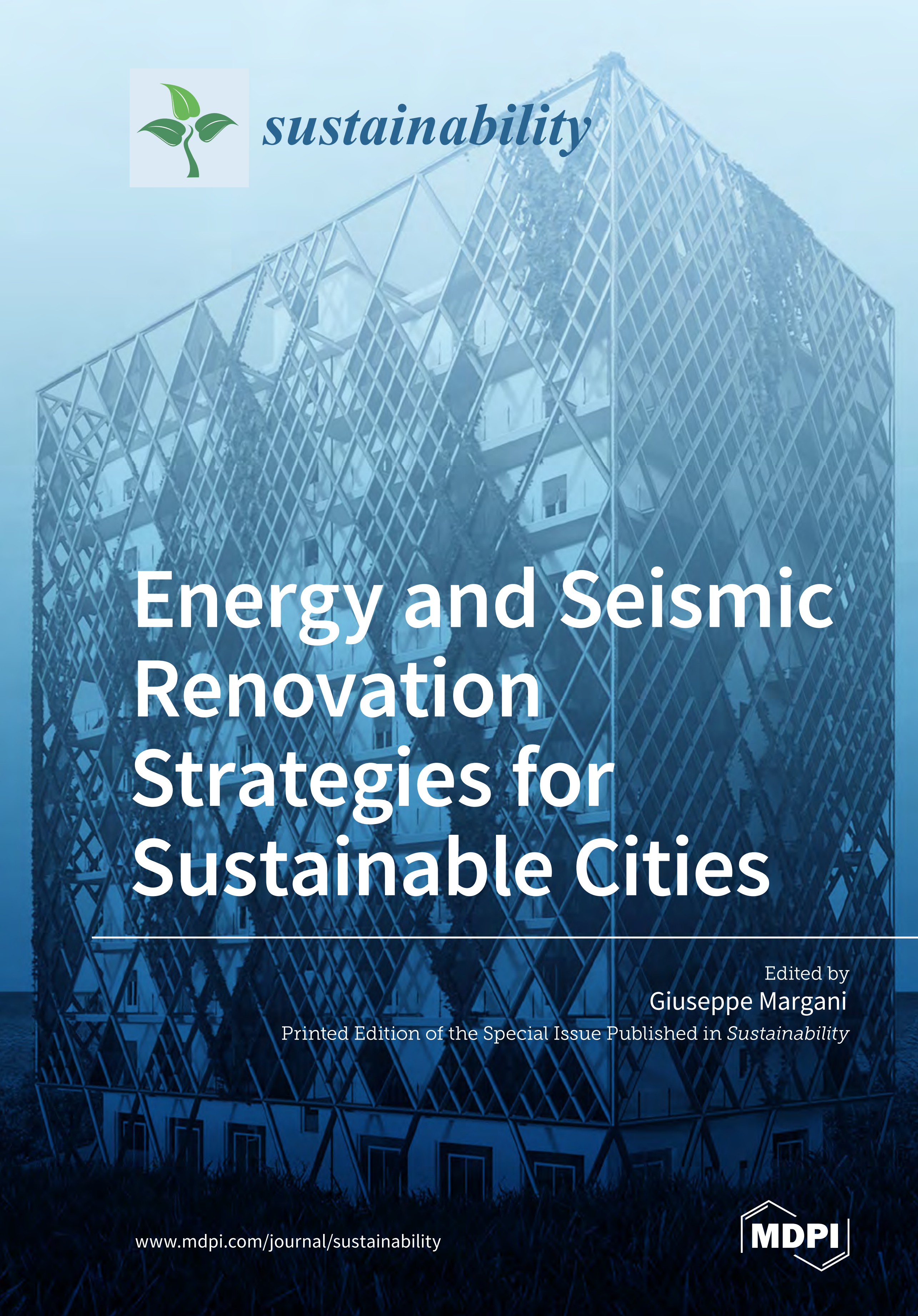

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Energy and Seismic Renovation Strategies for Sustainable Cities

Edited by
Giuseppe Margani

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Special Issue Editor

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Contents

About the Special Issue Editor

Giuseppe Margani, MEng, Ph.D., is associate professor of Building Construction at the Department of Civil Engineering and Architