analysis integration.

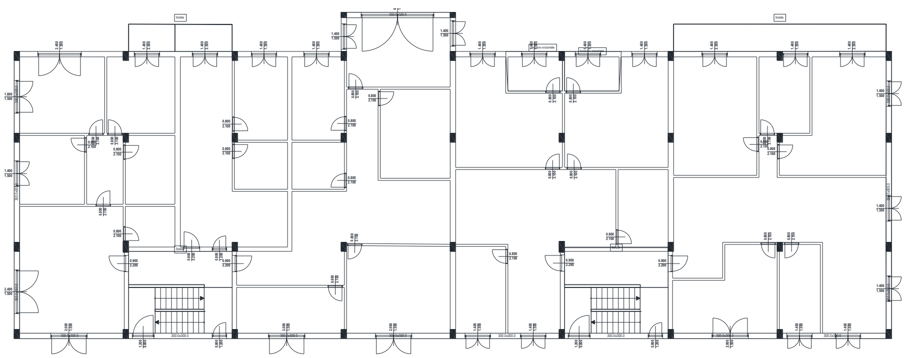


Figure 4.4 Floor Plan view

The model of the building has been realized with Edificius software produced by ACCA Software ® (Acca software SpA).
The building is the same as that analysed in Chapter 2.

Figure 4.5 3D Model

As described in the previous section, the structural model has been obtained from the BIM model of the building in order carry out structural analyses as shown in Figure 4.6. Hazard proprieties of the building site have been evaluated and implemented into the structural model assuming that the facility is located in Naples.

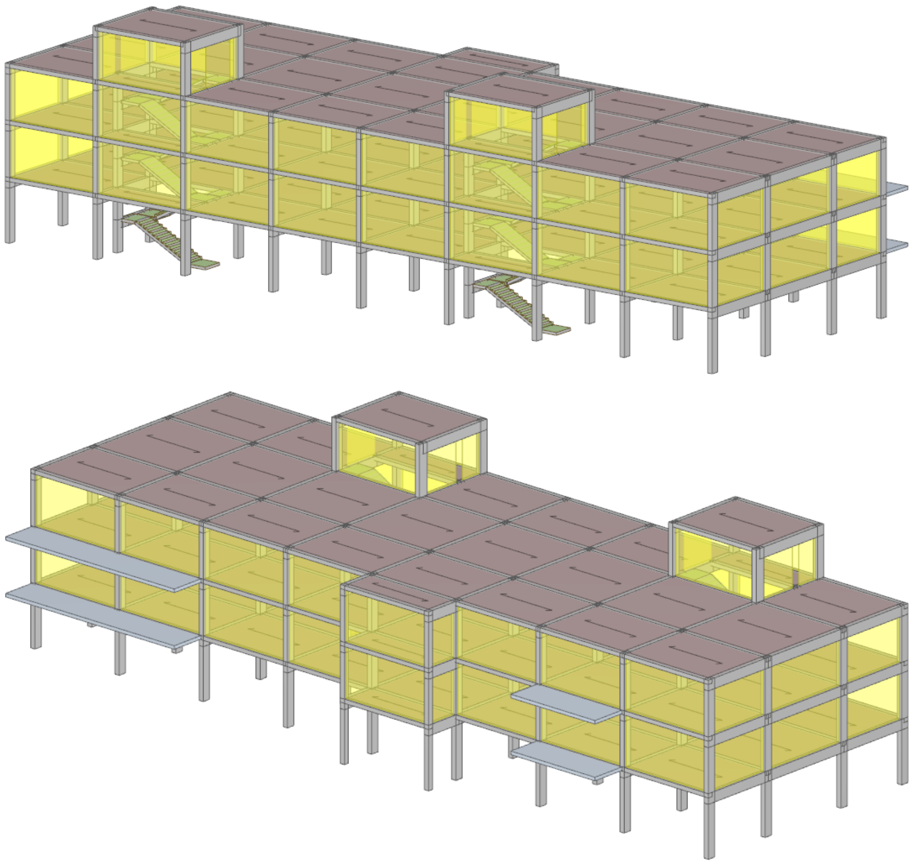


Figure 4.6 Structural model of the facility

Non-linear static analyses have been carried out for the two plan directions of the structure (X and Y directions) to simulate the non-linear building response. The structural analyses have been carried out with finite element software Edilus produced by ACCA Software ® (Acca software SpA). The software adopts a fiber-based distributed plasticity model for the non-linear behaviour of structural elements instead of a lumped plasticity model. Moreover, for this research project, ACCA Software ® provided an additional tool, in order to assess the economic loss assessment procedure developed. With this tool it is possible to assess the economic performance of the facility and to optimize the LCC analysis starting from a BIM model in a closed chain system.

The nominal life-time of the structure has been chosen to be equal to 50 years. Once the structural assessment is completed, the inter-storey drift ratios (IDR) of each floor are collected for each step of the pushover curve. Fragility curves have been implemented in the 3D model of the structure in order to simulate and assess the potential damage to the building. The EDPs are associated with the fragility curves of each building components for damage assessment. The fragility curves adopted in this application case are determined based on the IDR. The cost parameters related to each damage level of each component are introduced as shown in Figure 4.7. Accordingly, assessment of the probability of overcoming a damage level and restoration costs is simplified.

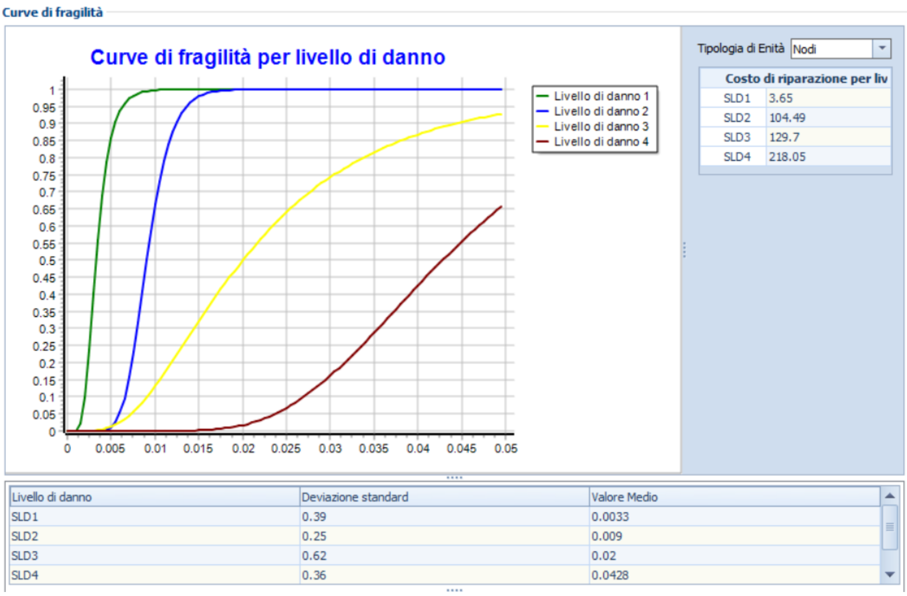


Figure 4.7 Fragility curves of a building component

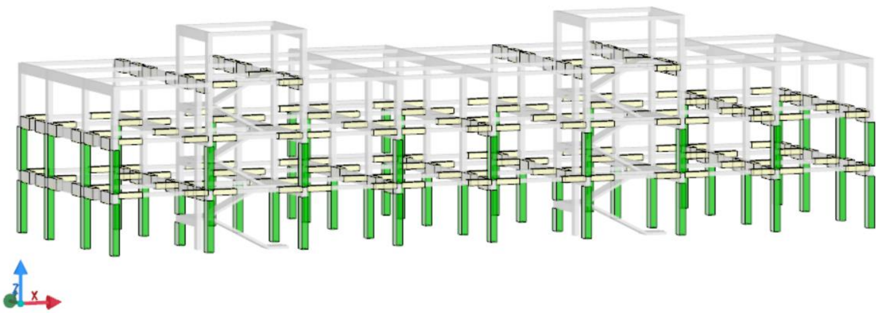
Fragility models adopted in this framework are the same implemented by Vitiello et al. in the simplified procedure shown in Chapter 3. Furthermore, the economic value of each component and the restoration costs have been computed with reference to the Campania Region price list.

Finally, the total economic loss may be computed multiplying the cost of the economic damage of each pushover step by the probability of occurrence of the corresponding displacement demand.

If the economic loss correspond to a low safety level, several strengthening techniques may be investigated such as FRP-based strengthening solution, as shown in Figure 4.8.

In order to carry out an analysis of the economic viability of the strengthening strategy, different strengthening levels have been considered and a price has been computed for each retrofit scenario, resulting from the sum of the costs of the materials and the operations needed to install the FRP systems. This has been completely developed through the additional tool by ACCA Software ®.

The BIM model automatically returns the bill of quantities of all the FRP interventions adopted to achieve the different safety levels, as shown in Figure 4.9.



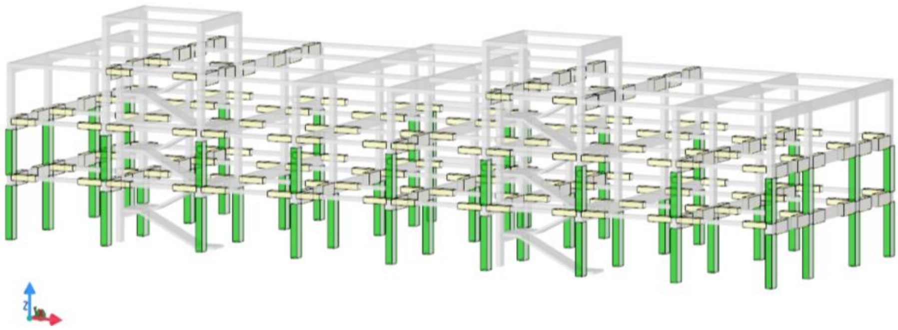
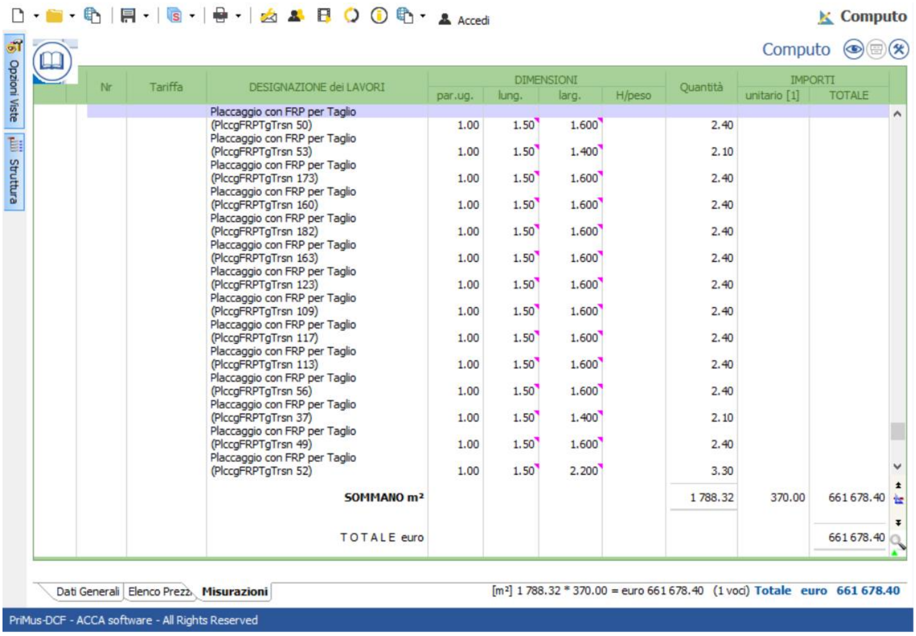


Figure 4.8 FRP Retrofit Strategy



Nr	Tariffa	DESIGNAZIONE dei LAVORI	DIMENSIONI par.ug.	lung.	larg.	H/peso	Quantità	IMPORTI unitario [1]	TOTALE
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 50)	1.00	1.50	1.600		2.40		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 53)	1.00	1.50	1.400		2.10		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 173)	1.00	1.50	1.600		2.40		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 160)	1.00	1.50	1.600		2.40		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 182)	1.00	1.50	1.600		2.40		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 163)	1.00	1.50	1.600		2.40		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 123)	1.00	1.50	1.600		2.40		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 109)	1.00	1.50	1.600		2.40		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 117)	1.00	1.50	1.600		2.40		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 113)	1.00	1.50	1.600		2.40		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 56)	1.00	1.50	1.600		2.40		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 37)	1.00	1.50	1.400		2.10		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 49)	1.00	1.50	1.600		2.40		
		Placcaggio con FRP per Taglio (PlccgFRPTgTrsn 52)	1.00	1.50	2.200		3.30		
		SOMMANO m²					1 788.32	370.00	661 678.40
		TOTALE euro							661 678.40

Figure 4.9 Cost estimation of FRP interventions for a safety level of 100%

The summation of the economic loss and strenhtening curves, plotted against the safety level, results in the total expected cost and identifies the most-cost effective strengthening level. Obviously, if the designer does not consider the resulting strengthening level enough for safety purposes, the retrofit strategy can be selected to balance between risks and costs.

Overall, this research aims to develop an integrated platform to implement sustainable design principles in the seismic retrofit operation with the support of BIM methodologies. For this reason, in future, this BIM framework may be enriched with further assessment procedures to formulate a financially and environmentally affordable refurbishment solution based on the Life-cycle Costing (LCC) and Life-cycle Assessment (LCA) methods simultaneously.

CHAPTER 5

A MULTI-STEP APPROACH TO ASSESS THE LIFE-CYCLE ECONOMIC IMPACT OF SEISMIC RISK ON ENERGY RETROFIT MEASURES

Most European buildings built before 80ies were constructed without any design concern for energy efficiency and environmental sustainability. However, the strong interaction between energy and structural aspects in building retrofit design has never been managed through an established procedure. The present chapter explores this knowledge gap by introducing a novel multi-step approach that addresses the retrofit of existing buildings by integrating energy, structural and economic aspects.

5.1 INTRODUCTION

A large share of the European building stock does not comply with current structural codes and, at the same time, suffers from physical/environmental degradation or even structural damage induced by hazardous events occurred over building lifetime. In this background, over the last decades, building retrofit has gained increasing interest among national institutions and governments, enabling prospects of upgrading external building envelope and energy systems in order to achieve energy efficiency goals. National policies have also encouraged the increment of safety levels for occupants of existing building, trying to align with more modern accommodations standards and structural codes. The design framework for retrofit/renovation interventions has been recognized as typically made up of a set of objectives, indicators or performance criteria belonging to the key objectives of sustainable development.

Building energy consumption keeps rising in the last decade due to growth in population, increasing demand for healthy, comfort, global climate changing, etc. Making buildings more energy efficient save energy consumptions and reduce CO_2 emissions that are responsible for global warming. Moreover, Rubin et al. (Rubin et al., 1992) estimated that energy enhancements (such as improvements in lighting, water heating, cooking, cooling, refrigeration, space heating, and ventilation efficiency) for both residential and commercial buildings may reduce the electricity consumption for the building sector by 45% and save nearly $30 billion a year.

However, many of the studies dealing with large-scale retrofit have focused deeply on single aspects, such as mechanical or energy performance of retrofitted/renovated existing structures (Asadi et al., 2012; Ascione, Bianco, De Stasio, Mauro, & Vanoli, 2015), while few works have dealt with the integration of other sustainability objectives. Recent approaches have also encompassed other sustainability criteria, such as economic benefits of refurbishment (Kanapeckiene, Kaklauskas, Zavadskas, & Raslanas, 2011) and social aspects (Saulius, Jurgita, & Nerija, 2011) related to the structural and functional performance of a building after earthquake induced damage. Even though energy performance seems to be recognized as the “core” of any sustainable retrofit process, the interaction with other aspects related to a given building system cannot be neglected. Thus far, at the retrofit design stage, the combination of energy, structural and environmental information cannot be effectively used in a general decision-making process, making the single aspect of the structural or energy performance insufficient to provide comparable and valuable retrofit solutions. Indeed, the choice of an energy strategy as well as the selection of a set of raw materials for building components cannot be separated from the effects they generate on the structure itself regarding: (i) overall structural performance, (ii) compliance with national/international construction standards and (iii) global costs. Therefore, the integration of these three aspects (i.e., energy, environment, and structure) at the design stage is a fundamental prerequisite to reliably incorporate sustainability principles in a decision-making process applied to existing buildings.

Building energy retrofit is a key factor in the achieving of environmental protection and sustainability but it is also a complex issue that involves two different representatives: on one hand the public representative that aims at reducing energy consumption and pollution; and on the other hand the private representative that aim at achieving economic benefits. For this reason the Energy Performance of Building Directive 2010/31/EU (EPBD Recast) (European Commision, 2012) prescribes the cost-optimal analysis in order to find a compromise between these two positions and to address building energy retrofit.

Within this context, this chapter introduces a sustainability assessment framework for the retrofit process of existing buildings based on the integration of energy and structural aspects. In particular, herein is proposed a novel multi-step approach that aims to identify the structural interactions arising from cost-optimal energy retrofit solutions applied to existing buildings. The overall outcomes of this integration are handled in terms of global life-cycle expected costs, which include investments and operating costs linked to energy uses as well as economic loss quantifications related to the structural performance of the building.

The quest for simultaneously achieving structural safety and energy efficiency goals is becoming a sustainability challenge especially in the case of existing buildings, for which several constraints on the intervention itself should be considered and, at the same time, high economic advantages can be envisioned for stakeholders. In this regard, the methodology is applied to an Italian multi-storey residential building by considering two different locations, namely Milan and Norcia. These latter are characterized by similar climatic conditions, since both of them belong to the Italian climatic zone E, but by a different level of seismic risk, which is higher for Norcia site.

5.2 METHODOLOGY

A proper retrofit strategy should be evaluated by using suitable economic, environmental, social and structural criteria with the final aim of implementing the most proper (cost-effective and/or sustainable) solution for a given existing building. Hence, a proper methodological framework should support the comparative assessment of a set of retrofit options.

To this scope, a novel multi-step approach is proposed, enabling to quantify the overall economic life-cycle costs associated with the energy and structural performances of a retrofitted building. In particular, the energy performance refers to a set of energy retrofit measures (ERMs) applied to the existing building whereas the structural performance is considered in order to quantify the economic losses due to seismic induced damage. The methodology comprises the following four main steps:

- Step (1) - Optimization of building energy retrofit: a wide set of possible and compatible combinations of retrofit solutions is considered among a set of ERMs, determining, at the end of this step, the most suitable configuration as the outcome of a cost-optimal analysis.

- Step (2) - Assessment of seismic economic losses: given that the existing building is prone to seismic risk, future costs associated with the reduction of the building structural capacity are handled in this step. In detail, the seismic induced damages and the related economic investment to restore the damaged components are quantified for the "as built" existing building throughout its lifetime.
- Step (3) – Integration of energy and structural aspects: the cost-optimal ERMs identified in step (1) are associated to proper engineering demand parameters and component performances of the existing building. In detail, the operation of the ERMs is linked to the level of seismic induced damage of the non-structural components onto which they are applied (e.g. walls, windows etc.).
- Step (4) – Assessment of the influence of energy retrofit on seismic economic losses: the analysis of step (2) is conducted for the retrofitted building as well, based on the constraints defined in step (3) and by considering the implementation of the cost-optimal energy retrofit solution identified in step (1). The difference in global costs (i.e., saving) is, in this way, quantified with respect to the as built configuration. The outcomes can be useful for the selection of proper ERMs, looking at the overall cost-effectiveness of the retrofit itself. On the other hand, they can be used to integrate combined energy and structural retrofit measures, with the final aim of reducing the overall cost (or, more in general, other sustainability parameters) of the intervention.

The steps described above are detailed in the following subsections.

5.2.1 Step (1) – Optimization of building energy retrofit

The proper design of energy retrofit is a complex issue that requires the consideration of a wide domain of packages of ERMs. Indeed, the best solution is affected by numerous factors, such as the stakeholders' wills and needs as well as the scenario in which the building is located, especially as concerns climatic conditions. In this study, the building energy retrofit is handled by means of a multi-stage optimization approach that implements a genetic algorithm (stage 1) and a smart sampling of retrofit scenarios (stage 2). This procedure, herein described, has been developed from the Energy Engineering Team of University of Naples "Federico II" who collaborated with the Department of Structures of University of Naples "Federico II".

Stage 1 aims to find optimal packages of energy retrofit measures (ERMs) by minimizing thermal energy demand and thermal discomfort, while stage 2 aims to find the final cost-optimal energy retrofit solution.

The multi-objective approach is more suitable than the single-objective one, because it takes into account, simultaneously, different competitive criteria, such as the energy demand, the thermal comfort, the investment costs and the emissions of CO_2-equivalent during the building operation.

Initially, the existing building is designed in EnergyPlus. It should be noted that in the pre-processing phase heating/cooling energy systems are not modeled because this stage aims to calculate thermal energy demand and not primary energy consumption, which is assessed later by means of MATLAB post-process. Hence, the annual values of Thermal Energy Demand TED for space heating (TED_{heat} [W h/ m^2 a]) and for space cooling (TED_{cool} [W h/m^2 a]) per unit of conditioned area are calculated. The sum of TED_{heat} and TED_{cool} provides the total thermal energy demand for space conditioning, denoted as TED_{sc}

[Wh/m^2 a]. Then, the parameters that affect the energy performance are identified like design variables. This selection can be performed through a sensitivity analysis or a detailed study of the system. The value assumed by each variable corresponds to a design decision and this can concerns the envelope (e.g., insulation thickness, type of windows) or the heating and cooling systems (e.g., kind of heat emitters, boilers, chillers).

The procedure is implemented by coupling EnergyPlus (EnergyPlus, n.d.) and MATLAB® (MathWorks, 2010). EnergyPlus is employed as simulation tool to run reliable energy simulations in dynamic conditions, whereas MATLAB® is employed as mathematical tool to implement optimization and sampling algorithms as well as to post-process EnergyPlus outcomes. A similar procedure was performed to address the energy retrofit of residential (Ascione, Bianco, De Masi, Mauro, & Vanoli, 2015; Ascione, Bianco, De Stasio, et al., 2015) and hospital buildings (Ascione, Bianco, De Stasio, Mauro, & Vanoli, 2016).

In particular, stage 1 investigates the implementation of ERMs for the reduction of:

- TED_{sc}: thermal energy demand for space conditioning;
- DH: annual percentage of discomfort hours, which are assessed according to the procedure described in Ascione et al. (Ascione, Bianco, De Stasio, et al., 2015) with the equation $DH = \frac{dh}{h} \times 100$ where *h* is the number of the yearly-occupied hours and *dh* is the number of these hours characterized by thermal discomfort (there is presence of people) in which the average value of predicted mean vote (PMV) (Fanger, 1970) is not included between -0.85 and 0.85.

Thus, a bi-objective optimization problem is solved. The two objective functions are the minimization of TED_{sc} and DH, respectively. The design variables express the implementation of ERMs that improve the energy performance of the building envelope as well as the variation of heating and cooling set point temperatures. A further constraint is also considered, since the retrofit solutions cannot cause an increase of DH compared to the baseline (DH_B). The two mentioned objective functions are chosen because they express the typical dilemma of building owners/occupants between consuming less and increasing comfort. In addition, their reliable assessment requires time-consuming dynamic simulations using proper software, e.g., EnergyPlus. Therefore, in this case, the use of optimization algorithms is highly effective because these perform a smart research, thereby implying a significant reduction of computational times compared to an exhaustive sampling.

Thus, the genetic algorithm (GA) is run by means of the coupling of EnergyPlus and MATLAB®. The GA is a variant of NSGA II (Deb, 2001) and provides the iterative "evolution" of a population of individuals, which represent packages of ERMs, through the processes of crossover, mutation and survival of the best individuals (elite), as detailed in (Ascione, Bianco, De Masi, et al., 2015; Ascione, Bianco, De Stasio, et al., 2016). The GA parameters are set according to the values used in (Ascione, Bianco, De Stasio, et al., 2016), to which the readers can refer for details.

Most notably, the maximum number of generations (i.e., iterations) is set equal to 20 and the population size is set equal to four times the number of design variables. In this regard, discrete variables are considered in order to reduce the explored solution domain as well as to make the approach more realistic (Ascione, Bianco, De Stasio, et al., 2015). The final outcome of the GA is the Pareto front collecting the non-dominated solutions, which provide optimal packages of ERMs as concerns the minimization of TED_{sc} and DH.

This multi-objective optimization may seem a mono-objective approach because TED_{heat} and TED_{cool} can be summed in TED_{tot}. Nevertheless, this may be true if the ultimate goal was the minimization of TED_{tot}, but the proposed methodology aims at the minimization of primary energy consumption and global cost.

Then, stage 2 is performed for optimizing the whole building energy retrofit by considering:

- the ERMs investigated in stage 1 that are addressed to the building envelope and to the variation of set point temperatures;
- ERMs for improving the energy performance of primary energy systems (such as the installation of new devices for heating, cooling and DHW production, the installation of combined heating and power (CHP) and combined cooling, heating and power (CCHP) systems), including the exploitation of renewable energy sources (RESs).

In particular, a smart sampling of retrofit scenarios is performed in order to conduct a robust cost-optimal analysis. A huge domain of retrofit solutions is explored. In this regard, all possible (and compatible) combinations among the ERMs for energy systems and the non-dominated packages of ERMs for the reduction of TED_{sc} and DH, provided by the GA, are investigated. In addition, the combinations of ERMs for energy systems are examined in absence of ERMs for the building envelope and for the variation of set point temperatures, since these latter ERMs could be energy-efficient but not cost-effective. The objective is minimizing the global cost related to energy uses over building lifecycle, as detailed in the Delegated Regulation (EU) No. 244/2012 (Commision delegated regulation (EU)

No 244/2012, 2012). For each retrofit scenario, primary energy consumption (PEC) and global cost (GC) are assessed in order to obtain the cost-optimal curve, which represents GC against PEC, and, thus, the cost-optimal retrofit solution (minimum of the cost-optimal curve).

The primary energy consumption (PEC[W h/ m2 a]) refers to energy uses for space conditioning, DHW, fans, pumps, lighting and equipment and is calculated per unit of conditioned area as recommended by the EPBD Recast (2010/31/EU) (European Commision, 2010, 2012).

GC is calculated according to the guidelines of the Energy Performance of Buildings Directive (EPBD) recast (2010/31/EU) over building life-cycle by considering investments and replacement costs of ERMs, state financial incentives and operation costs associated to the mentioned energy uses. The outcome is a cost-optimal curve that depicts the value of GC in function of PEC for all packages. The minimum point on the curve identifies the cost-optimal solution.

More in detail, in order to achieve more meaningful outcomes, the differences in PEC (dPEC = PEC - PEC_B) and GC (dGC = GC - GC_B) compared to the baseline (i.e., as built configuration, denoted with the subscript B) are estimated and represented. Clearly, negative values show energy and cost savings, respectively.

The described procedure is entirely carried out in MATLAB® environment, without needing further time-consuming EnergyPlus simulations. In particular, a MATLAB® code implements the performance curves of the energy systems in order to calculate PEC and GC starting from the hourly values of thermal energy and electricity demand for artificial lighting and equipment. These hourly values are provided by EnergyPlus in stage 1. The sampling is defined “smart” because of two main reasons. Firstly, as concerns ERMs for building envelope and the variation of set point temperatures, whose analysis requires EnergyPlus runs, it investigates only the non-dominated solutions obtained through the GA. Secondly, it needs low computational times because PEC and GC are evaluated under MATLAB® environment.

Finally, in order to offer a comprehensive characterization of the cost-optimal solution, other performance indicators are calculated, namely: the investment cost (IC), the discounted payback time (DPB) and difference in CO_2-eq emissions compared to the baseline (dEM = EM – EM_B).

This approach is applied for the evaluation of the cost-optimal solution with reference to the energy refurbishment of existing buildings. Analogously, this methodology may be also applied to new buildings.

5.2.2 Step (2) – Assessment of seismic economic losses

Life-cycle cost (LCC) analysis represents a fundamental engineering tool to assess initial and future costs associated with a facility/building throughout its entire lifetime. As far as structural behavior is concerned, different hazardous events taking place during the service life of a building (such as earthquakes, floods etc.) can affect the building structural integrity. Consequently, the reduction of the structural capacity due to the hazard induced damage may require a proper economic investment to restore the damaged components.

The economic loss assessment procedure implemented in this framework is the same described in the third chapter (U Vitiello, Asprone, et al., 2016) and is related to buildings prone to seismic risk. As described previously, the simplified methodology is based on the well-consolidated approach developed by the Pacific Earthquake Engineering Research (PEER) and carried out according to the performance-based earthquake engineering (PBEE) approach (Hesameddin Aslani & Miranda, 2005; Goulet et al., 2007).

5.2.3 Step (3) – Integration of energy and structural aspects

This step aims to model the possible interactions arising from different energy retrofit measures (ERMs) with the building structure itself. A proper strategy consists in first considering the building location from both sides of the retrofit process, i.e., energy and structural. Indeed, the geographic position of the building clearly affects the target of the energy retrofit design from one side; on the other hand, the building structural performance is strongly associated with the level of hazard risk relevant for that place. Within this constraint, technological and physical interactions should be determined for combining structural and energy retrofit strategies. In this study, particular attention is given to possible damages that prevent the proper operation of the ERMs installed on the existing buildings as a consequence of seismic induced damage.

The operational and damage level of ERMs and systems is linked to the structural performance of building components through the association with the corresponding engineering demand parameters (EDPs). In particular, the relations between EDPs and component performances are based on laboratory tests and analytical models.

Windows, mechanical and electrical equipment, HVAC (heating, ventilating and air conditioning) systems, electrical distribution and lighting systems are permanently attached to the building partition, thus can be related to the EDP of the partition walls consisting in the inter-storey drift ratio. Furthermore, ERMs can involve the installation of new components (e.g., photovoltaic systems) or the replacement of existing components (e.g., façade elements). In the former case, new fragility models have to be implemented in the seismic economic loss procedure, whereas in the latter, the replacement of the building components affects restoration and replacement costs.

5.2.4 Step (4) – Assessment of the influence of energy retrofit on seismic economic losses

The seismic economic losses of the building are assessed in correspondence of the cost-optimal energy retrofit solution, identified in step (1) as detailed 5.2.1. Thus, the potential global cost saving (GCS) is estimated over the residual building lifetime in the following two scenarios:

- scenario 1: seismic economic losses are not considered in global cost assessment; therefore the costs derive from the implementation of a merely energy approach;
- scenario 2: seismic economic losses are considered in global cost assessment as an additional annual cost in the form of discounted expected annual losses (EALs), thereby implementing a coupled energy-structural approach.

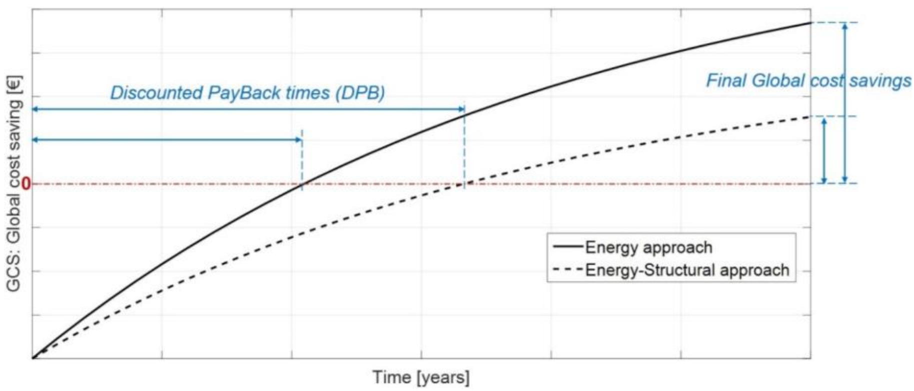


Figure 5.1 Qualitative temporal trend of the Global cost savings produced by building energy retrofit

In the scenario 2, the EAL is supposed constant over the estimation period and discounted at the first year, as done for the operating costs associated with energy consumptions.

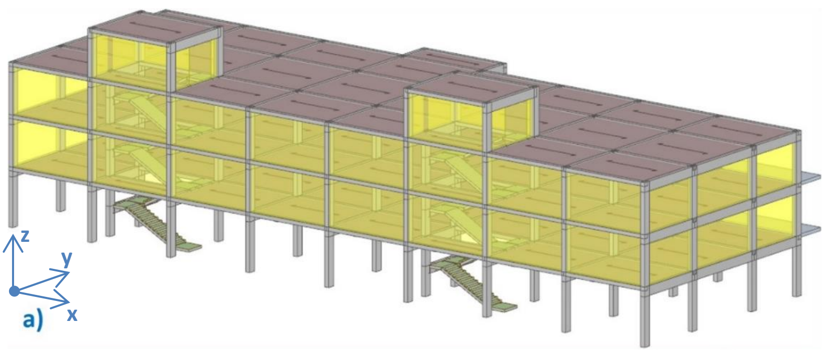
For example purposes, Figure 5.1 proposes a qualitative trend of GCS in function of time for the two described approaches. Clearly, when the seismic economic losses are considered, the potential global cost savings decrease compared with scenario 1, whereas the discounted payback time increases. Indeed, the implementation of energy retrofit inevitably causes an increment of EAL, since the economic value of the building components increases as well. It is worth noting that this effect depends on the existing building location, since it becomes more significant when the seismic hazard is higher. Definitely, the coupled energy-structural approach allows the estimation of the actual effectiveness of cost-optimal energy retrofit solutions, which could be, in some cases, even not profitable (i.e., payback time higher than lifetime) for locations characterized by high levels of seismic risk and vulnerable existing buildings.

5.3 CASE STUDY

A reinforced concrete (RC) structure has been chosen as case study for implementing the integrated procedure described above. The building is the same analysed in Chapter 2. It is a typical example of an Italian facility built in 1970s according to the old building code. In addition, the building envelope presents low thermal resistance, like large part of Italian existing buildings, and this implies inadequate energy performance given the high entity of energy demand for space conditioning. In this regard, the vertical external walls are in hollow bricks and have thermal transmittance (i.e., U-value) equal to 1.23 W/m^2K. The horizontal envelope is in mixed brick-reinforced concrete and the U-value is equal to 1.05 W/m^2K for the roof and to 0.90 W/m^2K for the basement floor. Finally, the windows are double-glazed with wooden frames and have U-value equal to 2.67 W/m^2K as well as solar heat gain coefficient (SHGC) equal to 0.691.

Each storey hosts five typical apartments of different extension. These are denoted with the letters A, B, C, D and E in Figure 5.2b and 5.2c, which also shows the subdivision into thermal zones, employed in EnergyPlus simulations.

The building is assumed to be located in two different Italian cities, namely Norcia (Central Italy) and Milan (Northern Italy). These are characterized by similar climatic conditions but by a different level of seismic risk, which is higher for Norcia site. As concerns the climatic scenario, both cities belong to the Italian climatic zone E, which collects all locations with heating degree days (HDDs) in the range 2101-3000. In particular, the value of HDDs is 2404 for Milan and 2608 for Norcia. Definitely, both cities present a heating-dominated climate, so that space heating demand is much higher than space cooling one.



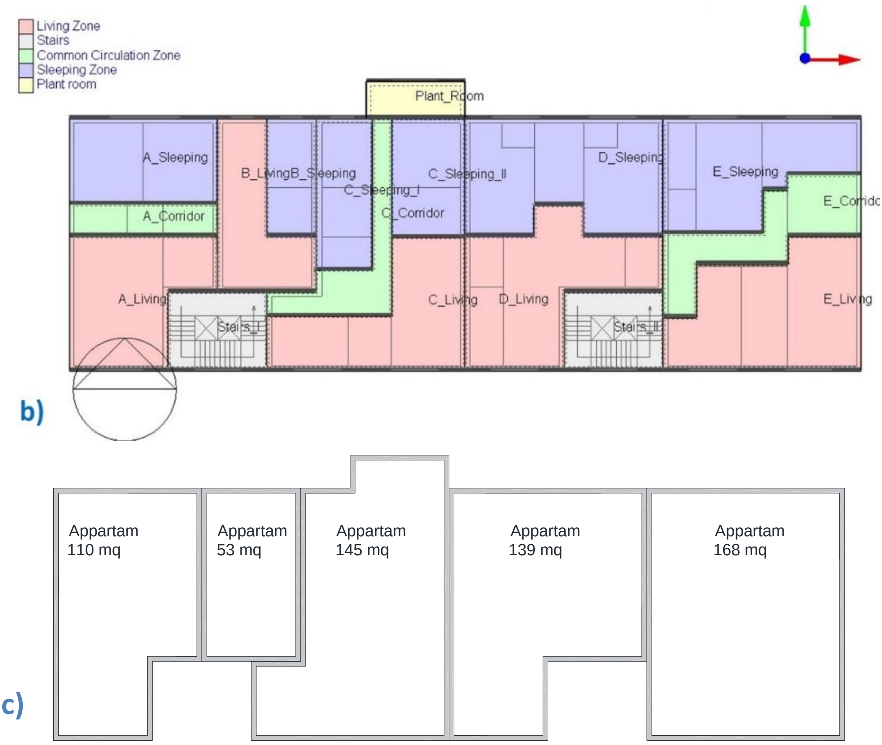


Figure 5.2 Building geometry: a) 3D view; b) Plan view c) Plan view of apartments

On the other hand, with regard to the seismic risk, the PGA (peak ground acceleration) demand value depends on the site hazard and, it is 0.049 g (gravitational acceleration) for Milan and 0.255 g for Norcia, respectively, considering as seismic demand a severe earthquake with a return period of 475 years, according to the Italian National Building Code (Ministero delle Infrastrutture, 2008).

5.3.1 Investigated energy retrofit measures (ERMs)

For both considered climatic locations, the following ERMs are investigated for the reduction of thermal energy demand and discomfort hours:

- variation of heating set point temperature (T_h), which cannot be higher than 22 °C according to Italian regulations (Decreto Legge, 1993);
- variation of cooling set point temperature (T_c);
- variation of the infrared emissivity of the external vertical walls (e_v) by means of the installation of external plasters;
- variation of the solar absorptance of the external vertical walls (a_v) by the installation of external plasters;
- variation of the infrared emissivity of the roof (e_r) by the installation of external plasters;
- variation of the solar absorptance of the roof (a_r) by the installation of external plasters;
- installation of an external layer of thermal insulation (thermal conductivity = 0.026 W/m K, density = 25 kg/m^3, specific heat = 1340 J/kg K) on the external vertical walls; the insulation layer's thickness is denoted as t_v;
- installation of an external layer of thermal insulation (see above properties) on the roof; the insulation layer's thickness is denoted as t_r;
- replacement of the windows with energy efficient ones; where the following eight options are considered:
    - w1) double-glazed air-filled windows with wooden frames: U_w = 2.67 W/m^{2}K; SHGC (solar heat gain coefficient) = 0.691; this option characterizes the baseline;
    - w2) double-glazed air-filled windows with low-emissive coatings and PVC frames: U_w = 1.96 W/m^{2}K, SHGC = 0.691;
    - w3) double-glazed air-filled windows with low-emissive, tinted coatings and PVC frames: U_w = 1.76 W/m^{2}K, SHGC = 0.380;

- w4) double-glazed air-filled windows with low-emissive, selective coatings and PVC frames: U_w = 1.64 W/m^{2}K, SHGC = 0.433;
- w5) double-glazed argon-filled windows with low-emissive coatings and PVC frames: U_w = 1.71 W/m^{2}K, SHGC = 0.691;
- w6) double-glazed argon-filled windows with low-emissive, tinted coatings and PVC frames: U_w = 1.49 W/m^{2}K; SHGC = 0.380;
- w7) double-glazed air-filled windows with low-emissive, selective coatings and PVC frames: U_w = 1.34 W/m^{2}K; SHGC = 0.433;
- w8) triple-glazed argon-filled windows with low-emissive coatings and PVC frames: U_w = 1.10 W/m^{2}K; SHGC = 0.579.

Different options are investigated for the described ERMs thereby implying the variables reported in Table 5.1.

Design Variable		Options	Number of Options	Number of Bits for Encoding
(1)	T_h [°C]	19, 20 (B *), 21, 22	4	2
(2)	T_c [°C]	24, 25, 26 (B), 27	4	2
(3)	e_v	0.1, 0.25, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 (B)	8	3
(4)	a_v	0.1, 0.25, 0.4, 0.5, 0.6 (B), 0.7, 0.8, 0.9	8	3
(5)	e_r	0.1, 0.25, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 (B)	8	3
(6)	a_r	0.1, 0.25, 0.4, 0.5, 0.6 (B), 0.7, 0.8, 0.9	8	3
(7)	t_v [m]	0 (B), 0.04, 0.05, 0.06, 0.08, 0.10, 0.12, 0.14	8	3
(8)	t_r [m]	0 (B), 0.04, 0.05, 0.06, 0.08, 0.10, 0.12, 0.14	8	3
(9)	Windows' type	w1 (B), w2, w3, w4, w5, w6, w7, w8	8	3

***** B: baseline (i.e., as built configuration)

Table 5.1 Design variables of the bi-objective optimization problem (solved through the GA) for the minimization of thermal energy demand and discomfort hours

These latter represent the design variables, which are nine, of the bi-objective optimization problem solved by running the GA described in §5.2.1. The options considered have been chosen based on building peculiarities, best-practices and outcomes of previous studies (Ascione, Bianco, De Masi, et al., 2015; Ascione, Bianco, De Stasio, et al., 2015, 2016). The investment costs of these ERMs are not characterized now but later, because only the optimal (non-dominated) solutions provided by the GA are subjected to the cost-optimal analysis.

As shown in Table 5.1, the total number of bits for variables' encoding is 25, and thus the domain that is explored by the GA is made of 2^{25} = 33554432 solutions. The investigation of each solution needs an EnergyPlus simulation. The use of an optimization algorithm, such as the employed GA, is fundamental to explore a so-wide domain in a reasonable computational time by conducting a smart research of the optimal solutions.

After the description of the ERMs investigated through the GA (stage 1), Table 5.2 shows the considered ERMs for primary energy systems, which are examined in stage 2 of the proposed methodology by performing a smart sampling. These ERMs address:

- the improvement of the energy efficiency of the primary heating system;
- the improvement of the energy efficiency of the primary cooling system;
- the improvement of the energy efficiency of the primary system for the production of domestic hot water (DHW);
- the installation of systems for the exploitation of RESs, namely photovoltaic (PV) panels.

In addition, in this case, different options are considered for the mentioned ERMs. The values of peak thermal power of the heating, cooling and DHW systems are set equal to the baseline's values. The investment costs are taken from literature (Ascione, Bianco, De Stasio, et al., 2016; Mauro, Hamdy, Vanoli, Bianco, & Hensen, 2015) and, when not available, from direct quotations of suppliers. Lastly, financial incentives, provided by current Italian law (Governo Italiano, 2015) for ERMs, are taken into account. The possible (compatible) combinations of the considered primary energy systems are 294.

		Description and Considered Options	Investment Cost (IC)	Incentives
HEATING SYSTEM	**Existing gas boiler (B *)**	Natural gas boiler with nominal efficiency (η), assessed considering the LCV (lower calorific value) of gas, equal to 0.85.	—	—
	Condensing gas boiler	Condensing natural gas boiler with nominal η equal to 1.06.	13,100 €	65% of IC up to 30 k€, accorded in 10
	Air-source heat pump	Air-source electric heat pump with nominal COP (coefficient of performance) equal to 3.8.	26,000 €	65% of IC up to 30 k€, accorded in 10 years
HEATING & COOLING	**Ground-source reversible heat pump**	Reversible ground-source electric heat pump with geothermal vertical probes: - Heating operation: nominal COP = 5.1 - Cooling operation: nominal EER (energy efficiency ratio) = 6.1.	97,500 €	65% of IC up to 30 k€, accorded in 10
COOLING SYSTEM	**Existing air-cooled chiller (B)**	Air-cooled electric chiller with nominal EER equal to 2.5.	—	—
	Efficient air-cooled chiller	Energy-efficient air-cooled electric chiller with nominal EER equal to 3.4.	19,250 €	—
DHW SYSTEM	**Existing gas boiler (B)**	Natural gas boiler with nominal η equal to 0.85.	—	—
	Efficient gas boiler	Energy-efficient natural gas boiler with nominal η equal to 0.95.	15,750 €	—
RESs	**Solar photovoltaic (PV) panels**	Solar PV panels on the roof, south-oriented with tilt angle of 34°. The size is expressed by “cov”: percentage of the available roof area (=600 m^2) covered by PV panels. Mutual shading is avoided. Cov can vary between 0% (B) and 100% with a step of 10%. Two typical PV types are considered: poly-crystalline silicon	250 € per m^2 of panels’ surface	50 % of IC up to 96 k€, accorded in 10 years
		mono-crystalline silicon	430 € per m^2 of panels’ surface	

***** B: baseline (i.e., as built configuration).

Table 5.2 Investigated primary energy systems

5.3.2 Simulation Assumptions

It should be noted that the following assumptions are made in the energy analysis:

- the primary energy conversion factor is set equal to 1.95 for electricity and 1.05 for natural gas, according to current Italian law (Ministero dello sviluppo economico, 2015);
- the energy price is set equal to 0.25 €/kWh$_{el}$ for electricity and 0.90 €/Nm3 for natural gas as done in (Mauro et al., 2015);
- produced electricity that is sold to the grid (in presence of PV panels) is remunerated at the price of 0.08 €/kWh$_{el}$, as done in (Ascione, Bianco, De Stasio, et al., 2016);
- the polluting emissions' factor is set equal to 0.708 tCO_2-eq/MWh$_{el}$ for electricity 0.237 tCO_2-eq/MWhp for natural gas (Covenant of Mayors, n.d.);
- the considered calculation period (i.e., lifetime) for the assessment of GC is 30 years as recommended in (European Commision, 2012) for residential buildings, and the assumed discount rate is equal to 3% (European Commision, 2012);
- in EnergyPlus simulations, the IWEC (international weather for energy calculations) weather data file related to Milan (EneryPlus, 2014) is used when Milan is considered as location; on the other hand, the IGDG (Italian climatic data collection "Gianni De Giorgio") weather data file related to Perugia (EneryPlus, 2014) is used for Norcia. In this regard, accredited weather data files are not available for Norcia, but the use of Perugia file provides a good approximation, since these two locations are very close (the distance is around 70 km) and characterized by similar climatic conditions.

On the other hand, as regards the structural analysis, the non-linear building response is simulated by means of the finite element software (SAP2000 (Computer and Structurers, n.d.)) using lumped plasticity models of beams and columns (i.e., four hinges for each structural member: top and bottom for both directions). The column and beam plastic hinge models are calculated according to the European Code UNI-EN 1998-3:2005 (E. Standard, 2005) as shown in Chapter 2. Non-linear static analyses are performed for the two plan directions of the structure independent from each other (i.e., x-x and y-y directions with an eccentricity of ±5% of the length side). The horizontal load-patterns assumed in the analyses are the first mode force pattern (obtained from the displacement distribution of the modal analysis) and a force pattern proportional to the mass distribution. Accordingly, for each direction and for each force pattern, the analyses with the lowest seismic capacity are chosen. The achievement of the first failure mechanism due to shear stress of a structural member identifies the PGA capacity of the structure and, consequently, the ratio between the capacity and the demand in terms of the PGA has been defined as the safety level. The safety levels computed from the non-linear static analyses, are summarized in the following Table 5.3.

Force Pattern	**Eccentricity**	**Safety Level**	
		Milan	**Norcia**
Mass X	X-E-	80%	15%
Mass Y	Y+E-	100%	50%
First Mode X	X-E+	75%	20%
First Mode Y	Y+E+	100%	24%

Table 5.3 Safety level of the non-linear analyses

5.4 MULTI-STEP APPROACH

The presentation and discussion of the results is organized in two subsections, which refer to the baseline (i.e. the as built building performance) and to the retrofitted building, respectively.

5.4.1 Baseline: as built building performance

As concerns the baseline energy performance, Table 5.4 shows thermal energy demand for space conditioning (TED_{sc}), percentage of discomfort hours (DH), primary energy consumption (PEC), global cost (GC) and polluting emissions (EM) for both climatic locations. Milan is characterized by more rigid climatic conditions in both seasons, thereby implying higher values, compared to Norcia, of all performance indicators.

Location	**TED$_{sc}$**	**DH**	**PEC**	**GC**	**EM** (CO_2-eq)
Milan	86.08 kWh$_t$/m^{2}a	31.43%	202.72 kWh$_p$/m^{2}a	419.19 €/m^2 (722.25 k€)	58.66 kg/m^{2}a (108.06 t/a)
Norcia	70.43 kWh$_t$/m^{2}a	26.94%	186.17 kWh$_p$/m^{2}a	388.07 €/m^2 (714.91 k€)	54.38 kg/m^{2}a (100.18 t/a)

Table 5.4 Energy characterization of the baseline

As concerns the baseline structural performance, according to the procedure previously described, the EDPs obtained from the structural analyses are implemented into fragility models to assess the probability of occurrence of a damage state for a specific building component. Converting the damage of a component into an economic loss allows the computation of the total loss of the entire building due to seismic events. The fragility models implemented in this case study are: Pagni and Lowes (Pagni & Lowes, 2006) for beam-column joints; Aslani and Miranda (Hesameddin Aslani & Miranda, 2005) for beams, columns and windows; Ruiz-Garcia and Negrete (Ruiz-García & Negrete, 2009) for internal and external partitions and systems (i.e. electric, hydraulic and energy system). The economic value of each component and of each ERM is evaluated through the support of the price list of the typography of the Italian civil engineering DEI. Furthermore, it is also necessary to evaluate the reconstruction cost of the building due to a destructive earthquake. For the total collapse, a reconstruction cost of 1200 €/m^2 is assumed. In this application case, the unavailability cost of the facility for a temporary suspension, the injuries and the casualties costs have not been considered.

The assessed expected seismic economic losses are reported in the following Table 5.5.

Force Pattern	**Eccentricity**	**Expected Annual Loss (EAL)**	
		Milan	**Norcia**
Mass X	X-E-	5.29 k€	59.74 k€
Mass Y	Y+E-	3.47 k€	42.11 k€
First Mode X	X-E+	5.58 k€	60.40 k€
First Mode Y	Y+E+	3.47 k€	43.38 k€

Table 5.5 Expected annual losses of the baseline

5.4.2 Building retrofit: energy optimization and economic loss assessment

In the first stage of the optimization of building energy retrofit, the genetic algorithm (GA) is implemented in order to find optimal packages of ERMs addressed to the building envelope and to the variation of set point temperatures. The objective functions are the minimization of TED_{sc} and DH, whereas the design variables have been presented in Table 5.1. The GA provides the Pareto front, which is depicted in Figure 5.3 for Milan site and in in Figure 5.4 for Norcia site.

Results hereafter reported have been computed by the energy team of Federico II and are reported for comprehension.

The Pareto front related to Milan collects 35 non-dominated solutions, while the front related to Norcia collects 47 solutions. In both cases, all Pareto solutions provide values of DH lower than the baseline (DH_B), and thus they are acceptable. It is noticed that all Pareto solutions for both locations include the following ERMs:

- 14cm-thick thermal insulation of both external vertical walls and roof;
- installation of triple glazed windows.

Therefore, in all cases, the maximum levels of thermal insulation are implemented for both opaque and transparent building envelopes. This occurs because the heating demand is much higher than cooling demand for both locations, and therefore high levels of insulation are extremely effective and do not cause the risk of summer overheating for the considered (i.e., residential) use destination. It should be noticed that higher values of insulation thickness have not been considered because they would imply just a slight decrease of thermal transmittance, and furthermore the installation of too-thick insulation layers is hardly feasible from a practical perspective. The investment costs (IC) of the mentioned optimal ERMs for the envelope have been taken from direct quotations of suppliers. In particular, IC is set equal to 50.8 €/m^2 for the 14cm-thick thermal insulation and to 290 €/m^2 for triple-glazed windows.

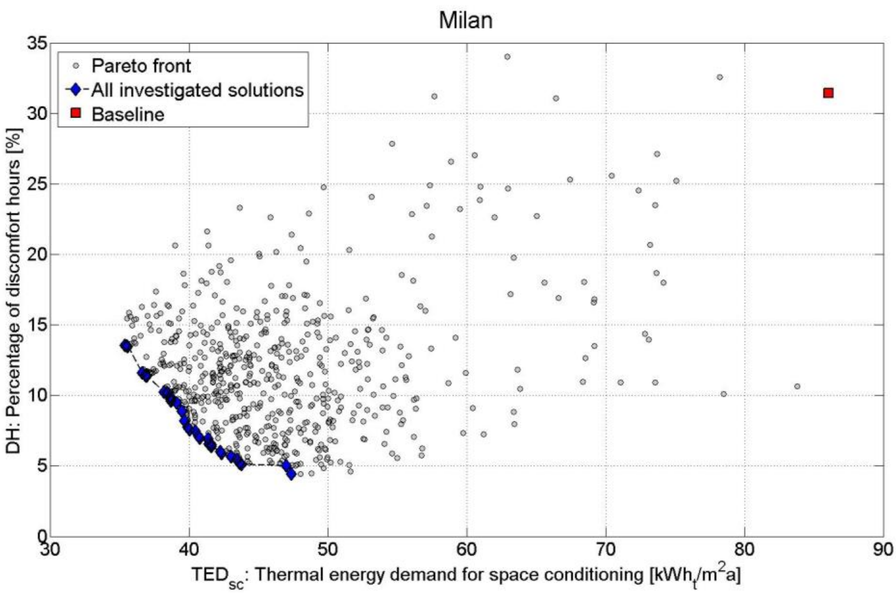


Figure 5.3 Optimization of the ERMs for the reduction of TEDsc and DH considering Milan as location

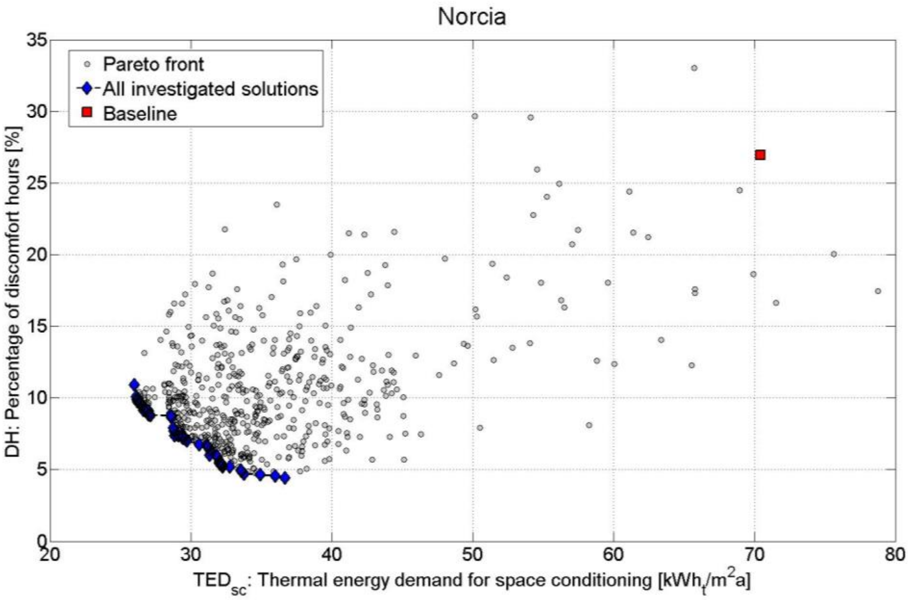


Figure 5.4 Optimization of the ERMs for the reduction of TEDsc and DH considering Norcia as location

The GA allows to find optimal packages of ERMs for the reduction of TED_{sc} and DH. Then, the second stage of the methodology is performed in order to consider also the implementation of new efficient primary energy systems (see Table 5.2). Thus, the smart sampling is carried out under MATLAB® environment. The total number of explored retrofit scenarios is given by the product of (Pareto solutions + 1) and (combinations of energy systems), where 1 is added to the number of Pareto solutions because the ERMs for energy systems are examined also in absence of ERMs for the building envelope and for the variation of set point temperatures. Hence, the total number of explored scenarios is equal to 10,584 for Milan and 14,112 for Norcia. For each scenario, the differences of PEC (denoted as dPEC) and GC (denoted as dGC), compared to the baseline, are evaluated thereby achieving the cost-optimal curves represented in Figure 5.5 for Milan and Figure 5.6 for Norcia. The star markers indicate the cost-optimal packages of ERMs, which are characterized in Table 5.6.

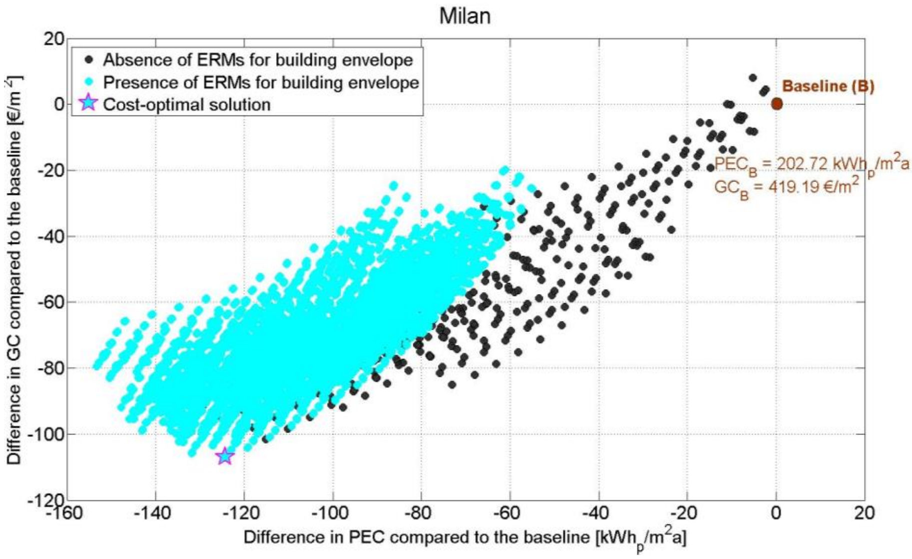


Figure 5.5 Cost-optimal curve of building energy retrofit considering Milan as location

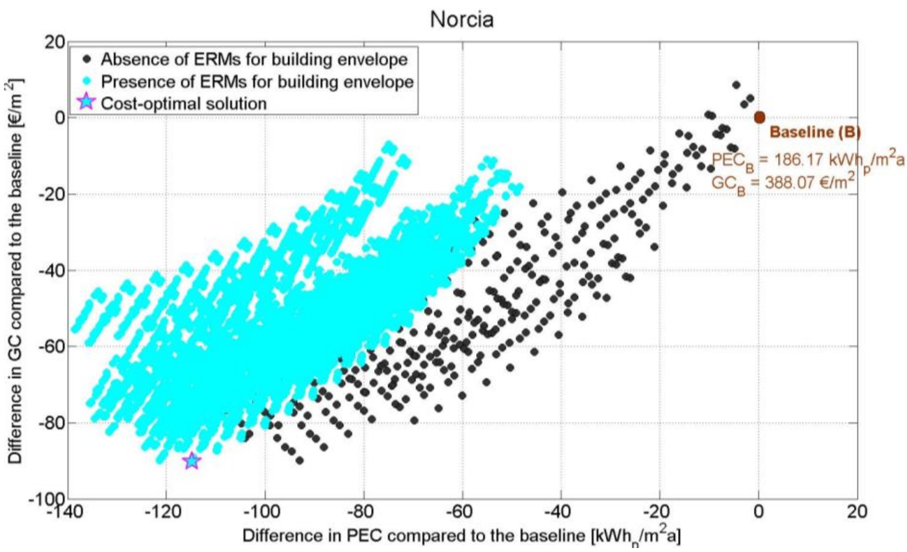


Figure 5.6 Cost-optimal curve of building energy retrofit considering Norcia as location

Location	TED_{sc}	DH	dPEC *	dGC *	IC	DPB	dEM * (CO_2-eq)
Milan	35.41 kWh_t/m^2a	13.55%	−124.26 kWh_p/m^2a	−106.96 €/m^2 (−197.05 k€)	267.6 k€	11 years	−36.22 kg/m^2a (−66.73 t/a)
	Cost-optimal energy retrofit solution ▪ Heating set point temperature (T_h) = 19 °C ▪ Cooling set point temperature (T_c) = 27 °C ▪ External plastering and 14 cm-thick thermal insulation of the external vertical walls: - e_v = 0.10 - a_v = 0.60 - U_v = 0.161 W/m^2K ▪ External plastering and 14 cm-thick thermal insulation of the roof: - e_r = 0.40 - a_r = 0.50 - U_r = 0.158 W/m^2K ▪ Installation of triple-glazed windows (w8): - U_w = 1.10 W/m^2K - SHGC = 0.579 ▪ Installation of the condensing boiler for space heating ▪ Installation of poly-crystalline PV, cov = 100%						
Location	**TED_{sc}**	**DH**	**dPEC ***	**dGC ***	**IC**	**DPB**	**dEM * (CO_2-eq)**
Norcia	26.13 kWh_t/m^2a	10.10%	−114.77 kWh_p/m^2a	−90.17 €/m^2 (−166.12 k€)	267.6 k€	12.1 years	−33.83 kg/m^2a (−62.32 t/a)
	Cost-optimal energy retrofit solution ▪ Heating set point temperature (T_h) = 19 °C ▪ Cooling set point temperature (T_c) = 27 °C ▪ External plastering and 14 cm-thick thermal insulation of the external vertical walls: - e_v = 0.40 - a_v = 0.60 - U_v = 0.161 W/m^2K ▪ External plastering and 14 cm-thick thermal insulation of the roof: - e_r = 0.10 - a_r = 0.25 - U_r = 0.158 W/m^2K ▪ Installation of triple-glazed windows (w8): - U_w = 1.10 W/m^2K - SHGC = 0.579 ▪ Installation of the condensing boiler for space heating ▪ Installation of poly-crystalline PV, cov = 100%						

***Negative values denote a reduction (i.e., a benefit) compared to the baseline**

Table 5.6 Characterization of the cost-optimal energy retrofit solutions

The outcomes about cost-optimality follow energy and economic considerations. As aforementioned, the maximum levels of thermal insulation are implemented for both opaque and building envelopes because the heating load is much higher than the cooling one. The increment of envelope's thermal resistance allows increasing the heat storage inside the building as well as the values of internal surface mean radiant temperatures. This yields an increase of occupants' thermal comfort, and thus a decrease of DH compared to the baseline, even if a lower heating set point temperature (19°C vs 20°C of baseline) and a higher cooling set point temperature (27°C vs 26°C of baseline) are set. The value of external plasters' solar absorptance (a) is higher for external walls compared to the roof in order to increase the absorption of solar radiation in the heating season (when radiation is a gain) and reduce such absorption in the cooling season (when radiation is a load). Indeed, in wintertime solar radiation is less perpendicular, and thus more impacting on the vertical walls, whereas in summertime is more perpendicular, and thus more impacting on the roof. As concerns the energy systems, the condensing boiler is preferred to the air-source electric heat pump, because the low values of external temperature during wintertime for the considered sites cause a significant worsening of heat pumps' performance. On the other hand, the condensing boiler is more cost-effective than the ground-source heat pump, given the much lower investment cost. No ERMs are implemented for cooling systems because of the low values of space cooling demand. In addition, the existing boiler for DHW production is not replaced because the proposed solution does not imply a substantial increase of energy efficiency and incentives are not available for this solution. Lastly, a full-roof PV system is installed because the overall electricity demand of the building is significant, and thus photovoltaic panels are extremely cost-effective, as also shown in (Ascione, Bianco, De Masi, et al., 2016).

Finally, Table 5.6 shows that the cost-optimal energy retrofit solutions imply significant reductions of energy consumption, global cost and polluting emissions with reasonable discounted payback times, slightly higher than ten years. The benefits are higher for Milan site because the baseline is characterized by higher energy consumption, and thus there are larger opportunities of energy and cost savings. It is highlighted that, for both locations, the cost-optimal solutions make the building very close to the standard of nearly zero energy building (nZEB).

In order to assess the seismic economic loss of the retrofitted building, it is important to highlight how energy retrofit solutions have been related to the fragility models and to the damage analysis step of the loss assessment procedure. Table 5.7 shows schematically the influence of the retrofit energy solutions on the seismic loss assessment.

Energy Retrofit Measure (ERM)	**Effects on Seismic Loss Assessment**
External plastering and 14 cm-thick thermal insulation of the walls	This ERM is applied on existing walls, and thus it is implemented in the fragility models of such walls. In particular, it influences the replacement cost of the walls that increases from 97 €/m^2 to 145 €/m^2.
External plastering and 14 cm-thick thermal insulation of the roof	The damage analysis assumes that each floor is a rigid diaphragm due to the thickness of the slab and cannot be damaged. For this reason, this ERM influences only the reconstruction cost of the whole building.
Installation of triple-glazed windows	This ERM influences the replacement cost of the component that increases from 200 €/m^2 to 290 €/m^2.
Installation of the condensing boiler	This ERM influences the replacement cost of the component (i.e., boiler) that increases from 7.8 k€ to 13.1 k€.
Installation of poly-crystalline PV	The damage analysis assumes that each floor is a rigid diaphragm due to the thickness of the slab and cannot be damaged. For this reason, this ERM influences only the reconstruction cost of the whole building.

Table 5.7 Influence of cost-optimal energy retrofit measures on seismic loss assessment

Once estimated the cost-optimal energy retrofit solutions, it is possible to assess the seismic economic loss of the retrofitted structure and the influence of the energy retrofit measures of these losses. The results are reported in Table 5.8.

Force Pattern	**Eccentricity**	**Expected Annual Loss (EAL)**	
		Milan	**Norcia**
Mass X	X-E-	7.69 k€	65.36 k€
Mass Y	Y+E-	3.70 k€	46.10 k€
First Mode X	X-E+	6.04 k€	66.07 k€
First Mode Y	Y+E+	3.71 k€	47.53 k€

Table 5.8 Expected annual losses of the facility after the implementation of cost-optimal energy retrofit strategies

Furthermore, Table 5.9 shows the increment of the expected annual losses for both locations in order to assess the influence of the cost-optimal energy retrofit on seismic losses. Results are reported in terms of percentage and cost (in €) increases, and are displayed for each force pattern along with the resulting average values.

Force Pattern	**Eccentricity**	**Increment of the Expected Annual Loss (EAL)**			
		Milan [%]	**Norcia** [%]	**Milan** [€]	**Norcia** [€]
Mass X	X-E-	8.13%	9.41%	0.43 k€	5.62 k€
Mass Y	Y+E-	6.63%	9.48%	0.23 k€	3.99 k€
First Mode X	X-E+	8.24%	9.39%	0.46 k€	5.67 k€
First Mode Y	Y+E+	6.92%	9.57%	0.24 k€	4.15 k€
Average Values		7.48%	9.46%	0.34 k€	4.86 k€

Table 5.9 Increment of the Expected Annual Losses after the implementation of cost-optimal energy retrofit strategies

Finally, it is clear that the implementation of the cost-optimal energy retrofit strategies exert different economic impacts depending on the location of the existing building. As is obvious, the energy retrofit requires an initial investment cost (IC), and, globally, during the building residual lifetime (life-cycle), it turns into an economic benefit due to the reduction of global cost for energy uses (GC); however, at the same time, it causes an increase of expected economic losses (i.e. EALs) linked to the seismic risk. In particular, the proposed energy retrofit causes a maximum increase of EAL, assessed in the worst seismic scenario, equal to 460 €/year for Milan and to 5670 €/year for Norcia. Clearly, this increment is more significant for Norcia because this location is characterized by higher seismic risk. Definitely, as shown in Figure 5.7, the potential global cost savings (GCS) produced by the retrofit solutions decrease when the coupled energy-structural approach is used considering the seismic economic losses in global cost assessment. On the other hand, the use of a merely energy approach, which does not consider seismic losses, could imply an overestimation of economic benefits over the building lifetime(life-cycle).

Figure 5.7 allows the assessment of the global effectiveness of the identified robust cost-optimal retrofit strategies; these latter were obtained by using the proposed multi-step approach that integrates energy and structural considerations. From an overall perspective, the retrofit strategies mentioned above are cost-effective for both Milan and Norcia sites because, in both cases, they yield positive values of global cost saving (GCS) with discounted payback times (DPB) between 11 and 20 years. However, if the coupled energy-structural approach is used instead of the merely energy one, the economic benefits decrease, as detailed below:

- for Milan, the final GCS changes from 197.05 k€ to 188.94 k€, and the DPB from 11 to 11.2 years; and
- for Norcia, the final GCS changes from 166.12 k€ to 54.98 k€, and the DPB from 12.1 to 20 years.

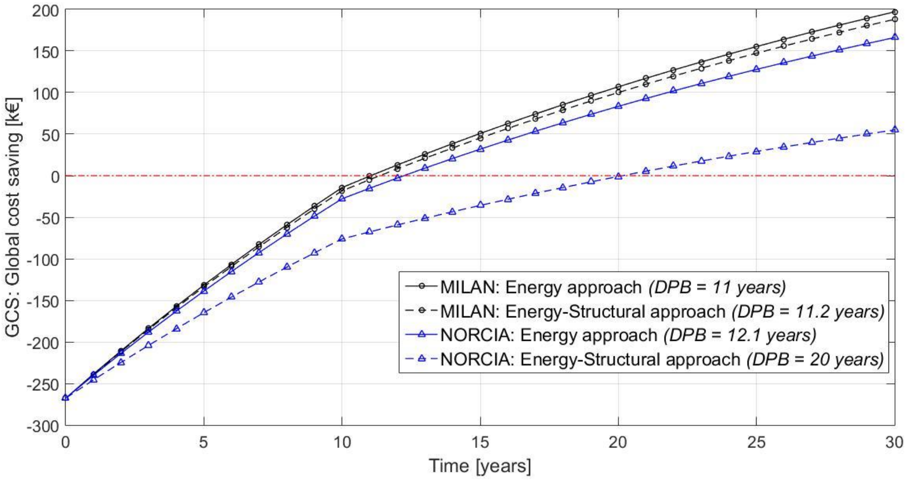


Figure 5.7 Temporal trend of the Global cost saving produced by the cost-optimal energy retrofit solution considering seismic economic losses

The use of energy efficient equipment reduce the operational energy consumption of the building, which constitutes the greater part of energy costs during the life-cycle. The initial investment for this equipment may be higher; but, this will be generally paid back by future savings as shown. The required information to analyse energy consumption in building is quite complex and includes data about the external environment, the shape, the configuration and the orientation of the building, lighting mechanical systems and air distribution. Thus, for accurate prediction of energy consumption, an integrated simulation tools should be used such as a BIM model able to connect all the information created over the building's life-cycle. This multi-step approach proposed herein, that integrates structural and energy aspects, may be enriched with a BIM modelling able to optimize data flow as shown schematically in Figure 5.8.

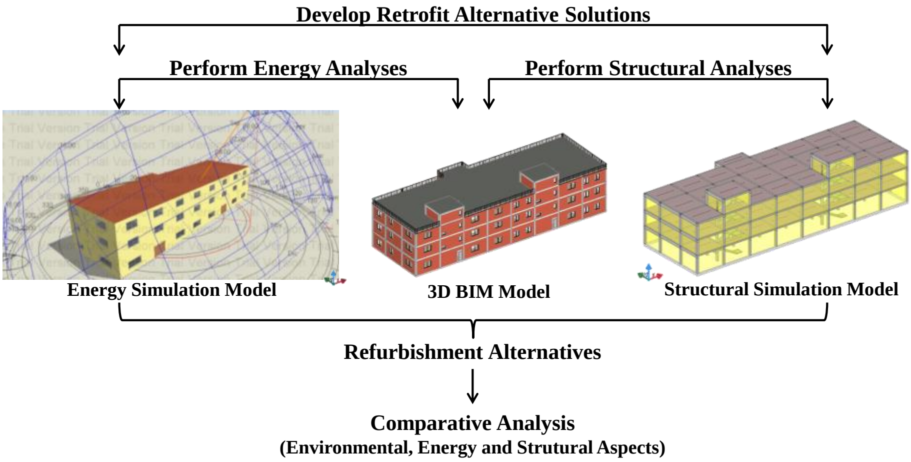


Figure 5.8 Multi-step approach integrated into a BIM environment

Overall, the outcomes show that, for similar climatic conditions, the level of seismic risk highly affects the effectiveness of the initial investment for energy retrofit, which is much lower for Norcia site. In this regard, the potential GCS may be not sufficient for prompting building owners/occupants to implement building energy retrofit. In other words, the economic benefit could be not sufficient to overcome the "status quo" bias. Therefore, in this case, building energy retrofit should be combined with seismic retrofit measures in order to reduce the seismic economic losses. This issue will be handled in the next chapter, which will focus on the integrated optimization of energy and seismic retrofit by means of a life-cycle approach.

CHAPTER 6

AN INTEGRATED APPROACH FOR THE ENERGY AND SEISMIC RETROFIT OPTIMIZATION OF EXISTING BUILDINGS

European existing buildings do not comply with current building codes and suffer from a physical, an environmental and a structural point of view over the building lifetime. The present chapter proposes an innovative lifecycle approach to address the retrofit of existing buildings. In this regard, the proper retrofit design requires to explore a wide domain of scenarios concerning the implementation of energy and seismic measures. Finally, the retrofit measures are combined to show the advantages of a coupled approach compared to a standard-alone procedure.

6.1 INTRODUCTION

Over the last decade, building retrofit has gained the attention of practitioners, homeowners and national governments. Indeed, national policies have recently encouraged the increment of both the energy efficiency and safety levels for the upgrading of the building envelope.

The design of retrofit interventions should implement energy and structural objectives, nevertheless, as highlighted in the previous chapter, the “core” of any retrofit process seems to be brought back to the energy retrofit, neglecting the interaction with other aspects as the seismic retrofit. Moreover, in such case the economic benefit of the energy retrofit could be not sufficient to overcome the “status quo” bias.

Within this context, this chapter introduces an integrated approach for the energy and seismic retrofit optimization of existing buildings. The combined approach is based on the retrofit optimization procedure of the chapters 3 and 5, addressing all the sustainability concepts. Seismic retrofit optimization impacts on the economic and social pillars of sustainability safeguarding human lives and optimizing the economic effort. The energy retrofit optimization, instead, influences all pillars of sustainability, reducing environmental impacts, increasing the overall comfort of the building envelope and optimizing the total spending.

In this regard, the methodology is applied to the Italian multi-storey residential building analysed in the previous chapter by considering three different building sites that are Benevento, Lattarico and Spoleto. These latter are characterized by the same level of seismic risk but different climatic conditions, since they belong respectively to the Italian climatic zone C, D and E.

6.2 METHODOLOGY

Herein a multi-step approach is proposed that aims to evaluate a proper retrofit strategy that addresses the sustainability criteria in order to implement the most proper (cost-effective and/or sustainable) solution for a given existing building. The multi-step approach proposed hereafter aims to optimize the energy and structural performances of a retrofitted building quantifying the overall economic life-cycle costs associated. In particular, the overall outcomes of this integration are handled in terms of global life-cycle expected costs, which include investments and operating costs over the lifetime of the building.

The methodology consists of four steps:

1. Building assessment in the as-built configuration;
2. Energy retrofit optimization;
3. Seismic retrofit optimization;
4. Combined retrofit optimization.

In the first step the building is analysed in the as-built configuration. The structural capacity and the energy features are evaluated. Accordingly, a set of energy measures and retrofit strategies are identified for the upgrading of the building envelope.

In the second step, the energy retrofit procedure proposed in chapter 5 is implemented to identify the most cost-effective solution by means of a multi-stage optimization approach that implements a genetic algorithm (stage 1) and a smart sampling of retrofit scenarios (stage 2). The global cost saving produced by the retrofit solution is assessed considering the economic loss related to the ERMs in order to avoid an overestimation of the economic benefits.

In the third step, the seismic retrofit optimization proposed in chapter 3 is applied to identify the cost-optimal retrofit level and the retrofit strategy.

Finally, in the last step the retrofit procedures are combined to show the advantages of a coupled approach. The investment cost is computed as the sum of the cost of the energy retrofit measures and the seismic retrofit interventions. The global cost saving function is obtained computing the benefits produced by the global cost savings of the ERMs and the global cost savings of the structural strengthening operations.

The advantages of a combined approach are showed with and without the influences of the financial incentives provided by the government.

The steps described above are implemented in the case study reported in the following subsections.

6.3 CASE STUDY

The reinforced concrete (RC) structure of the previous chapter has been assumed as case study for implementing the procedure described above. The building is a typical example of an Italian facility built in the 1970s according to the old building code and without any seismic prevision.

The building envelope presents low thermal resistance, like large part of Italian existing buildings. The vertical external walls are in hollow bricks and have thermal transmittance (i.e., U-value) equal to 1.23 W/m^2K. The horizontal envelope is in mixed brick-reinforced concrete and the U-value is equal to 1.05 W/m^2K for the roof and to 0.90 W/m2K for the basement floor. Finally, the windows are double-glazed with wooden frames and have U-value equal to 2.67 W/m^2K as well as solar heat gain coefficient (SHGC) equal to 0.691.

As regards the structural behaviour of the building materials, the following mechanical properties are assumed: concrete compressive strength (f_{cm}) equal to 15 MPa; steel tensile strength (f_{ym}) equal to 220 MPa.

The building is assumed to be located in three different Italian cities, namely Benevento, Lattarico and Spoleto. These are characterized by different climatic conditions but a similar level of seismic risk. Indeed, the PGA (peak ground acceleration) demand values are 0.251 g for Benevento, 0.260 g for Lattarico and 0.221 g for Spoleto, considering as seismic demand a severe earthquake with a return period of 475 years. As concerns the climatic scenario, Benevento, Lattarico and Spoleto belong, respectively, to the Italian climatic zone C, D and E.

Benevento is characterized by 1316 HDDs (heating degree days), and thus it belongs to the Italian climatic zone C that collects all locations with HDDs in the range 901–1400; Lattarico is characterized by 1644 HDDs, and thus it belongs to the Italian climatic zone D that collects

all locations with HDDs in the range 1401–2100; Spoleto is characterized by 2427 HDDs, and thus it belongs to the Italian climatic zone E that collects all locations with HDDs in the range 2101–3000.
Definitely, the locations present different climatic conditions. Benevento has a balanced-climate, so that space heating and cooling demands are similar. Spoleto has a heating-dominated climate, so that space heating demand is much higher than space cooling demand. Lattarico provides an intermediate situation between Benevento and Spoleto.
The assumption about the building sites is a consequence of the results obtained in Chapter 5. Indeed, the global cost savings produced by the coupled energy-structural approach showed its most significant results when the seismicity of the site was the highest. The choice of this three building high seismicity sites, characterized by different climatic conditions, allows to explore a wide domain of scenarios in which the combined energy-seismic retrofit approach may be implemented to show the related benefits and advantages.
As regards the structural analysis, non-linear static analyses have been carried out to simulate the non-linear building response with finite element software Edilus produced by ACCA Software ® (Acca software SpA). The software adopts a fiber-based distributed plasticity model for the non-linear behaviour of structural elements instead of a lumped plasticity model.
The horizontal load-patterns assumed in the analyses are the first mode force pattern (obtained from the displacement distribution of the modal analysis) and a force pattern proportional to the mass distribution. Accordingly, the analysis with the lowest seismic capacity is chosen. The achievement of the first failure mechanism due to shear stress of a structural member identifies the PGA capacity of the structure and, consequently, the ratio between the capacity and the demand in terms

of the PGA has been defined as the safety level. The safety levels computed from the non-linear static analyses are summarized in Table 6.1.

Safety Level		
Benevento	Lattarico	Spoleto
24%	24%	30%

Table 6.1 Safety levels of the building in the different sites

As regards the energy analysis, the following assumptions have been considered:

- the primary energy conversion factor is set equal to 1.95 for electricity and 1.05 for natural gas, according to current Italian law (Ministero dello sviluppo economico, 2015);
- the energy price is set equal to 0.25 €/kWh$_{el}$ for electricity and 0.90 €/Nm3 for natural gas as done in (Mauro et al., 2015);
- produced electricity that is sold to the grid (in presence of PV panels) is remunerated at the price of 0.08 €/kWh$_{el}$, as done in (Ascione, Bianco, De Stasio, et al., 2016);
- the polluting emissions' factor is set equal to 0.708 tCO2-eq/MWh$_{el}$ for electricity 0.237 tCO_2-eq/MWhp for natural gas (Covenant of Mayors, n.d.);
- the considered calculation period (i.e., lifetime) for the assessment of GC is 30 years as recommended in (European Commision, 2012) for residential buildings;
- in EnergyPlus simulations, the IWEC (international weather for energy calculations) weather data file related to Benevento (EneryPlus, 2014) is used when Milan is considered as location; on the other hand, the IGDG (Italian climatic data collection "Gianni De Giorgio") weather data file related to Bonifati (EneryPlus, 2014) is used for Lattarico and the weather data file related to Perugia (EneryPlus, 2014) is used

for Spoleto. In this regard, accredited weather data files are not available for Lattarico and Spoleto, but the use of Bonifati and Perugia file provides a good approximation, since the locations are very close (the distance is respectively around 30 km and 40 km) and characterized by similar climatic conditions.

6.3.1 Investigated energy retrofit measures

For all the considered climatic locations, the following ERMs have been investigated for the reduction of thermal energy demand and discomfort hours:

- variation of heating set point temperature (T_h), which cannot be higher than 22 °C according to Italian regulations (Decreto Legge, 1993);
- variation of cooling set point temperature (T_c);
- variation of the infrared emissivity of the external vertical walls (e_v) by means of the installation of external plasters;
- variation of the solar absorptance of the external vertical walls (a_v) by the installation of external plasters;
- variation of the infrared emissivity of the roof (e_r) by the installation of external plasters;
- variation of the solar absorptance of the roof (a_r) by the installation of external plasters;
- installation of an external layer of thermal insulation (thermal conductivity = 0.026 W/m K, density = 25 kg/m^3, specific heat = 1340 J/kg K) on the external vertical walls; the insulation layer's thickness is denoted as t_v;
- installation of an external layer of thermal insulation (see above properties) on the roof; the insulation layer's thickness is denoted as t_r;

- replacement of the windows with energy efficient ones; where the following eight options are considered:
  - w1) double-glazed air-filled windows with wooden frames: U_w = 2.67 W/m^{2}K; SHGC (solar heat gain coefficient) = 0.691; this option characterizes the baseline;
  - w2) double-glazed air-filled windows with low-emissive coatings and PVC frames: U_w = 1.96 W/m^{2}K, SHGC = 0.691;
  - w3) double-glazed air-filled windows with low-emissive, tinted coatings and PVC frames: U_w = 1.76 W/m^{2}K, SHGC = 0.380;
  - w4) double-glazed air-filled windows with low-emissive, selective coatings and PVC frames: U_w = 1.64 W/m^{2}K, SHGC = 0.433;
  - w5) double-glazed argon-filled windows with low-emissive coatings and PVC frames: U_w = 1.71 W/m^{2}K, SHGC = 0.691;
  - w6) double-glazed argon-filled windows with low-emissive, tinted coatings and PVC frames: U_w = 1.49 W/m^{2}K; SHGC = 0.380;
  - w7) double-glazed air-filled windows with low-emissive, selective coatings and PVC frames: U_w = 1.34 W/m^{2}K; SHGC = 0.433;
  - w8) triple-glazed argon-filled windows with low-emissive coatings and PVC frames: U_w = 1.10 W/m^{2}K; SHGC = 0.579.

Different options are investigated for the described ERMs thereby implying the variables reported in Table 6.2.

Design Variable		Options	Number of Options	Number of Bits for Encoding
(1)	T_h [°C]	19, 20 (B *), 21, 22	4	2
(2)	T_c [°C]	24, 25, 26 (B), 27	4	2
(3)	e_v	0.1, 0.25, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 (B)	8	3
(4)	a_v	0.1, 0.25, 0.4, 0.5, 0.6 (B), 0.7, 0.8, 0.9	8	3
(5)	e_r	0.1, 0.25, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 (B)	8	3
(6)	a_r	0.1, 0.25, 0.4, 0.5, 0.6 (B), 0.7, 0.8, 0.9	8	3
(7)	t_v [m]	0 (B), 0.04, 0.05, 0.06, 0.08, 0.10, 0.12, 0.14	8	3
(8)	t_r [m]	0 (B), 0.04, 0.05, 0.06, 0.08, 0.10, 0.12, 0.14	8	3
(9)	Windows' type	w1 (B), w2, w3, w4, w5, w6, w7, w8	8	3

***** B: baseline (i.e., as built configuration)

Table 6.2 Design variables of the bi-objective optimization problem (solved through the GA) for the minimization of thermal energy demand and discomfort hours.

These latter represent the design variables of the bi-objective optimization problem solved by running the GA described in §5.2.1.

Table 6.3 shows the considered ERMs for primary energy systems, which are examined in stage 2 of the energy retrofit optimization. These ERMs address:

- the improvement of the energy efficiency of the primary heating system;
- the improvement of the energy efficiency of the primary cooling system;
- the improvement of the energy efficiency of the primary system for the production of domestic hot water (DHW);
- the installation of systems for the exploitation of RESs, namely photovoltaic (PV) panels.

In addition, in this case, different options are considered for the mentioned ERMs. The values of peak thermal power of the heating, cooling and DHW systems are set equal to the baseline's values. The investment costs are taken from literature (Ascione, Bianco, De Stasio, et al., 2016; Mauro et al., 2015) and, when not available, from direct quotations of suppliers. Lastly, financial incentives, provided by current Italian law (Governo Italiano, 2015) for ERMs, are taken into account.

		Description and Considered Options	Investment Cost (IC)	Incentives
HEATING SYSTEM	**Existing gas boiler (B *)**	Natural gas boiler with nominal efficiency (η), assessed considering the LCV (lower calorific value) of gas, equal to 0.85.	—	—
	Condensing gas boiler	Condensing natural gas boiler with nominal η equal to 1.06.	13,100 €	65% of IC up to 30 k€, accorded in 10
	Air-source heat pump	Air-source electric heat pump with nominal COP (coefficient of performance) equal to 3.8.	26,000 €	65% of IC up to 30 k€, accorded in 10 years
HEATING & COOLING	**Ground-source reversible heat pump**	Reversible ground-source electric heat pump with geothermal vertical probes: - Heating operation: nominal COP = 5.1 - Cooling operation: nominal EER (energy efficiency ratio) = 6.1.	97,500 €	65% of IC up to 30 k€, accorded in 10
COOLING SYSTEM	**Existing air-cooled chiller (B)**	Air-cooled electric chiller with nominal EER equal to 2.5.	—	—
	Efficient air-cooled chiller	Energy-efficient air-cooled electric chiller with nominal EER equal to 3.4.	19,250 €	—
DHW SYSTEM	**Existing gas boiler (B)**	Natural gas boiler with nominal η equal to 0.85.	—	—
	Efficient gas boiler	Energy-efficient natural gas boiler with nominal η equal to 0.95.	15,750 €	—
RESs	**Solar photovoltaic (PV) panels**	Solar PV panels on the roof, south-oriented with tilt angle of 34°. The size is expressed by “cov”: percentage of the available roof area (=600 m^2) covered by PV panels. Mutual shading is avoided. Cov can vary between 0% (B) and 100% with a step of 10%. Two typical PV types are considered: poly-crystalline silicon	250 € per m^2 of panels’ surface	50 % of IC up to 96 k€, accorded in 10 years
		mono-crystalline silicon	430 € per m^2 of panels’ surface	

***** B: baseline (i.e., as built configuration).

Table 6.3 Investigated primary energy systems

6.3.2 Investigated seismic retrofit strategies

Strengthening strategies implemented aim to improve the structural capacity of structures prone to seismic risk. In this case study, retrofit strategies aiming at increasing ductility, stiffness, and strength, or all of them, have been selected. In particular, the following retrofit strategies have been investigated:

1) Insertion of RC shear wall-based strengthening solution (i.e. insertion of shear walls to sustain the seismic action in both the longitudinal and transverse directions).
2) RC jacketing-based strengthening solution (i.e. RC jacketing of beams and columns to increase the flexural and shear capacity of members, as well as ductility, and to increase the global structural stiffness).
3) FRP – RC jacketing-based strengthening solution (i.e. a combined strengthening solution based on the previous solution and the shear strengthening of beam-column joints and beams using FRP sheets to prevent brittle failure mechanisms). .

The first strategy aims to increase the strength and the stiffness of the structure by the insertion (compatibly with the geometry of the structure) of two RC shear walls for both directions.

The second and third intervention strategies aim to improve the seismic performance of the individual elements with RC jacketing with a thickness at least of 5 cm or the application of quadriaxial FRP sheets to the surface of the beam-column joint panels and uniaxial FRP sheets onto the beams as shear strengthening. With these intervention strategies, the structure increases its capacity in terms of both stiffness and ductility.

In order to carry out an analysis of the economic viability of a retrofit strategy, the performance of the building is improved at different strengthening levels. The strengthening levels have been related to the safety levels, which are computed as the ratios between the structural capacity and the seismic demand in terms of the PGA. The safety level of 100% corresponds to strengthening interventions that provide a structural capacity equal to the structural demand related to a severe earthquake with a return period of 475 years.

6.4 RESULTS

The presentation and discussion of the results is organized in four subsections, which refer to the baseline (i.e., the as built building performance) to the energy-retrofitted building, to the seismic-retrofitted building and to the combined-retrofitted (both energy and seismic) building respectively.

6.4.1 Assessment of the building in the baseline configuration

As concerns the baseline energy performance, Table 6.4 shows thermal energy demand for space conditioning (TEDsc), percentage of discomfort hours (DH), primary energy consumption (PEC), global cost (GC) and polluting emissions (EM) for each site. These indicators show that, from climatic zone C to E, the energy needs, the global costs, the polluting emissions and the percentage of discomfort hours increase. Therefore, heating-dominated climates cause higher needs for microclimatic control over a typical year. This implicates that the climatic conditions are more rigid over the year by considering both space heating and cooling needs.

Location	**TED$_{sc}$**	**DH**	**PEC**	**GC**	**EM** (CO_2-eq)
Benevento (zone C)	41.24 kWh_t/m^2a	19.77%	141.92 kWh_p/m^2a	310.16 €/m^2 (571.37 k€)	43.83 kg/m^2a (80.74 t/a)
Lattarico (zone D)	47.85 kWh_t/m^2a	21.37%	153.62 kWh_p/m^2a	329.84 €/m^2 (607.63 k€)	46.47 kg/m^2a (85.60 t/a)
Spoleto (zone E)	70.43 kWh_t/m^2a	26.94%	186.17 kWh_p/m^2a	388.07 €/m^2 (714.91 k€)	54.38 kg/m^2a (100.18 t/a)

Table 6.4 Energy characterization of the baseline

As concerns the baseline structural performance, according to the procedure previously described, the EDPs obtained from the structural analyses are implemented into fragility models to assess the probability of occurrence of a damage state for a specific building component. The

EDPs adopted in the case study are related to the inter-storey drift ratios (IDR) of each floor. Converting the damage of a component into an economic loss allows the computation of the total loss of the entire building due to seismic events. The fragility models implemented in this case study are: Pagni and Lowes (Pagni & Lowes, 2006) for beam-column joints; Aslani and Miranda (Hesameddin Aslani & Miranda, 2005) for beams, columns and windows; Ruiz-Garcia and Negrete (Ruiz-García & Negrete, 2009) for internal and external partitions and systems (i.e. electric, hydraulic and energy system). The economic value of each component and of each retrofit technique is evaluated through the support of the price list of the typography of the Italian civil engineering DEI. Moreover, for a destructive earthquake has been assumed a reconstruction cost of 1200 €/m^2.

The assessed expected seismic economic losses are reported in the following Table 6.5. Results slightly differ from each other, due to the similar hazard condition of the sites.

Expected Annual Loss		
Benevento	Lattarico	Spoleto
€ 56'685.28	€ 57'120.73	€ 57'755.56

Table 6.5 Expected seismic economic losses for the building sites

6.4.2 Energy retrofit optimization

In the first stage of the optimization of building energy retrofit, the genetic algorithm (GA) is implemented in order to find optimal packages of ERMs addressed to the building envelope and to the variation of set point temperatures. The objective functions are the minimization of TEDsc and DH.

Then, the second stage of the methodology is performed in order to consider also the implementation of new efficient primary energy systems. For each scenario, the differences of PEC (denoted as dPEC) and GC (denoted as dGC), compared to the baseline, are evaluated thereby achieving the cost-optimal solution for each site. The cost-optimal packages of ERMs are reported in Table 6.6-6.8.

Location	TED_{sc}	DH	dPEC *	dGC *	IC	DPB	dEM * (CO_2-eq)
Benevento	41.24 kWh_t/m^2a	19.77%	−85.18 kWh_p/m^2a	−78.51 €/m² (−144.64 k€)	94.71 k€	10.4 years	−26.17 kg/m^2a (−48.21 t/a)
	Cost-optimal energy retrofit solution ▪ Heating set point temperature (T_h) = 20 °C ▪ Cooling set point temperature (T_c) = 26 °C ▪ Installation of a heat pump for space heating ▪ Installation of poly-crystalline PV, cov = 100%						

***Negative values denote a reduction (i.e., a benefit) compared to the baseline**

Table 6.6 Characterization of the cost-optimal energy retrofit solutions for climatic zone C

Location	TED_{sc}	DH	dPEC *	dGC *	IC	DPB	dEM * (CO_2-eq)
Lattarico	15.50 kWh_t/m^2a	9.38%	−93.62 kWh_p/m^2a	−69.68 €/m² (−128.37 k€)	258.74 k€	27.4 years	−28.83 kg/m^2a (−53.11 t/a)
	Cost-optimal energy retrofit solution ▪ Heating set point temperature (T_h) = 19 °C ▪ Cooling set point temperature (T_c) = 27 °C ▪ External plastering and 14 cm-thick thermal insulation of the external vertical walls: - e_v = 0.60 - a_v = 0.60 - U_v = 0.161 W/m^2K ▪ External plastering and 14 cm-thick thermal insulation of the roof: - e_r = 0.40 - a_r = 0.10 - U_r = 0.158 W/m^2K ▪ Installation of triple-glazed windows (w8): - U_w = 1.10 W/m^2K - SHGC = 0.579 ▪ Installation of a natural gas condensing boiler for space heating ▪ Installation of poly-crystalline PV, cov = 100%						

Table 6.7 Characterization of the cost-optimal energy retrofit solutions for climatic zone D

Location	TED_{sc}	DH	dPEC *	dGC *	IC	DPB	dEM * (CO_2-eq)
Spoleto	26.13 kWh_t/m^2a	10.10%	−114.21 kWh_p/m^2a	−104.79 €/m^2 (−193.05 k€)	261.94 k€	20.3 years	−33.65 kg/m^2a (−61.98 t/a)
	<u>Cost-optimal energy retrofit solution</u> ▪ Heating set point temperature (T_h) = 19 °C ▪ Cooling set point temperature (T_c) = 27 °C ▪ External plastering and 14 cm-thick thermal insulation of the external vertical walls: - e_v = 0.40 - a_v = 0.60 - U_v = 0.161 W/m^2K ▪ External plastering and 14 cm-thick thermal insulation of the roof: - e_r = 0.10 - a_r = 0.25 - U_r = 0.158 W/m^2K ▪ Installation of triple-glazed windows (w8): - U_w = 1.10 W/m^2K - SHGC = 0.579 ▪ Installation of a natural gas condensing boiler for space heating ▪ Installation of poly-crystalline PV, cov = 100%						

Table 6.8 Characterization of the cost-optimal energy retrofit solutions for climatic zone E

The outcomes about cost-optimality follow energy and economic considerations.

Table 6.6-6.8 show that the cost-optimal energy retrofit solutions imply significant reductions of energy consumption, global cost and polluting emissions with reasonable discounted payback times, slightly higher than ten years. The benefits are higher for Spoleto site because the baseline is characterized by higher energy consumption, and thus there are larger opportunities of energy and cost savings. It is highlighted that, for all the locations, the cost-optimal solutions make the building very close to the standard of nearly zero energy building (nZEB).

The multi-step approach described in the previous chapter is implemented to quantify the overall economic lifecycle costs associated to a set of energy retrofit measures (ERMs) applied to the existing building. The structural performance is considered in order to quantify the economic losses due to seismic induced damage.

The technological and physical interactions between seismic and energy aspects are the same adopted in Chapter 5. The operational and damage level of ERMs and systems is linked to the structural performance of building components through the association with the corresponding engineering demand parameters (EDPs).

Once the cost-optimal energy retrofit solutions is estimated, it is possible to assess the seismic economic loss of the retrofitted structure and the influence of the energy retrofit measures of these losses. The results are reported in Table 6.9 Table 6.10 and Table 6.11. The implementation of the cost-optimal energy retrofit strategies exert different economic impacts depending on the location of the existing building.

The energy retrofit requires an initial investment cost (IC), and, globally, during the building residual lifecycle, it turns into an economic benefit due to the reduction of global cost for energy uses (GC); however, at the same time, it causes an increase of expected economic losses (i.e., EALs) linked to the seismic risk. Moreover, it has been assumed that after 20 years there is a replacement cost RC of the systems, thus after 30 years the energy retrofit measures may have a Residual Value RV. Financial incentives provided by the Italian government have not been take into account. Discount rate has been set equal to 3,00%.

In particular, the proposed energy retrofit causes an increase of EAL equal to 2361 €/y for Benevento, 3512€/y for Lattarico and to 3552 €/y for Spoleto. Clearly, this increment is more significant for Lattarico and Spoleto because these locations are characterized by higher Investment Cost for the energy retrofit measures.

dCE	DPB,$_{energ}$	EAL,$_{as\text{-}built}$	EAL,$_{ERMs}$	ΔEAL	DPB,$_{energy\text{-}struct}$	RC	RV
[€]	[year]	[€]	[€]	[€]	[year]	[€]	[€]
10'734.00	10.40	56'685.28	59'046.43	-2'361.15	14.02	14'000.00	0.00

Table 6.9 Parameters of the cost-optimal energy retrofit solution for Benevento site

dCE	DPB,$_{energ}$	EAL,$_{as\text{-}built}$	EAL,$_{ERMs}$	ΔEAL	DPB,$_{energy\text{-}struc}$	RC	RV
[€]	[year]	[€]	[€]	[€]	[year]	[€]	[€]
13'968.00	27.45	57'120.73	60'632.96	-3'512.23	45.89	3'900.00	28'697.00

Table 6.10 Parameters of the cost-optimal energy retrofit solution for Lattarico site

dCE	DPB,$_{energ}$	EAL,$_{as\text{-}built}$	EAL,$_{ERMs}$	ΔEAL	DPB,$_{energy\text{-}struc}$	RC	RV
[€]	[year]	[€]	[€]	[€]	[year]	[€]	[€]
17'412.00	20.31	57'755.55	61'308.07	-3'552.51	29.20	5'300.00	28'697.00

Table 6.11 Parameters of the cost-optimal energy retrofit solution for Spoleto site

Definitely, as shown in Chapter 5 and in Figures 6.1-6.3, the potential global cost savings (GCS) produced by the retrofit solutions decrease when the coupled energy-structural approach is used considering the seismic economic losses in global cost assessment. On the other hand, the use of a merely energy approach, which does not consider seismic losses, could imply an overestimation of economic benefits over building lifecycle.

From an overall perspective, the retrofit strategies mentioned above are cost-effective for Benevento and Spoleto because the discounted payback time (DPB) is lower that the lifetime period assumed equal to 30 years as recommended in (European Commision, 2012) for residential buildings.

For Lattarico site, the retrofit measures, instead, seem to be not cost-effective in the lifetime assumed. In other words, the economic benefit could be not sufficient to overcome the “status quo” bias. Therefore, in this case, building energy retrofit should be combined with seismic retrofit measures in order to reduce the seismic economic losses. This issue will be handled in next sections, which will focus on the integrated optimization of energy and seismic retrofit by means of a lifecycle approach.

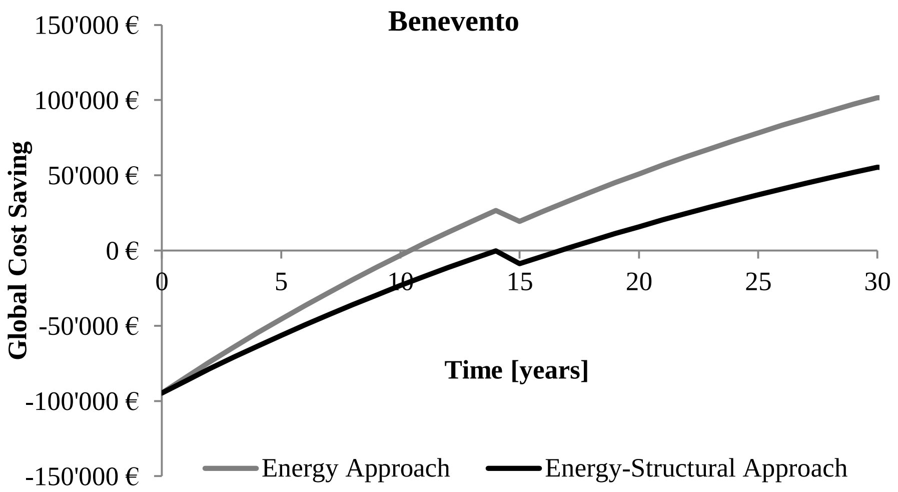


Figure 6.1 Temporal trend of the global cost saving produced by the cost-optimal energy retrofit solution considering the seismic economic losses for Benevento site

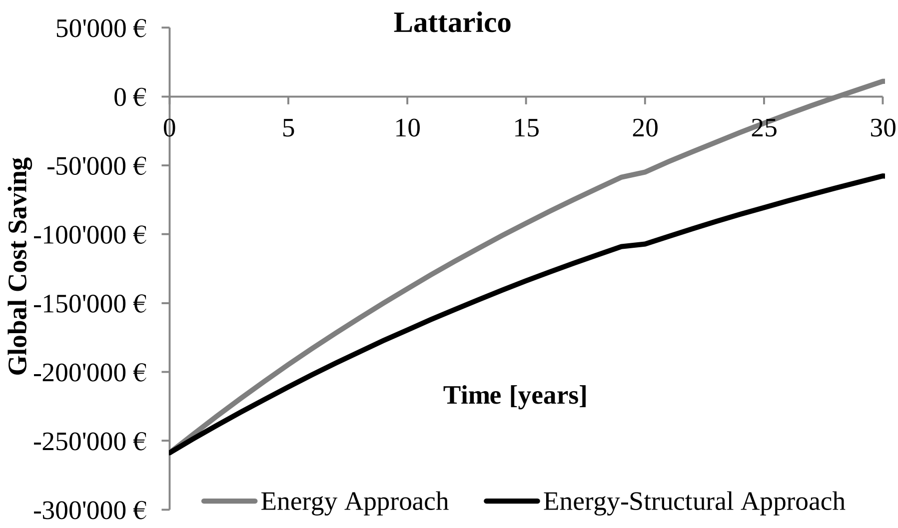


Figure 6.2 Temporal trend of the global cost saving produced by the cost-optimal energy retrofit solution considering the seismic economic losses for Lattarico site

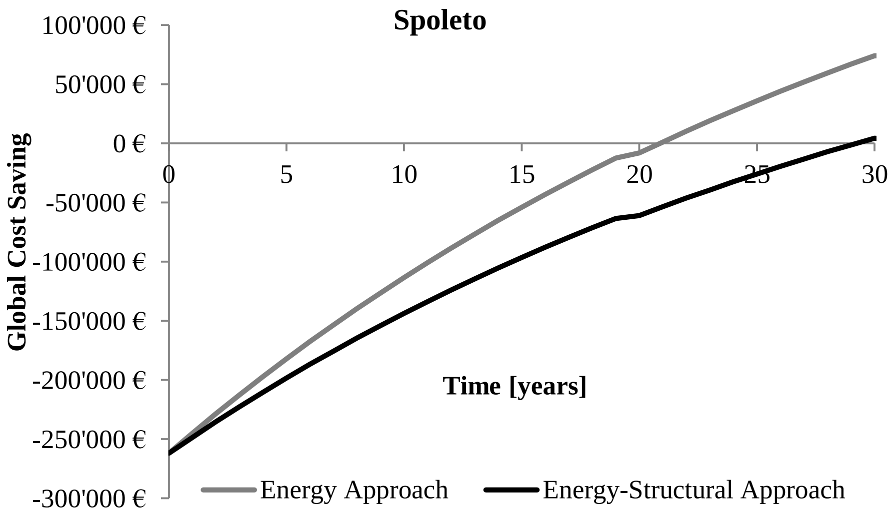


Figure 6.3 Temporal trend of the global cost saving produced by the cost-optimal energy retrofit solution considering the seismic economic losses for Spoleto site

The change in the slope of the curves occur after 20 years due to the replacement costs of the systems.

When the seismic economic losses are considered, the potential global cost savings decreases whereas the discounted payback time increases. It is important to highlight again that this effect depends on the existing building location, since it becomes more significant when the seismic hazard is higher. Figure 6.4 and Table 6.12 summarise the change of the discounted payback times between the two different approaches for the three building site. The best scenario is for Benevento site because the investment cost is significantly lower than the other sites. For Lattarico and Spoleto the investment costs are similar, but the energy consumption saved in Spoleto is higher than Lattarico, thus the worst scenario is for Lattarico site.

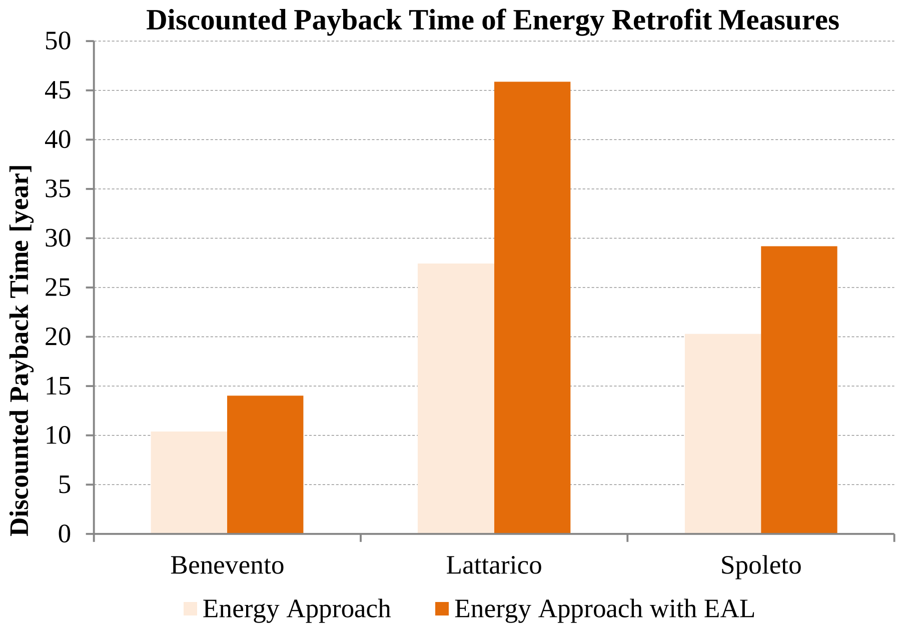


Figure 6.4 Discounted payback time of the cost-optimal energy retrofit solution

DPB Time	Benevento	Lattarico	Spoleto
Energy Approach	10.40	27.45	20.31
Energy-Structural Approach	14.02	45.89	29.20

Table 6.12 Discounted payback time of the cost-optimal energy retrofit solution

6.4.3 Seismic retrofit optimization

The seismic retrofit strategies optimization procedure described in Chapter 2 has been applied to assess the optimal seismic retrofit solution for the examined building. In particular, the optimization strategy has been implemented for the three site and for the three retrofit strategies described in section 6.3.2.

The first step is the assessment of the retrofit costs for each safety level achieved for each retrofit strategy. With the progress of the pushover curve (i.e. by increasing the top displacement), there is an increase in the failures that may occur in the elements. Increasing the number of failures, obviously, also increases the cost of achieving a given safety level for the structure. The result is a cost curve that gradually increases with the increase of the safety level of the building for each selected retrofit strategy. The curves have been computed up to a safety level of 100%.

The curves related to the RC jacketing and RC Jacketing with FRP strategies have an almost linear trend. In the shear wall case, the curve shows an initial strong increase in costs, even for a slight increase of safety levels. This is because these strategies imply a significant initial cost investment of applying the retrofit technique.

The next step consists of calculating the economic losses for the different safety levels for which the building is gradually strengthened.

To check if a reinforcement intervention is cost effective for an owner, it is necessary to add the cost of the strengthening intervention and the loss of the structure for each safety level, thereby obtaining the total expected cost.

Discount rate has been set equal to 3,00% as in the energy retrofit optimization. Financial incentives provided by the Italian government have not been take into account.

Figure 6.5 to 6.13 show the discounted expected annual losses EALd curve, the seismic retrofit cost SRC curve and expected total cost ETC curve for each retrofit strategy and for each site.

Table 6.13 to 6.21 provide, instead, a breakdown of economic annual loss, retrofit cost and total cost of each retrofit scheme of each building site.

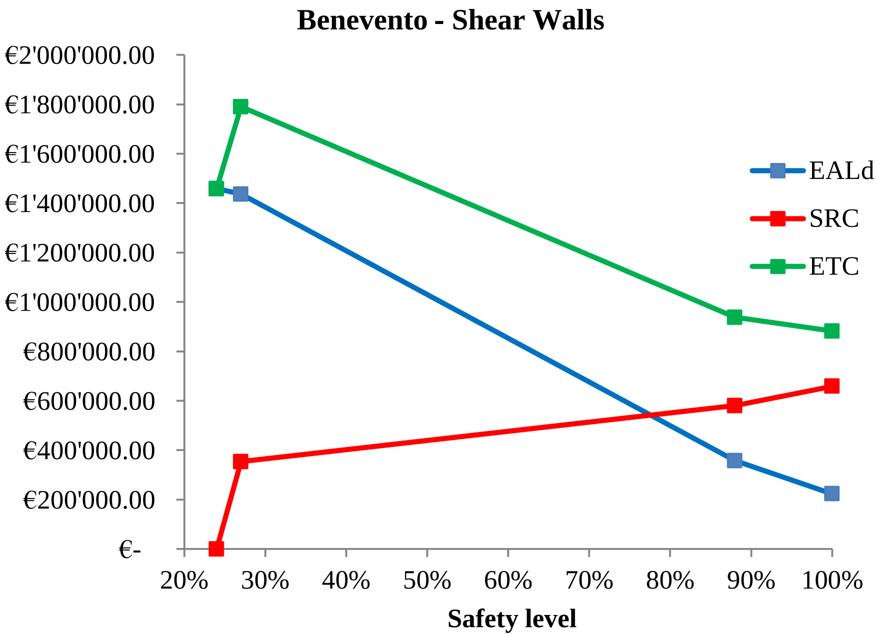


Figure 6.5 Discounted expected losses EALd curve, seismic retrofit cost SRC curve and expected total cost ETC curve for shear walls retrofit strategy and for Benevento site

BENEVENTO – SHEAR WALLS				
$\alpha_{,SLV}$	**EAL**	**EALd**	**SRC**	**ETC**
24%	€ 56'685.28	€ 1'458'498.88	€ -	€ 1'458'498.88
27%	€ 55'817.91	€ 1'436'181.57	€ 353'671.59	€ 1'789'853.16
88%	€ 13'891.96	€ 357'436.97	€ 580'456.10	€ 937'893.07
100%	€ 8'687.53	€ 223'528.15	€ 658'387.39	€ 881'915.54

Table 6.13 Expected annual losses EAL, discounted expected losses EALd, seismic retrofit cost SRC and expected total cost ETC parameters for different streghtening levels for shear walls retrofit strategy and for Benevento site

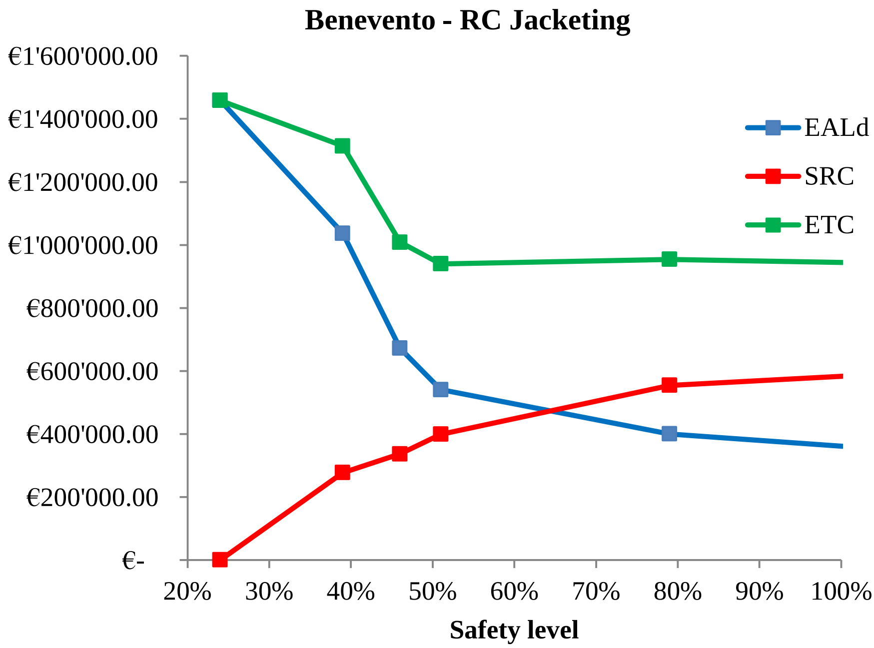


Figure 6.6 Discounted expected losses EALd curve, seismic retrofit cost SRC curve and expected total cost ETC curve for RC jacketing retrofit strategy and for Benevento site

BENEVENTO – RC JACKETING				
$\alpha_{,SLV}$	**EAL**	**EALd**	**SRC**	**ETC**
24%	€ 56'685.28	€ 1'458'498.88	€ -	€ 1'458'498.88
39%	€ 40'306.36	€ 1'037'073.24	€ 277'042.48	€ 1'314'115.72
46%	€ 39'348.20	€ 672'064.83	€ 336'686.33	€ 1'008'751.16
51%	€ 26'120.13	€ 540'719.48	€ 399'251.88	€ 939'971.36
79%	€ 21'015.33	€ 387'546.45	€ 554'340.99	€ 941'887.44
115%	€ 15'062.18	€ 333'952.10	€ 603'705.92	€ 937'658.02

Table 6.14 Expected annual losses EAL, discounted expected losses EALd, seismic retrofit cost SRC and expected total cost ETC parameters for different streghtening levels for RC jacketing retrofit strategy and for Benevento site

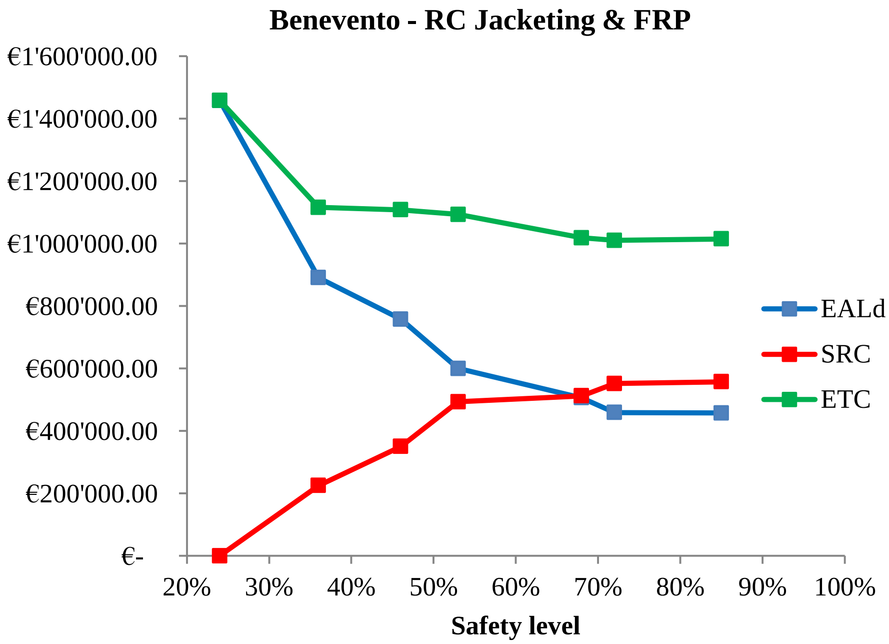


Figure 6.7 Discounted expected losses EALd curve, seismic retrofit cost SRC curve and expected total cost ETC curve for RC jacketing & FRP retrofit strategy and for Benevento site

BENEVENTO – RC JACKETING & FRP				
$\alpha_{,SLV}$	**EAL**	**EALd**	**SRC**	**ETC**
24%	€ 56'685.28	€ 1'458'498.88	€ -	€ 1'458'498.88
36%	€ 34'610.34	€ 890'515.88	€ 225'162.80	€ 1'115'678.68
46%	€ 29'461.69	€ 758'042.24	€ 350'000.00	€ 1'108'042.24
53%	€ 27'932.98	€ 600'000.00	€ 493'263.39	€ 1'093'263.39
68%	€ 27'935.87	€ 506'027.95	€ 512'245.26	€ 1'018'273.21
72%	€ 19'667.03	€ 458'783.60	€ 551'502.62	€ 1'010'286.22
85%	€ 17'830.85	€ 457'259.30	€ 557'400.50	€ 1'014'659.80

Table 6.15 Expected annual losses EAL, discounted expected losses EALd, seismic retrofit cost SRC and expected total cost ETC parameters for different streghtening levels for RC jacketing & FRP retrofit strategy and for Benevento site

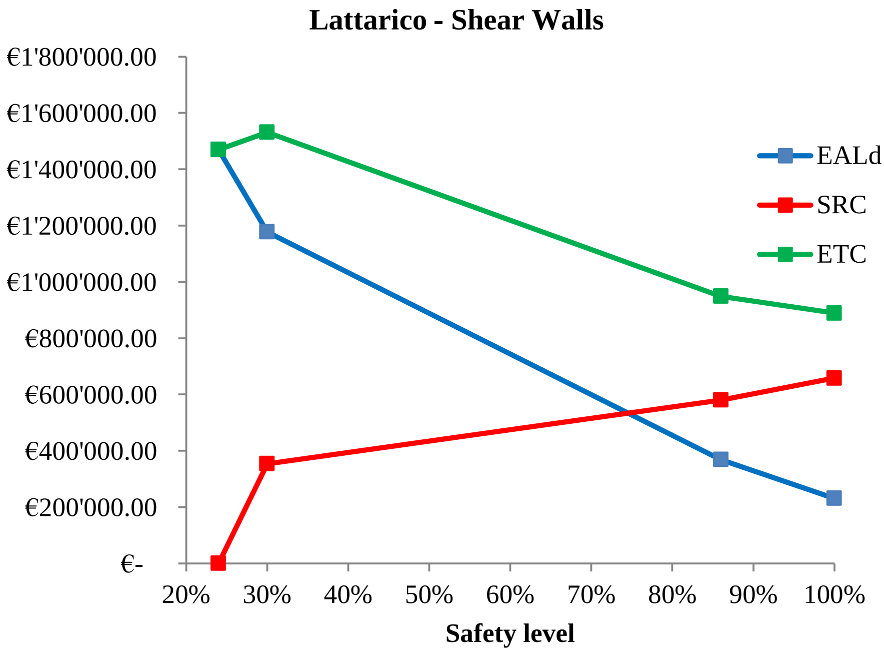


Figure 6.8 Discounted expected losses EALd curve, seismic retrofit cost SRC curve and expected total cost ETC curve for shear walls retrofit strategy and for Lattarico site

LATTARICO – SHEAR WALLS				
α,SLV	**EAL**	**EALd**	**SRC**	**ETC**
24%	€ 57'120.73	€ 1'469'702.99	€ -	€ 1'469'702.99
30%	€ 45'771.64	€ 1'177'693.42	€ 353'671.59	€ 1'531'365.01
86%	€ 14'321.26	€ 368'482.71	€ 580'456.10	€ 948'938.81
100%	€ 8'972.65	€ 230'864.06	€ 658'387.39	€ 889'251.45

Table 6.16 Expected annual losses EAL, discounted expected losses EALd, seismic retrofit cost SRC and expected total cost ETC parameters for different streghtening levels for shear walls retrofit strategy and for Lattarico site

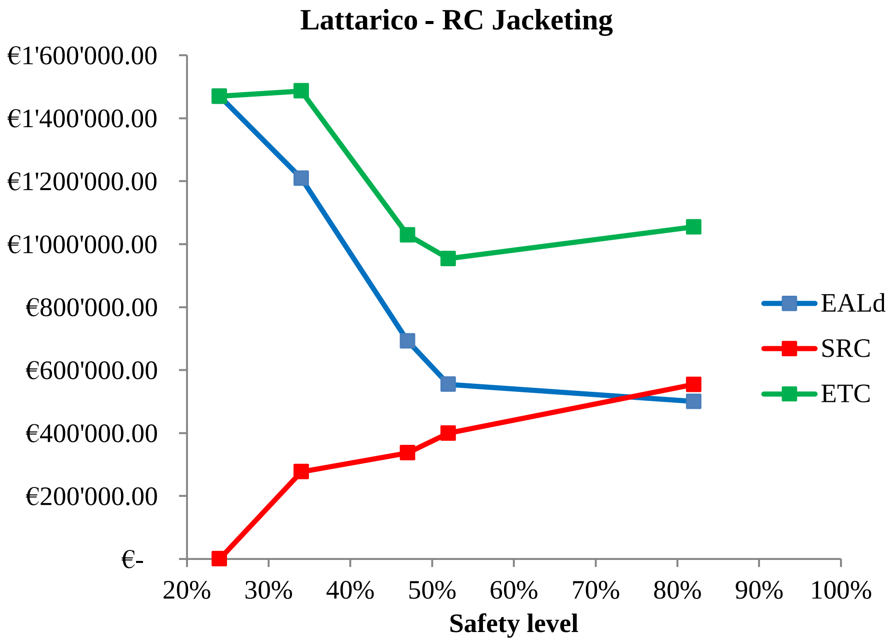


Figure 6.9 Discounted expected losses EALd curve, seismic retrofit cost SRC curve and expected total cost ETC curve for RC jacketing retrofit strategy and for Lattarico site

LATTARICO – RC JACKETING				
$\alpha_{,SLV}$	**EAL**	**EALd**	**SRC**	**ETC**
24%	€ 57'120.73	€ 1'469'702.99	€ -	€ 1'469'702.99
34%	€ 47'003.34	€ 1'209'384.93	€ 277'042.48	€ 1'486'427.41
47%	€ 40'067.72	€ 692'465.16	€ 336'686.33	€ 1'029'151.49
52%	€ 26'913.00	€ 554'817.40	€ 399'251.88	€ 954'069.28
82%	€ 21'563.25	€ 500'290.45	€ 554'340.99	€ 1'054'631.44

Table 6.17 Expected annual losses EAL, discounted expected losses EALd, seismic retrofit cost SRC and expected total cost ETC parameters for different streghtening levels for RC jacketing retrofit strategy and for Lattarico site

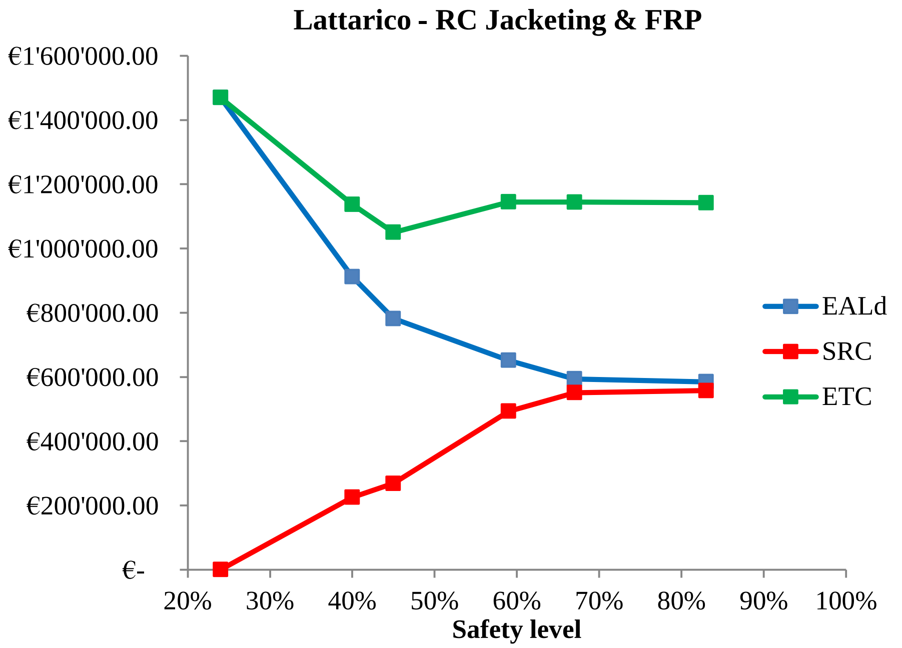


Figure 6.10 Discounted expected losses EALd curve, seismic retrofit cost SRC curve and expected total cost ETC curve for RC jacketing & FRP retrofit strategy and for Lattarico site

LATTARICO – RC JACKETING & FRP				
$\alpha_{,SLV}$	**EAL**	**EALd**	**SRC**	**ETC**
24%	€ 57'120.73	€ 1'469'702.99	€ -	€ 1'469'702.99
40%	€ 35'450.53	€ 912'133.75	€ 225'162.80	€ 1'137'296.55
45%	€ 30'376.21	€ 781'572.64	€ 268'390.50	€ 1'049'963.14
59%	€ 25'322.65	€ 651'545.83	€ 493'263.39	€ 1'144'809.22
67%	€ 23'074.62	€ 593'704.55	€ 550'875.72	€ 1'144'580.27
83%	€ 22'656.80	€ 585'000.00	€ 557'400.50	€ 1'142'400.50

Table 6.18 Expected annual losses EAL, discounted expected losses EALd, seismic retrofit cost SRC and expected total cost ETC parameters for different streghtening levels for RC jacketing & FRP retrofit strategy and for Lattarico site

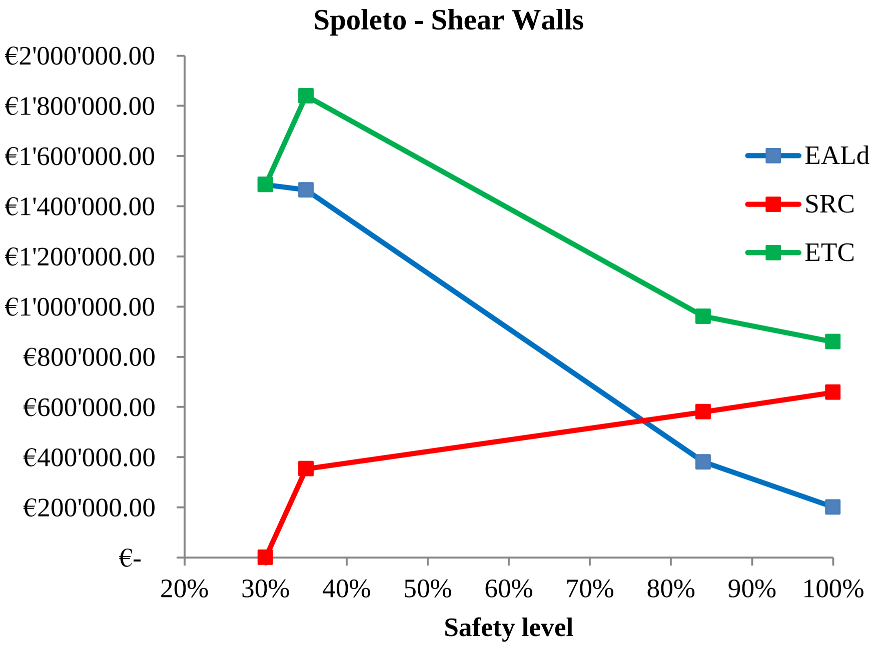


Figure 6.11 Discounted expected losses EALd curve, seismic retrofit cost SRC curve and expected total cost ETC curve for shear walls retrofit strategy and for Spoleto site

SPOLETO – SHEAR WALLS				
$\alpha_{,SLV}$	**EAL**	**EALd**	**SRC**	**ETC**
30%	€ 57'755.56	€ 1'486'036.93	€ -	€ 1'486'036.93
35%	€ 56'917.21	€ 1'464'466.47	€ 353'671.59	€ 1'839'708.52
84%	€ 14'801.60	€ 380'841.74	€ 580'456.10	€ 961'297.84
100%	€ 7'813.99	€ 201'052.09	€ 658'387.39	€ 859'439.48

Table 6.19 Expected annual losses EAL, discounted expected losses EALd, seismic retrofit cost SRC and expected total cost ETC parameters for different streghtening levels for shear walls retrofit strategy and for Spoleto site

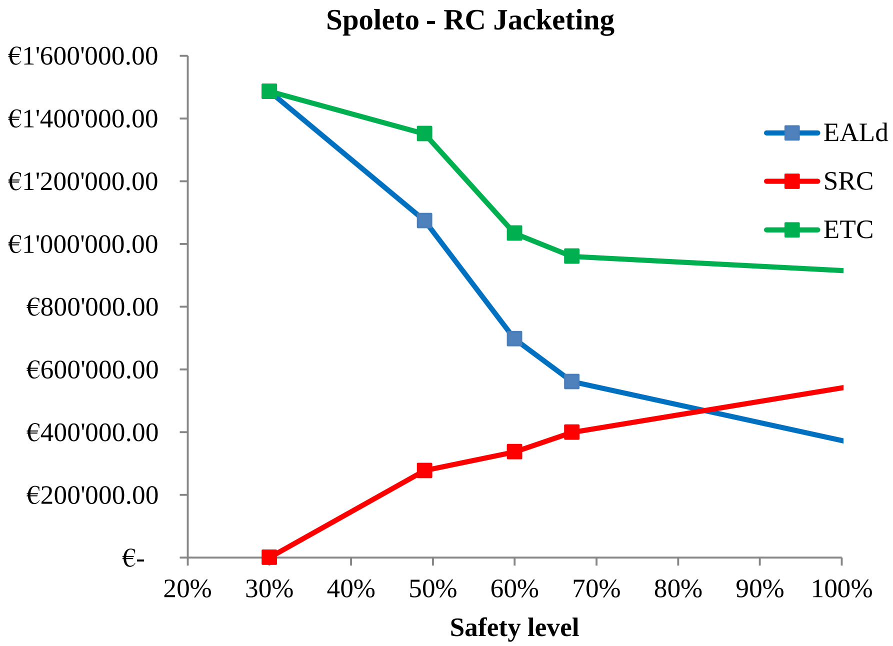


Figure 6.12 Discounted expected losses EALd curve, seismic retrofit cost SRC curve and expected total cost ETC curve for RC jacketing retrofit strategy and for Spoleto site

SPOLETO – RC JACKETING				
$\alpha_{,SLV}$	**EAL**	**EALd**	**SRC**	**ETC**
30%	€ 57'755.56	€ 1'486'036.93	€ -	€ 1'486'036.93
49%	€ 41'735.13	€ 1'073'835.05	€ 277'042.48	€ 1'350'877.53
60%	€ 40'899.24	€ 696'910.92	€ 336'686.33	€ 1'033'597.25
67%	€ 27'085.79	€ 560'647.26	€ 399'251.88	€ 959'899.14
103%	€ 21'789.83	€ 356'051.61	€ 554'340.99	€ 910'392.60

Table 6.20 Expected annual losses EAL, discounted expected losses EALd, seismic retrofit cost SRC and expected total cost ETC parameters for different streghtening levels for RC jacketing retrofit strategy and for Spoleto site

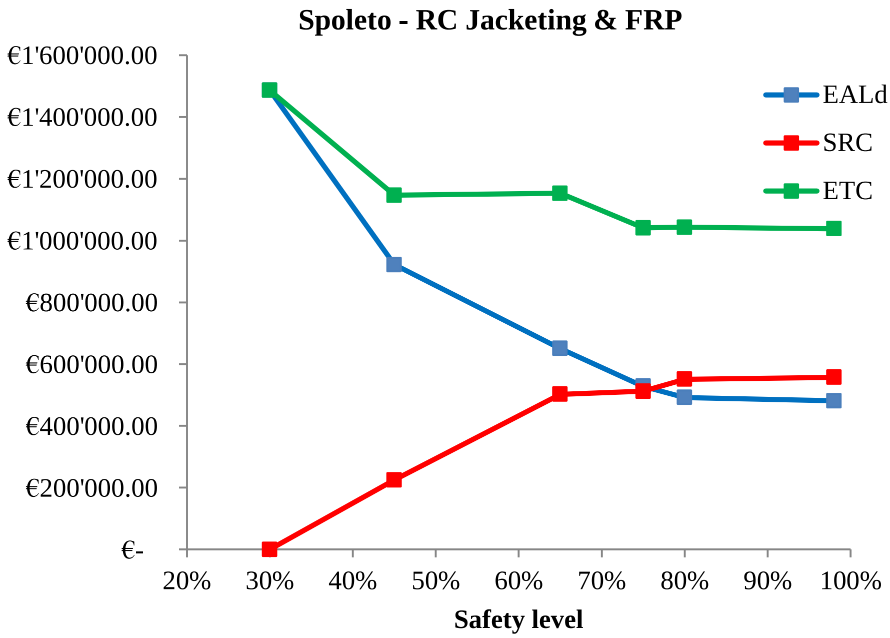


Figure 6.13 Discounted expected losses EALd curve, seismic retrofit cost SRC curve and expected total cost ETC curve for RC jacketing & FRP retrofit strategy and for Spoleto site

SPOLETO – RC JACKETING & FRP				
$\alpha_{,SLV}$	**EAL**	**EALd**	**SRC**	**ETC**
30%	€ 57'755.56	€ 1'486'036.93	€ -	€ 1'486'036.93
45%	€ 35'813.43	€ 921'470.97	€ 225'162.80	€ 1'146'633.77
65%	€ 30'670.98	€ 650'604.16	€ 502'324.19	€ 1'152'928.35
75%	€ 29'128.59	€ 528'305.28	€ 512'245.26	€ 1'040'550.54
80%	€ 25'286.05	€ 491'876.98	€ 550'875.72	€ 1'042'752.70
98%	€ 20'532.85	€ 480'998.39	€ 557'400.50	€ 1'038'398.89

Table 6.21 Expected annual losses EAL, discounted expected losses EALd, seismic retrofit cost SRC and expected total cost ETC parameters for different streghtening levels for Rc jacketing & FRP retrofit strategy and for Spoleto site

The Figures show that in some cases the optimal retrofit level is achieved for a safety level lower than 50%. For this reason, it has been assumed that the safety level to achieve is at least the 80% as indicated in the new Italian building code.

Finally, as reported for the energy optimization case, the potential global cost savings (GCS) produced by the seismic retrofit solutions has been plotted to assess the discounted payback time (DPB) of the strategies.

Figure 6.14-6.16 and Table 6.22-6.24 report the temporal trend of the GCS function and the parameters of the cases.

The assumption of a safety level of at least 80% implicates that the results are similar to each other due to the same seismicity of the sites. Thus, the discounted payback times of the cases are slightly different.

For Benevento and Lattarico site, the best solution is the insertion of shear walls because this retrofit solution shows the lowest DPB time.

For Spoleto site, instead, the best seismic retrofit solution is the RC jacketing of the structural members. The differences from the sites may be a consequence of the seismicity of them: indeed Benevento and Lattarico have a PGA value higher than 0.25g, while Spoleto has a PGA value equal to 0.22g.

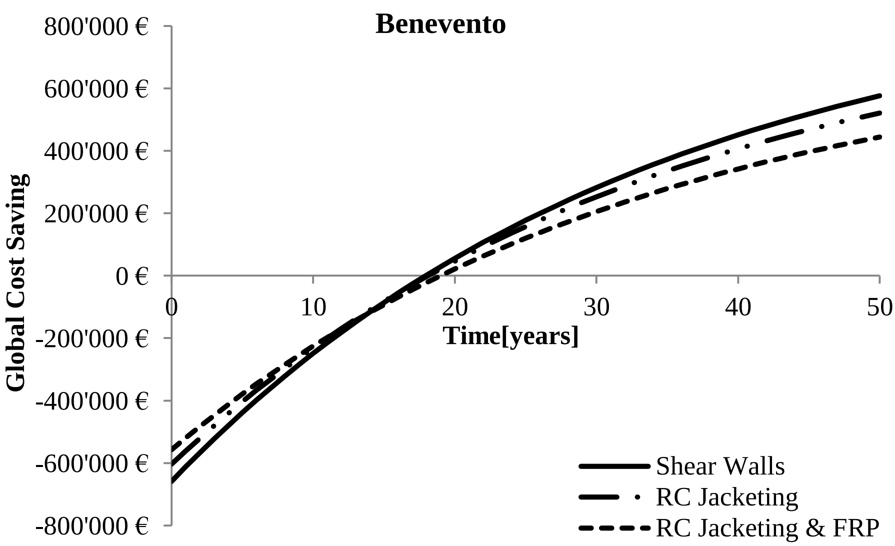


Figure 6.14 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit solution for Benevento site

Benevento	CI,$_{Retrofit}$ [€]	EAL,$_{as-built}$ [€]	EAL,$_{retrofitted}$ [€]	ΔEAL [€]	DPB [year]
Shear Walls	€ 658'387.39	€ 56'685.28	€ 8'687.53	€ 47'997.75	17.94
RC Jacketing	€ 603'705.92	€ 56'685.28	€ 12'979.21	€ 43'706.07	18.10
RC Jack. & FRP	€ 557'400.50	€ 56'685.28	€ 17'771.61	€ 38'913.67	19.00

Table 6.22 Parameters of the cost-optimal seismic retrofit solution for Benevento site

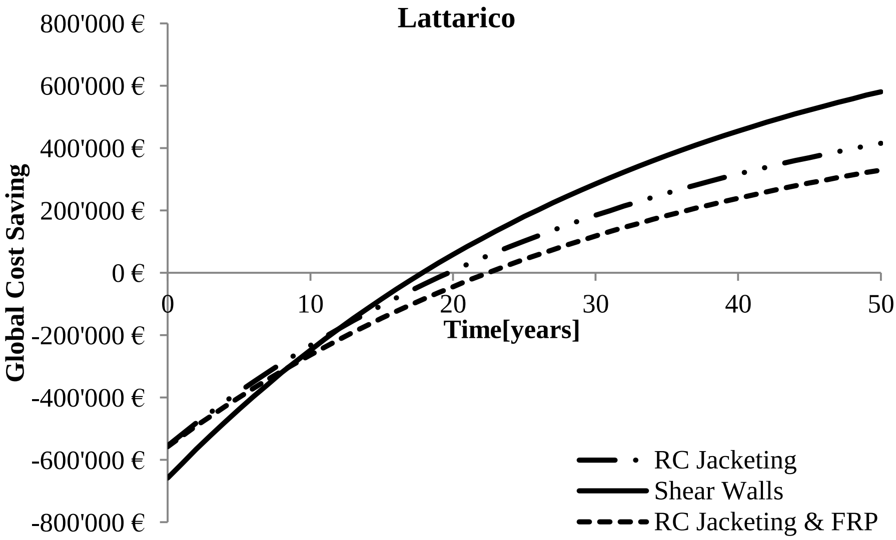


Figure 6.15 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit solution for Lattarico site

Lattarico	CI,$_{Retrofit}$ [€]	EAL,$_{as-built}$ [€]	EAL,$_{retrofitted}$ [€]	ΔEAL [€]	DPB [year]
Shear Walls	€ 658'387.39	€ 57'120.73	€ 8'972.65	€ 48'148.09	17.86
RC Jacketing	€ 554'340.99	€ 57'120.73	€ 19'444.04	€ 37'676.70	19.70
RC Jack. & FRP	€ 557'400.50	€ 57'120.73	€ 22'656.80	€ 34'463.93	22.46

Table 6.23 Parameters of the cost-optimal seismic retrofit solution for Lattarico site

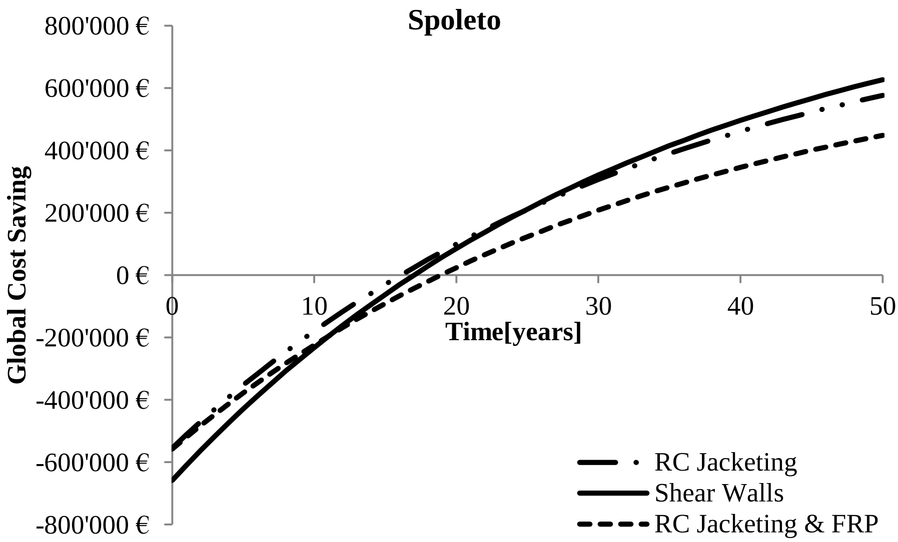


Figure 6.16 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit solution for Spoleto site

Spoleto	**CI,$_{\text{Retrofit}}$**	**EAL,$_{\text{as-built}}$**	**EAL,$_{\text{retrofitted}}$**	**ΔEAL**	**DPB**
	[€]	**[€]**	**[€]**	**[€]**	**[year]**
Shear Walls	€ 658'387.39	€ 57'755.56	€ 7'813.99	€ 49'941.57	17.03
RC Jacketing	€ 554'340.99	€ 57'755.56	€ 13'838.12	€ 43'917.44	16.10
RC Jack. & FRP	€ 557'400.50	€ 57'755.56	€ 18'694.24	€ 39'061.32	18.90

Table 6.24 Parameters of the cost-optimal seismic retrofit solution for Spoleto site

Figure 6.17 and Table 6.25 summarise the discounted payback times of the three retrofit strategies for the three building sites. The best scenario is for Spoleto site with RC Jacketing seismic retrofit solution. Overall, in each case the seismic retrofit interventions are cost-effective in the lifetime assumed. In other words, the economic benefits overcome the “status quo” bias.

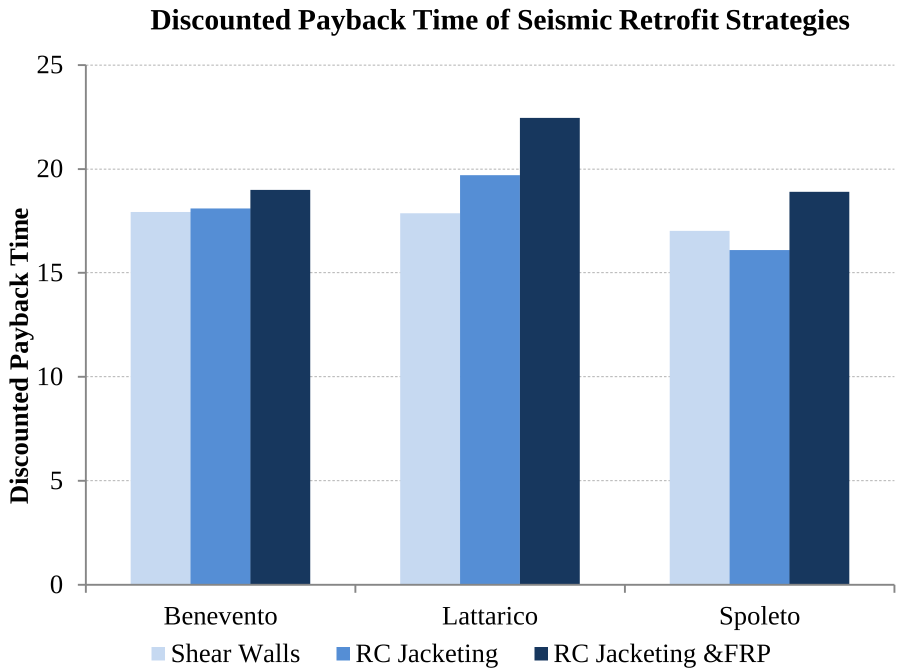


Figure 6.17 Discounted payback time of the cost-optimal seismic retrofit solution

DPB Time	Benevento	Lattarico	Spoleto
Shear Walls	17.94	17.86	17.03
RC Jacketing	18.10	19.70	16.10
RC Jacketing &FRP	19.00	22.46	18.90

Table 6.25 Discounted payback time of the cost-optimal seismic retrofit solution

6.4.4 Combined energy-seismic retrofit optimization

A combined approach is applied in this section to assess the overall economic lifecycle costs associated to an existing building when it is retrofitted from a structural and energetic point of view.

The energy retrofit optimization procedure and the seismic retrofit optimization procedure are combined to estimate and to highlight the benefits of a coupled approach.

Sometimes a coupled approach may be necessary, as showed for Lattarico site in the energy retrofit optimization procedure because the benefits were not sufficient in the lifetime assumed. Nevertheless, a combined approach should be a “standard rule” with which to improve the performance of an existing buildings.

Benefits related to a coupled approach seismic-energetic retrofit optimization are clearly showed in Figure 6.18-6.20 and Table 6.26-6.28. Figures show the temporal trend of the global cost saving in function of time. The investment cost is the sum of the investment cost for seismic retrofit and the investment cost for energy retrofit.

Tables report the parameters of the cost-optimal coupled solution: dCE and ΔEAL are the amount of money saved every year respectively for the energy retrofit measures and the seismic retrofit measures; EAL is the expected annual loss in the as-built configuration; EAL* is the expected annual loss of the retrofitted building that takes into account also the influence of the energy retrofit measures on the economic value of the building components; I_S is the safety level achieved through the seismic retrofit measures.

The coupled approach is implemented for each retrofit strategy analysed.

Combined Energy-Seismic Retrofit	BENEVENTO		
	Shear Walls	**RC Jacketing**	**RC Jack. & FRP**
$CI_{,ERMs}$	€ 94'705.00	€ 94'705.00	€ 94'705.00
$CI_{,Retrofit}$	€ 658'387.39	€ 603'705.92	€ 557'400.50
$CI_{,tot}$	€ 753'092.39	€ 698'410.92	€ 652'105.50
dCE	€ 10'734.00	€ 10'734.00	€ 10'734.00
$EAL_{,as\text{-}built}$	€ 56'685.28	€ 56'685.28	€ 56'685.28
$EAL^{*}_{,retrofitted}$	€ 8'764.50	€ 13'242.48	€ 18'117.63
ΔEAL	€ 47'920.78	€ 43'442.80	€ 38'567.65
DPB	16.85	16.97	17.59
Is	100%	100%	85%

Table 6.26 Parameters of the cost-optimal seismic retrofit solution the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Benevento site

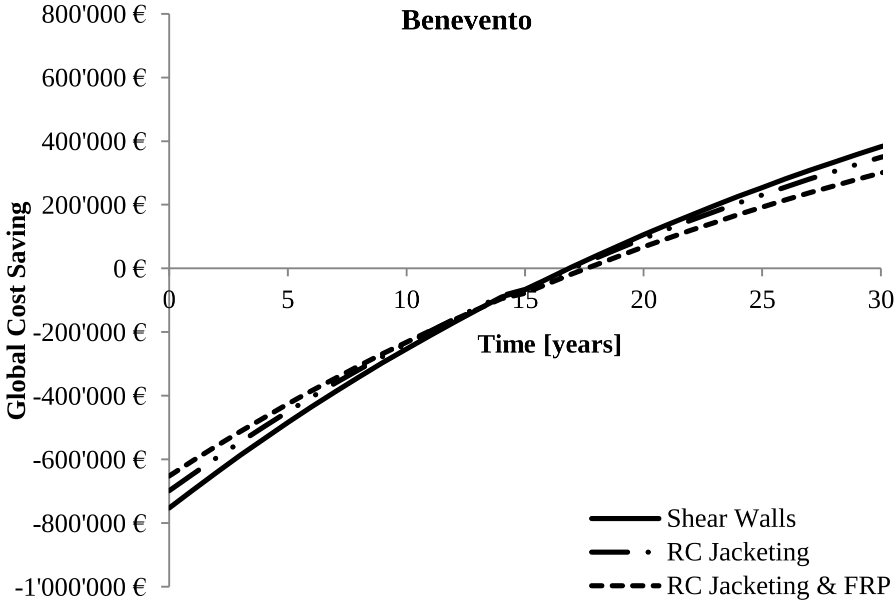


Figure 6.18 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Benevento site

Combined Energy-Seismic Retrofit	LATTARICO		
	Shear Walls	**RC Jacketing**	**RC Jack. & FRP**
CI,$_{\mathbf{ERMs}}$	€ 258'742.00	€ 258'742.00	€ 258'742.00
CI,$_{\mathbf{Retrofit}}$	€ 658'387.39	€ 554'340.99	€ 557'400.50
CI,$_{\mathbf{tot}}$	€ 917'129.39	€ 813'082.99	€ 816'142.50
dCE	€ 13'968.00	€ 13'968.00	€ 13'968.00
EAL,$_{\mathbf{as\text{-}built}}$	€ 57'120.73	€ 57'120.73	€ 57'120.73
EAL*,$_{\mathbf{retrofitted}}$	€ 9'322.83	€ 20'388.78	€ 24'089.51
ΔEAL	€ 47'797.90	€ 36'731.95	€ 33'031.22
DPB	20.06	22.35	25.08
Is	100%	82%	83%

Table 6.27 Parameters of the cost-optimal seismic retrofit solution the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Lattarico site

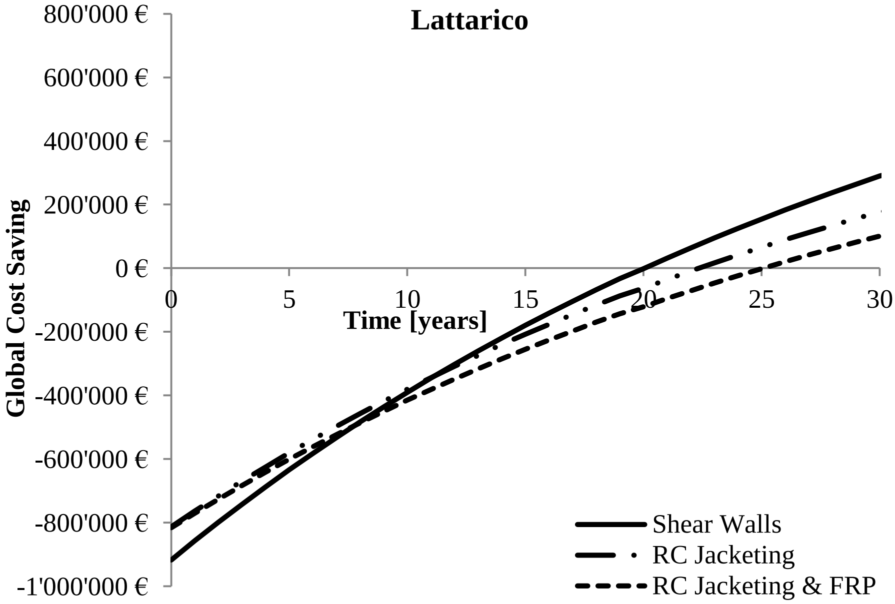


Figure 6.19 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Lattarico site

Combined Energy-Seismic Retrofit	SPOLETO		
	Shear Walls	**RC Jacketing**	**RC Jack. & FRP**
$CI_{,ERMs}$	€ 261'942.00	€ 261'942.00	€ 261'942.00
$CI_{,Retrofit}$	€ 658'387.39	€ 554'340.99	€ 557'400.50
$CI_{,tot}$	€ 920'329.39	€ 816'282.99	€ 819'342.50
dCE	€ 17'412.00	€ 17'412.00	€ 17'412.00
$EAL_{,as\text{-}built}$	€ 57'755.56	€ 57'755.56	€ 57'755.56
$EAL^*_{,retrofitted}$	€ 8'094.22	€ 14'355.18	€ 19'902.82
ΔEAL	€ 49'661.34	€ 43'400.38	€ 37'852.74
DPB	17.95	17.44	20.08
Is	100%	100%	98%

Table 6.28 Parameters of the cost-optimal seismic retrofit solution the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Spoleto site

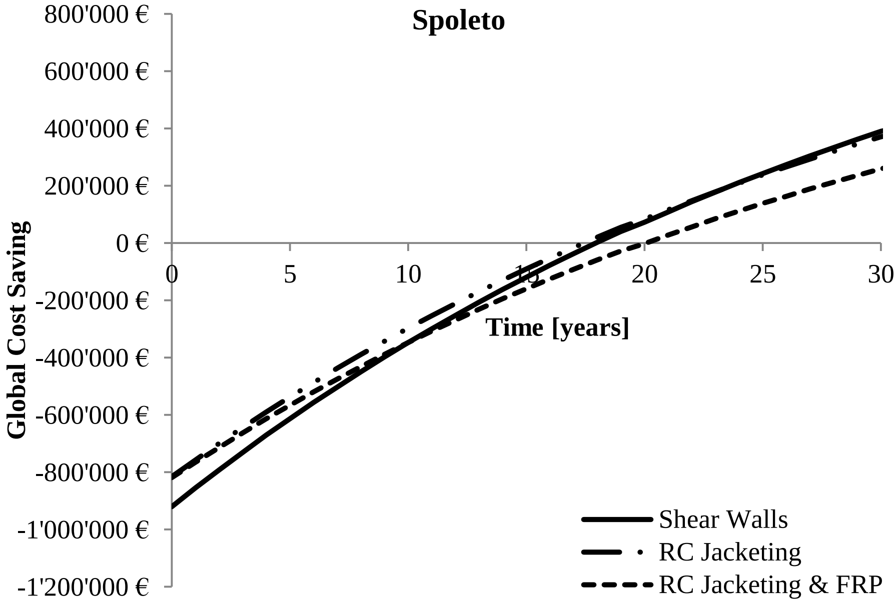


Figure 6.20 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Spoleto site

Figure 6.21 and Table 6.29 summarise the discounted payback times of the three approaches for the three building sites. For sake of simplicity, the lowest payback times of the seismic retrofit procedure and of the combined retrofit procedure have been reported. For the energy retrofit procedure, it has been reported the payback time with the influence of the seismic economic annual loss.

In each case the coupled approach is cost-effective in the lifetime assumed. Indeed, the discounted payback times of the combined approach are among the discounted payback times of the seismic retrofit approach and the energy retrofit approach.

In particular, for Benevento site the discounted payback time of the combined approach is higher than the discounted payback time of the energy retrofit measures but lower than the payback time of the seismic interventions. This is a consequence of the investment costs:

indeed the investment cost for the energy retrofit measures are significantly lower than the seismic retrofit measures.

For Lattarico and Spoleto sites, instead, the discounted payback time of the combined approach is lower than the discounted payback time of the energy retrofit measures but higher than the payback time of the seismic interventions. Indeed, for the two sites the investment costs are significant for the energy retrofit measures that have big discounted payback times. This influences the discounted payback times of the combined approach that are slightly higher than the seismic case.

Overall, the coupled approach is always profitable.

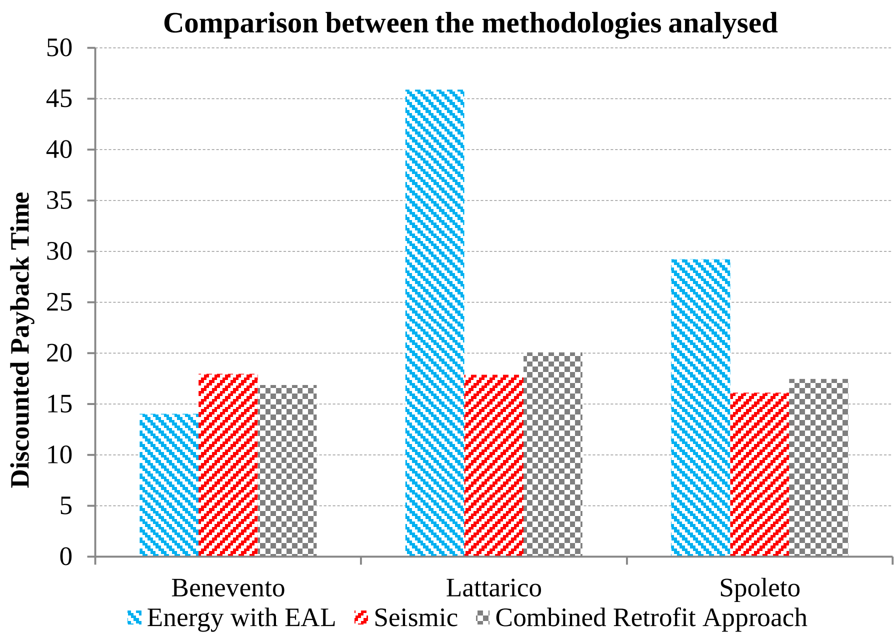


Figure 6.21 Discounted payback time of the three approach analysed

DPB Time	Benevento	Lattarico	Spoleto
Energy with EAL	14.02	45.89	29.20
Seismic	17.94	17.86	16.10
Combined Retrofit Approach	16.85	20.06	17.44

Table 6.29 Discounted payback time of the three approach analysed

6.4.5 The influence of the financial incentive on the retrofit optimization procedures

6.4.5.1 Energy retrofit optimization with financial incentives

The approach implemented in section 6.4.2 to quantify the economic lifecycle costs associated to a set of energy retrofit measures (ERMs) is enriched with the financial incentives provided by the Italian government.

Table 6.30-6.32 report the annual incentive for each site. The financial incentives are provided by the Italian government in ten years (Governo Italiano, 2015) and may amount up to 65% of the investment cost for retrofit measures.

With the support of the financial incentives also for Lattarico site the energy retrofit measures become cost-effective in the lifetime assumed also when the economic annual loss is taken into account. Indeed, the discounted payback times are lower than 30 years. This implicates that the Global Cost Saving increases in the temporal trend considered.

$CI,_{ERMs}$	dCE	IN	$DPB,_{energy}$	ΔEAL	$DPB,_{energy\text{-}structural}$
[€]	[€]	[€]	[year]	[€]	[year]
€ 94'705.00	€ 10'734.00	€ 5'035.30	6.72	-€ 2'361.15	8.06

Table 6.30 Parameters of the cost-optimal energy retrofit solution for Benevento site with Bonus

$CI,_{ERMs}$	dCE	IN	$DPB,_{energy}$	ΔEAL	$DPB,_{energy\text{-}structural}$
[€]	[€]	[€]	[year]	[€]	[year]
€ 258'742.00	€ 13'968.00	€ 10'379.00	15.40	-€ 3'512.23	23.42

Table 6.31 Parameters of the cost-optimal energy retrofit solution for Lattarico site with Bonus

$CI,_{ERMs}$	dCE	IN	$DPB,_{energy}$	ΔEAL	$DPB,_{energy\text{-}structural}$
[€]	[€]	[€]	[year]	[€]	[year]
€ 261'942.00	€ 17'412.00	€ 10'587.00	11.86	-€ 3'552.51	15.72

Table 6.32 Parameters of the cost-optimal energy retrofit solution for Spoleto site with Bonus

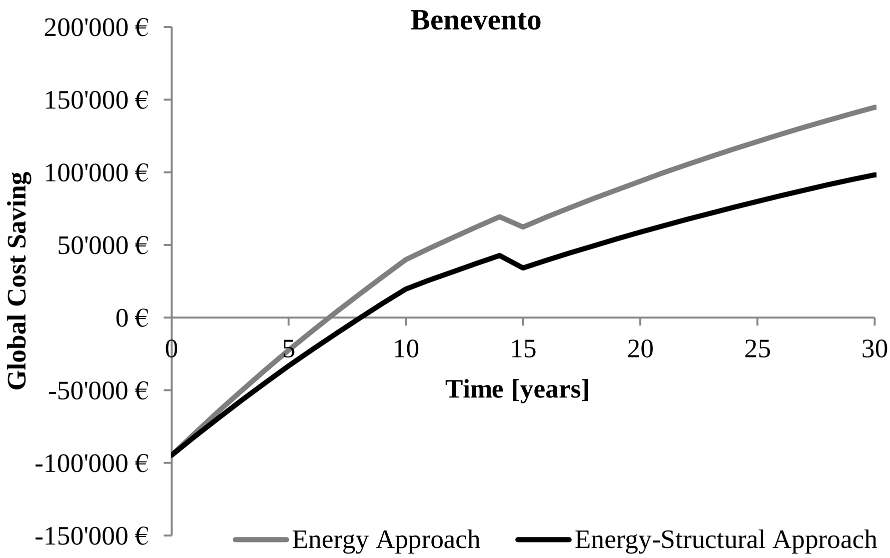


Figure 6.22 Temporal trend of the global cost saving produced by the cost-optimal energy retrofit solution considering the seismic economic losses for Benevento site with Bonus

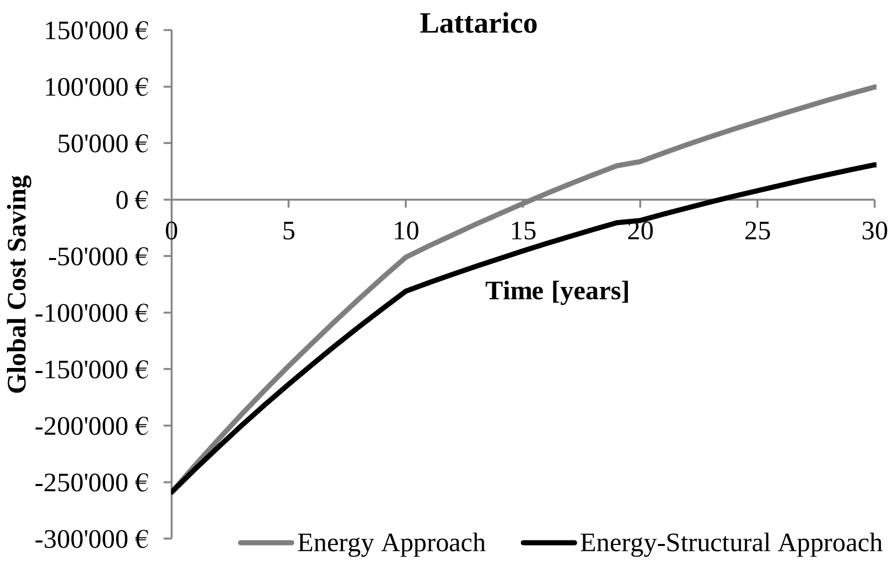


Figure 6.23 Temporal trend of the global cost saving produced by the cost-optimal energy retrofit solution considering the seismic economic losses for Lattarico site with Bonus

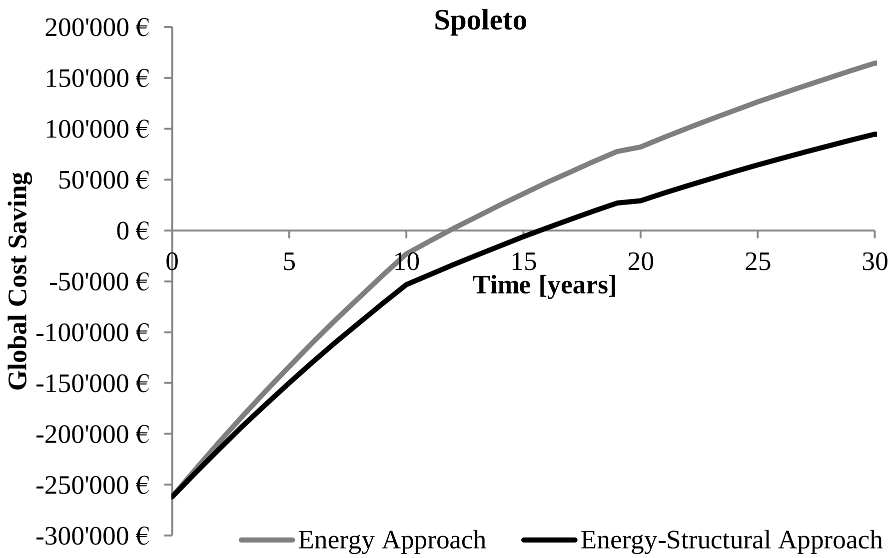


Figure 6.24 Temporal trend of the global cost saving produced by the cost-optimal energy retrofit solution considering the seismic economic losses for Spoleto site

Finally, in Figure 6.25 and Table 6.33 summarise the discounted payback times of the cost-optimal energy retrofit solution with and without the financial incentives. The incentives significantly decrease the discounted payback times.

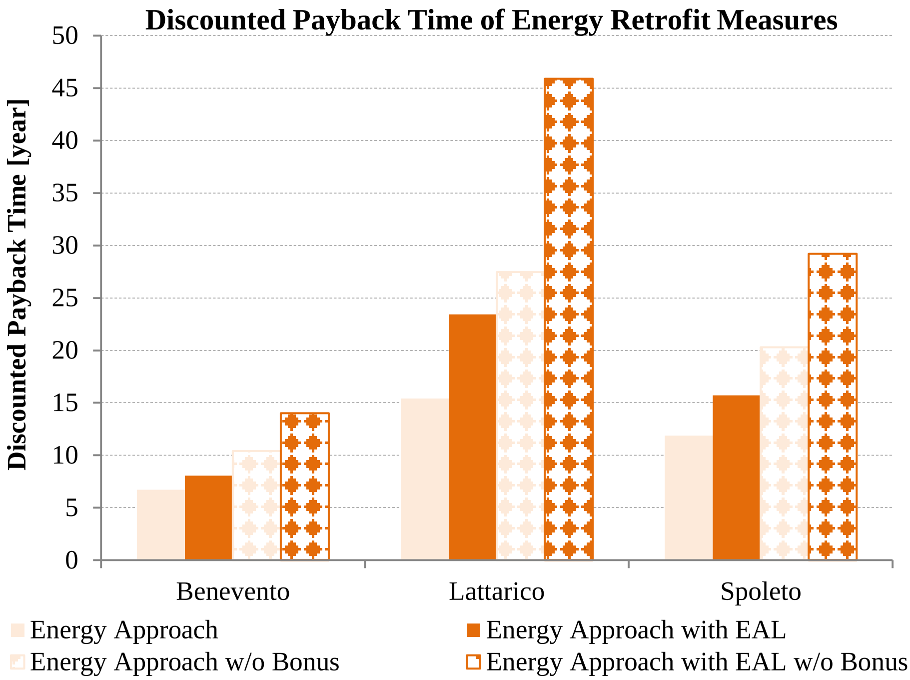


Figure 6.25 Discounted payback time of the cost-optimal energy retrofit solution with and without Bonus

DPB Time	Benevento	Lattarico	Spoleto
Energy Approach	6.72	15.40	11.86
Energy Approach with EAL	8.06	23.42	15.72
Energy Approach w/o Bonus	10.40	27.45	20.31
Energy Approach with EAL w/o Bonus	14.02	45.89	29.20

Table 6.33 Discounted payback time of the cost-optimal energy retrofit solution with and without Bonus

6.4.5.2 Seismic retrofit optimization with financial incentives

The seismic retrofit strategies optimization procedure is enriched with the financial incentives provided by the Italian government (Governo Italiano, 2017).

Table 6.34-6.36 report the annual incentives for each site. The financial incentives are provided by the Italian government in five years and may amount up to 80% of the investment cost for retrofit measures.

The financial incentives significantly affect the discounted payback times pushing them to have values close to the five years. This implicates that the Global Cost Saving increases in the temporal trend considered.

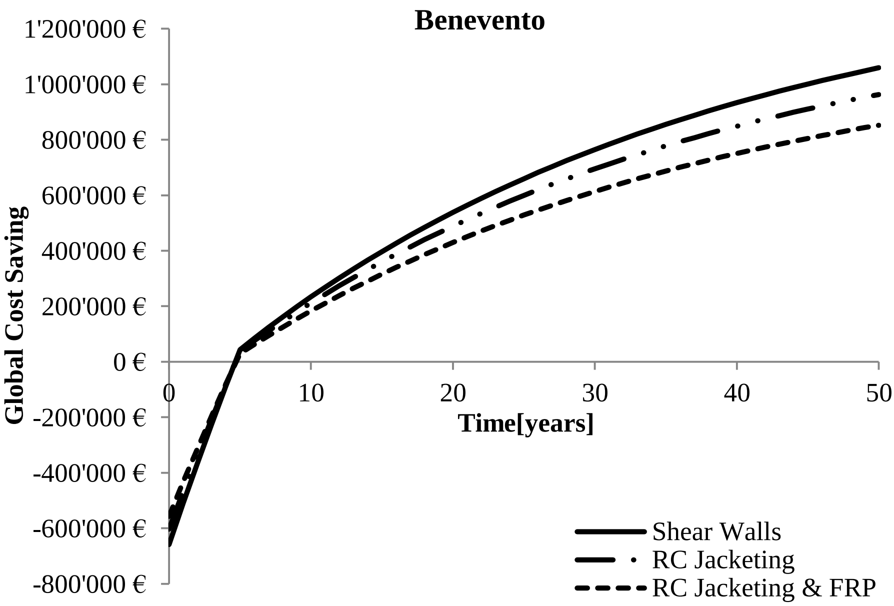


Figure 6.26 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit solution for Benevento site with Bonus

Benevento	**$CI_{,Retrofit}$**	**IN**	**ΔEAL**	**DPB**
	[€]	**[€]**	**[€]**	**[year]**
Shear Walls	€ 658'387.39	€ 105'341.98	€ 47'997.75	4.67
RC Jacketing	€ 603'705.92	€ 96'592.95	€ 43'706.07	4.68
RC Jacketing & FRP	€ 557'400.50	€ 89'184.08	€ 38'913.67	4.73

Table 6.34 Parameters of the cost-optimal seismic retrofit solution for Benevento site with Bonus

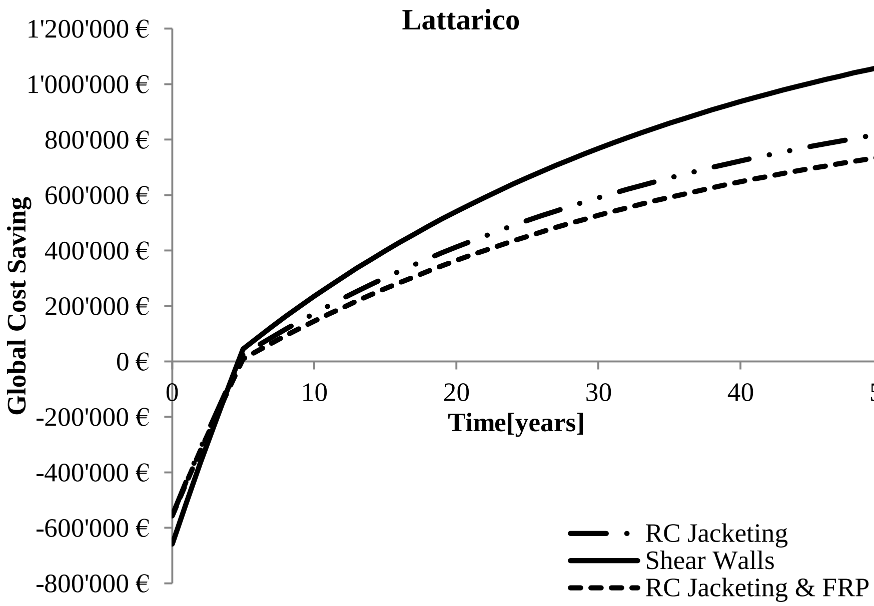


Figure 6.27 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit solution for Lattarico site with Bonus

Lattarico	$CI_{,Retrofit}$ [€]	IN [€]	ΔEAL [€]	DPB [year]
Shear Walls	€ 658'387.39	€ 105'341.98	€ 48'148.09	4.66
RC Jacketing	€ 554'340.99	€ 88'694.56	€ 37'676.70	4.77
RC Jacketing & FRP	€ 557'400.50	€ 89'184.08	€ 34'463.93	4.92

Table 6.35 Parameters of the cost-optimal seismic retrofit solution for Lattarico site with Bonus

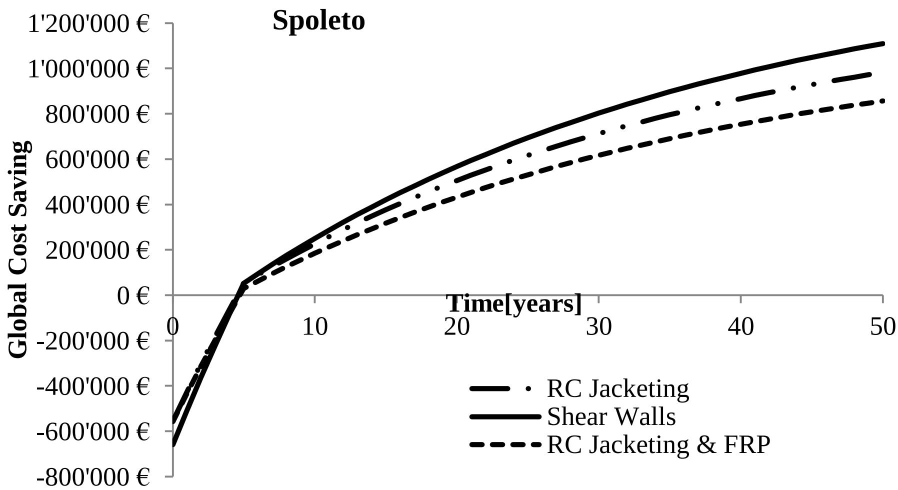


Figure 6.28 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit solution for Spoleto site with Bonus

Spoleto	**CI,$_{\text{Retrofit}}$**	**IN**	**ΔEAL**	**DPB**
	[€]	**[€]**	**[€]**	**[year]**
Shear Walls	€ 658'387.39	€ 105'341.98	€ 49'941.57	4.60
RC Jacketing	€ 554'340.99	€ 88'694.56	€ 43'917.44	4.53
RC Jacketing & FRP	€ 557'400.50	€ 89'184.08	€ 39'061.32	4.73

Table 6.36 Parameters of the cost-optimal seismic retrofit solution for Spoleto site with Bonus

Finally, in Figure 6.29 and Table 6.37 summarise the discounted payback times of the seismic retrofit strategies for the three building sites with and without the financial incentives. The incentives significantly decrease the discounted payback times that are, in this case, lower than five years. In this way, each seismic retrofit strategy seems to be competitive.

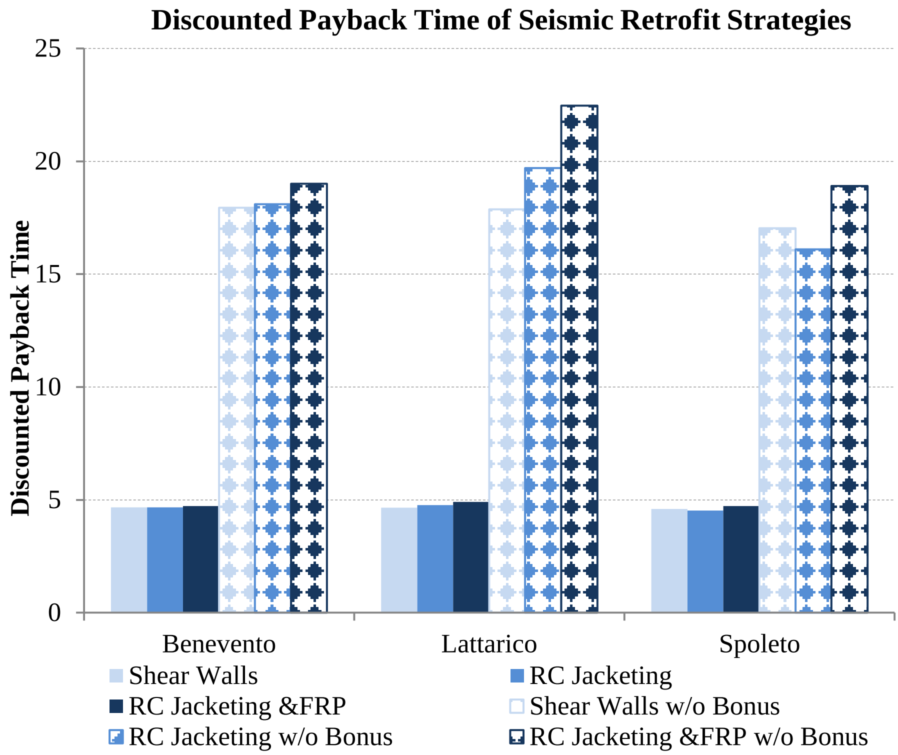


Figure 6.29 Discounted payback time of the cost-optimal seismic retrofit solution with and without Bonus

DPB Time	Benevento	Lattarico	Spoleto
Shear Walls	4.67	4.66	4.60
RC Jacketing	4.68	4.77	4.53
RC Jacketing &FRP	4.73	4.92	4.73
Shear Walls w/o Bonus	17.94	17.86	17.03
RC Jacketing w/o Bonus	18.10	19.70	16.10
RC Jacketing &FRP w/o Bonus	19.00	22.46	18.90

Table 6.37 Discounted payback time of the cost-optimal seismic retrofit solution with and without Bonus

6.4.5.3 Combined energy-seismic retrofit optimization with financial incentives

The combined approach is enriched with the financial incentives provided by the Italian government for both energy retrofit measures and seismic retrofit measures (Governo Italiano, 2015, 2017).

Table 6.38-6.40 report, as summary, the annual incentive for each retrofit measure and for each site.

The financial incentives provided by the Italian government for the seismic retrofit measures significantly affect the discounted payback times pushing them to have values close to five years. Indeed, the investment cost for seismic retrofit measures is higher than the investment cost for energy retrofit measures. Thus, the financial incentives for the seismic measures are higher and, moreover, they are provided in the first five years instead of the first ten years.

This implicates, also, that the Global Cost Saving increases in the temporal trend considered whereas the discounted payback times decrease.

Combined Energy-Seismic Retrofit	BENEVENTO		
	Shear Walls	**RC Jacketing**	**RC Jack. & FRP**
CI,$_{ERMs}$	€ 94'705.00	€ 94'705.00	€ 94'705.00
CI,$_{Retrofit}$	€ 658'387.39	€ 603'705.92	€ 557'400.50
CI,$_{tot}$	€ 753'092.39	€ 698'410.92	€ 652'105.50
dCE	€ 10'734.00	€ 10'734.00	€ 10'734.00
IN,$_{energ}$	€ 5'035.30	€ 5'035.30	€ 5'035.30
IN,$_{seismic}$	€ 105'341.98	€ 96'592.95	€ 89'184.08
EAL,$_{as-built}$	€ 56'685.28	€ 56'685.28	€ 56'685.28
EAL*,$_{retrofitted}$	€ 8'764.50	€ 13'242.48	€ 18'117.63
ΔEAL	€ 47'920.78	€ 43'442.80	€ 38'567.65
DPB	4.85	4.89	4.96
Is	100%	100%	85%

Table 6.38 Parameters of the cost-optimal seismic retrofit solution the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Benevento site with Bonus

Combined Energy-Seismic Retrofit	LATTARICO		
	Shear Walls	**RC Jacketing**	**RC Jack. & FRP**
$CI_{,ERMs}$	€ 258'742.00	€ 258'742.00	€ 258'742.00
$CI_{,Retrofit}$	€ 658'387.39	€ 554'340.99	€ 557'400.50
$CI_{,tot}$	€ 917'129.39	€ 813'082.99	€ 816'142.50
dCE	€ 13'968.00	€ 13'968.00	€ 13'968.00
$IN_{,energ}$	€ 10'379.00	€ 10'379.00	€ 10'379.00
$IN_{,seismic}$	€ 105'341.98	€ 88'694.56	€ 89'184.08
$EAL_{,as\text{-}built}$	€ 57'120.73	€ 57'120.73	€ 57'120.73
$EAL^{*}_{,retrofitted}$	€ 9'322.83	€ 20'388.78	€ 24'089.51
ΔEAL	€ 47'797.90	€ 36'731.95	€ 33'031.22
DPB	6.75	7.55	8.11
Is	100%	82%	83%

Table 6.39 Parameters of the cost-optimal seismic retrofit solution the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Lattarico site with Bonus

Combined Energy-Seismic Retrofit	SPOLETO		
	Shear Walls	**RC Jacketing**	**RC Jack. & FRP**
$CI_{,ERMs}$	€ 261'942.00	€ 261'942.00	€ 261'942.00
$CI_{,Retrofit}$	€ 658'387.39	€ 554'340.99	€ 557'400.50
$CI_{,tot}$	€ 920'329.39	€ 816'282.99	€ 819'342.50
dCE	€ 17'412.00	€ 17'412.00	€ 17'412.00
$IN_{,energ}$	€ 10'587.00	€ 10'587.00	€ 10'587.00
$IN_{,seismic}$	€ 105'341.98	€ 88'694.56	€ 89'184.08
$EAL_{,as\text{-}built}$	€ 57'755.56	€ 57'755.56	€ 57'755.56
$EAL^{*}_{,retrofitted}$	€ 8'094.22	€ 14'355.18	€ 19'902.82
ΔEAL	€ 49'661.34	€ 43'400.38	€ 37'852.74
DPB	6.26	6.40	7.01
Is	100%	100%	98%

Table 6.40 Parameters of the cost-optimal seismic retrofit solution the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Spoleto site with Bonus

Figure 6.30-6.32 show the temporal trend of the global cost saving in function of the time for each retrofit strategy.

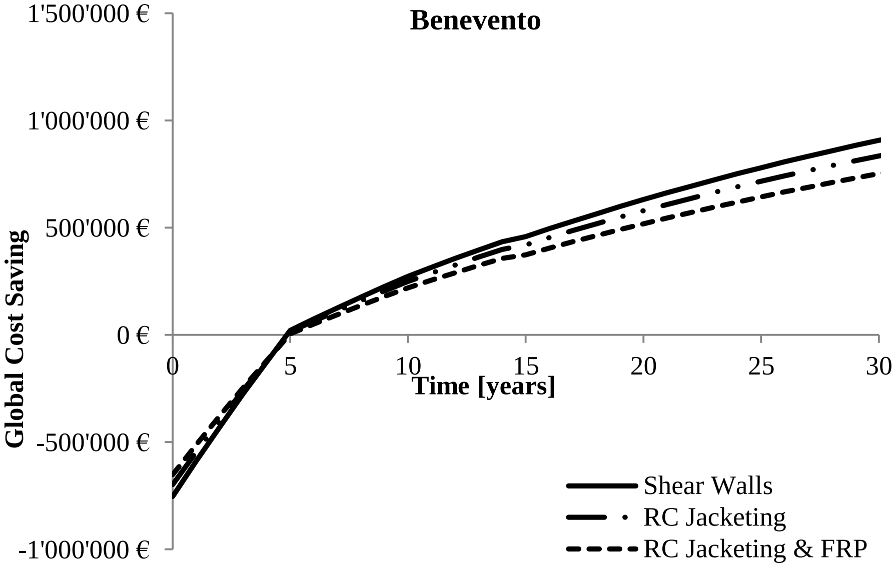


Figure 6.30 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Benevento site with Bonus

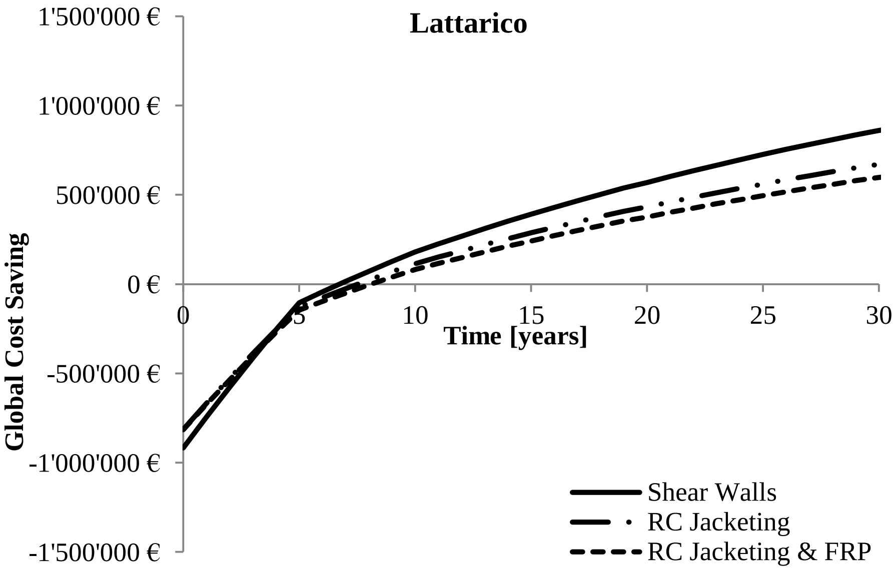


Figure 6.31 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Lattarico site with Bonus

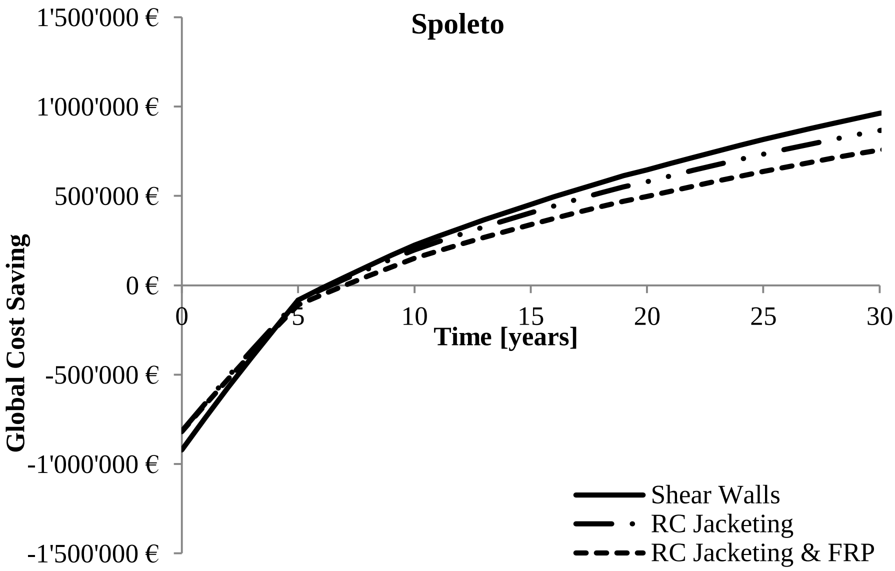


Figure 6.32 Temporal trend of the global cost saving produced by the cost-optimal seismic retrofit level and the cost-optimal energy retrofit solution for the strenghtening strategies for Spoleto site with Bonus

Finally, Figure 6.33 and Table 6.41 summarise the discounted payback times of the three approaches for the three building sites with and without the financial incentives. For sake of simplicity, the lowest payback times of the seismic retrofit procedure and of the combined retrofit procedure have been reported. For the energy retrofit procedure, it has been reported the payback time with the influence of the seismic economic annual loss.

The incentives significantly decrease the discounted payback times of the combined approach pushing them close to five years. Indeed, the discounted payback times of the combined approach are among the discounted payback times of the seismic retrofit approach and the energy retrofit approach with values between 4.85 years and 6.26 years.

In particular, due to the significant influence of the financial incentives for the seismic retrofit measures, the discounted payback times of the combined approach are lower than the discounted payback times of the energy retrofit measures but higher than the payback times of the seismic interventions.

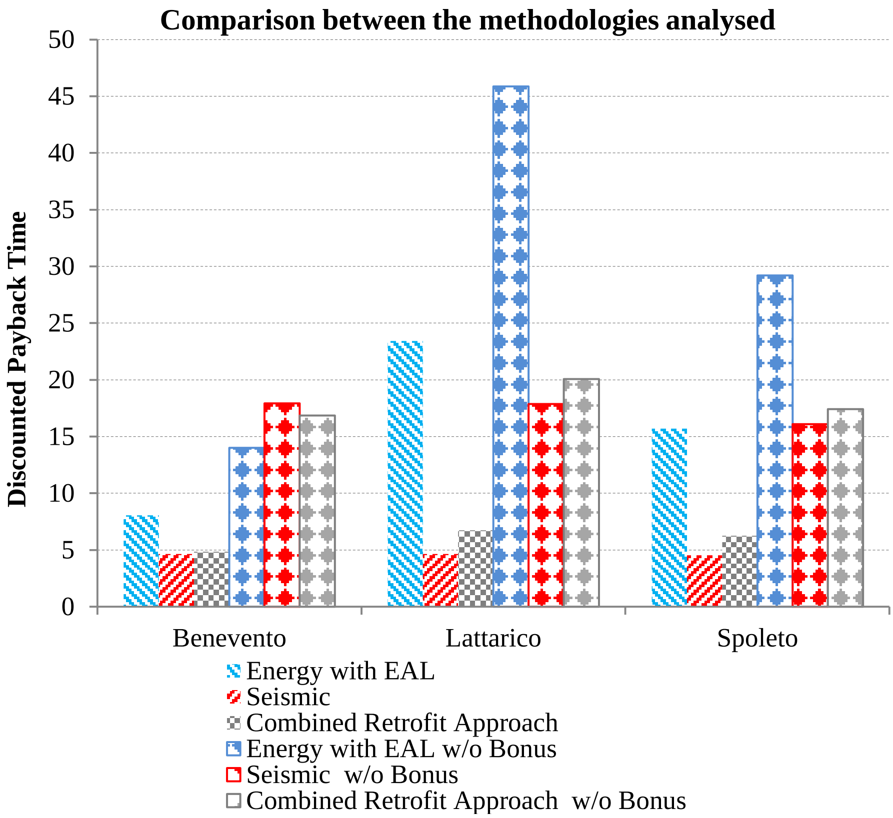


Figure 6.33 Discounted payback time of the three approach analysed with and without Bonus

DPB Time	Benevento	Lattarico	Spoleto
Energy with EAL	8.06	23.42	15.72
Seismic	4.67	4.66	4.53
Combined Retrofit Approach	4.85	6.75	6.26
Energy with EAL w/o Bonus	14.02	45.89	29.20
Seismic w/o Bonus	17.94	17.86	16.10
Combined Retrofit Approach w/o Bonus	16.85	20.06	17.44

Table 6.41 Discounted payback time of the three approach analysed with and without Bonus

CHAPTER 7

CONCLUSIONS

The present PhD Thesis work has been developed to address issues related to sustainability of retrofit operations on existing building prone to seismic risk. Facility Management is the longest period in the life-cycle phase, and generally thus constitutes the main expense and includes all the operations that ensure that buildings continue to fulfil their functions. Refurbishment is generally carried out to improve the performance of a building and, sometimes, to meet the requirements of owners and building codes.

This study has developed an integrated platform where refurbishment and renovation operations are integrated with energy, economic and environmental elements. Once the technical operations to refurbish the building and to increase the structural capacity against seismic actions are estimated, their long-term consequences are evaluated. Thus, seismic retrofit strategies are connected to environmental, economic and energy aspects. Moreover, sustainable design principles are implemented into BIM methodologies to show how BIM enables the management of large amounts of data and improves the feasibility of the processes.

A particular focus is done in ***Chapter 1*** to highlight the great attention that the concept of sustainability has gained from the worldwide scientific community, according to different features and applications.

The origin of the concept of sustainability and its definitions have been investigated. Sustainability is an interdisciplinary issue and has its roots in both the physical and the social sciences. The need for sustainability is embedded in achieving a balance between economic activities and their associated ecological and social impact (Muhammad Asif et al., 2008). Thus, the three main dimensions of sustainability have been exposed (environmental, economic, and societal).

The deep link between sustainability and construction industry has been highlighted. Construction industry is one of the major causes of both the consumption of natural resources and environmental pollution. In fact, buildings have a significant environmental impact during their life-cycle, consuming huge amounts of energy and natural assets and affecting the air and water quality in our cities.

The method identified to assess the sustainability performance of products is the Life-cycle Sustainability Assessment (LCSA). It assesses product performance considering the environmental, economic, and social dimensions over the whole life-cycle and can be used to compare different products supporting decision makers and stakeholders in making a more sustainable decision (Traverso et al., 2012). Klöpffer put the LCSA framework into the conceptual formula (Klöpffer, 2007), where the life-cycle sustainability assessment (LCSA) is a Life-cycle Assessment (LCA), a Life-cycle Costing (LCC) and a Social Life-cycle Analysis (SLCA), done in a consecutive way. LCA is a well-established methodology to assess the environmental aspects and potential environmental impacts throughout a product's life-cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. LCC is an assessment of all relevant real money flows associated with the whole life-cycle of a product and with all the stakeholders in the product life-cycle (Swarr et al., 2011). SLCA methodology, instead, is still under constant development despite the publication of guidelines for social life-cycle assessment of products by the United Nations Environment Programme (UNEP-SETAC, 2009)..

The last consideration highlighted in Chapter 1 it that Building Information Models are a way to produce sustainability models because BIM-based model contribute to each dimension of sustainability. Kriegel and Nies (Krygiel & Nies, 2008) indicates that BIM may aid in the aspects of sustainable design which are building orientation (which may reduce the cost of the project), building massing (to analyse building form and optimize the building envelope), day lighting analysis, water harvesting (reducing water needs in a building), energy modelling (reducing energy needs and analysing how renewable energy options can contribute to low energy costs), sustainable materials (reducing material needs and using recycled materials) and site and logistics management (to reduce waste and carbon footprints). Digital models produced also aim to mitigate risks (such as seismic risks), as well as increase efficiency and effectiveness.

Chapter 2 sets out a systematic approach to assess the environmental sustainability of materials and processes related to retrofit strategies for existing RC building using an LCA. In particular, once the structural requirements are satisfied, the proposed approach analyses and compares the environmental performances of four retrofit strategies, with the purpose being to identify the most environmentally suitable retrofit approach. These strengthening solutions are: the application of FRP sheets to the surface of structural elements; the RC jacketing of columns and the application of FRP sheets to the surface of beams and joints; building two RC shear walls; and base isolation of the building. In order to carry out a comparison of the strengthening strategies, the performance of the building is improved at the same level with the different retrofit options. A cradle-to-gate system boundary is considered in this study for each retrofit solution and analyses are carried out using the SimaPro software, which is an efficient tool for collecting sustainability data and analysing and monitoring the sustainability performance of products and processes. The IMPACT2002+ methodology has been used to assess the environmental impact of the straightening processes.

This kind of result only makes designers aware of what is the most environmentally sustainable retrofit strategy. In the final decision on the various strengthening interventions, other criteria have to be considered such as costs and social impact, meaning that the best solution from an environmental point of view may not be the retrofit strategy adopted. Moreover, the environmental impact obtained is strictly dependent on the case study considered. The vulnerability of a facility and the seismic hazard of a building site significantly influence the results. The environmental outcomes also depend on the databases that practitioners use, the accuracy of the LCA and the system boundary.

Usually, LCA practitioners use 2D drawings and enter data about building and materials manually. However, manual re-entry of the project data into the LCA tool is generally one of the main drawbacks. A way to overcome this issue is the integration of LCA procedures or tools in BIM models. The use of BIM helps to avoid unnecessary waste of time and resources caused by inefficient data management. The easiest way to implement BIM, in fact, is to support quantity take-off and estimation for the tasks that involve counting, such as doors, windows, and plumbing fixtures (Eastman et al., 2011). Indeed, building information models provide data that can more readily integrate with LCA tools during the whole life-cycle, from conceptual design to construction and then to facility operation and management.

A semi-probabilistic methodology is proposed in ***Chapter 3*** for assessing the economic performance of a building prone to seismic risk. The methodology is based on the PEER's approach by replacing the use of non-linear time-history structural analysis by means of a static non-linear one. In particular, the proposed methodology is based on the use of a nonlinear static analysis carried out excluding the torsional effects, the occurrence of plastic hinges due to shear deformation, and assuming only one EDP for the structural and nonstructural elements belonging to the same storey, as commonly assumed by practitioners involved in the assessment of seismic capacity of existing buildings.

LCC procedures may be used to compare alternative design strategies and to evaluate the cost effectiveness of them, by considering the initial and operational costs that are incurred over the lifetime. More specifically, LCC may be used to support decision-making in a number of ways: to assess total cost of an asset, considering the complete life-cycle (from cradle to gate) or a selected intermediate period; to select choices between different means of achieving the same objectives; to achieve a balance between initial costs and future revenue costs; to identify cost-effective alternative solution during sustainability analyses; such as HVAC (Heating, Ventilation and Air Conditioning) systems with high-energy efficiency; to assess options in relation to component replacements and/or refurbishment (for example the selection of component with long service life or reduced maintenance requirements); to plan maintenance, repair and replacement work; to identify alternative uses of the facility; to identify end-of-life considerations such as strategies for disposal, options for demolition and strategies for recycling (Langdon, 2007).

Hence, the proposed methodology aims to identify the most cost-effective strengthening strategies and strengthening levels (i.e.

strengthening intervention associated with a given safety level) for existing structures over their life-cycle.

Both interventions that increase structural stiffness (and thus limit displacements), and those that increase ductility, generate a potential level of damage to the structure in its life-time that is lower than that which would occur to the structure if it were not strengthened. The goal is to assess whether the cost of the strengthening is beneficial enough to justify the intervention in the structural life-time of the building, and to identify the optimal strengthening level. The application case has clearly showed that the cost-effectiveness of retrofitting is highly dependent on the cost of the retrofit, the level of strengthening, the seismicity of the region, and the time horizon considered.

Chapter 4 evaluates the possibility of integrating the simplified assessment procedure for economic losses due to a seismic event into a BIM based design approach. This is to improve the feasibility of these procedures and to deal with the large amount of data referred to the damage and cost analyses of the components that constitute a facility. In this way, the BIM model shows the economic condition of a building and becomes an updated database that can be constantly improved and queried at any time to obtain information on the structure and assess the costs of future interventions, including the expected economic losses caused by seismic events. This system data optimize the lifecycle of components, increase efficiency in the preventive maintenance, and provide accurate and electronic as-built documents. These aspects are at the core of BIM’s fundamental promise to do away with the need for multiple data entry for different analysis applications, allowing the model to be analysed directly and within very short cycle times (Eastman et al., 2011).

Furthermore, this integration provides owners with a simple tool that can be used at different stages of the lifecycle of a facility. This tool may also be able to optimize the maintenance phases accounting for possible seismic retrofit operations and carrying out an LCC analysis.
Finally, ***Chapter 5*** and ***Chapter 6*** propose an innovative lifecycle approach to address the retrofit of existing buildings by integrating energy, structural and environmental aspects.
Chapter 5 performs a multi-stage energy optimization by implementing a genetic algorithm and a smart research strategy. The cost-optimal energy retrofit solution is identified and the impact of the expected economic losses due to seismic damage is assessed throughout the building lifecycle. The methodology is applied to a multi-story residential building, considering the effects of two different building locations. These latter are characterized by similar climatic conditions but by a different level of seismic risk. The outcomes show that the selection of the optimal energy retrofit measures should be related to the building structural behaviour in order to achieve reliable economic and sustainability benefits.
Chapter 6, shows a combined approach for the energy retrofit and the seismic retrofit of existing building. First of all, the two retrofit methodologies described in Chapter 3 and 5 are carried out separately, and afterwards are combined to show benefit and advantages of a coupled approach. The methodologies have been applied considering three different locations characterized by the same seismic risk but different climatic condition (Zone C, Zone D and Zone E). In each case the coupled approach is cost-effective in the lifetime assumed. Indeed, the discounted payback times of the combined approach are among the discounted payback times of the seismic retrofit approach and the energy retrofit approach.

In this background, over the last decades, building retrofit has gained increasing interest among national institutions and governments, enabling prospects of upgrading external building envelope and energy systems to achieve energy efficiency goals. National policies have also encouraged the increment of safety levels for occupants of existing building, trying to align with more modern accommodation standards and structural codes. For this reason, the approach has been also implemented taking into account the influence of the financial incentives of the Italian government. The incentives significantly decrease the discounted payback times of the combined approach pushing them close to five years. In particular, due to the significant influence of the financial incentives for the seismic retrofit measures, the discounted payback times of the combined approach are lower than the discounted payback times of the energy retrofit measures. With these financial incentives, the combined approach is extremely profitable.

As a final word, in this PhD thesis, life cycle thinking is addressed to re-conceive traditional seismic retrofit methodologies and approaches, guaranteeing structural safety and minimising costs and environmental impacts over the building life cycle. To do this, information from energy, economic and environmental elements converge into a sole dataset to drive the refurbishment of existing buildings characterized by low energy efficiency, living discomfort and prone to seismic risk. Generally, demolition and reconstruction may be practiced very rarely, because implicates raw material depletion and waste production. For this reason the best solution often consists of a renovation program that is approached by solving sporadic problems without any references to other deficiencies. Thus, the retrofit is carried out following a non-integrated approach. The approach proposed in this research work overcomes failings of the traditional practice. The integrated platform, where refurbishment and renovation operations are integrated with energy, economic and environmental elements, highlights the importance of a combined sustainable approach and the related benefits.

In conclusion, the sustainable framework proposed offers an enhancement of the traditional design methodologies, focusing on seismic retrofit, economic and environmental aspects as well as energy efficiency.

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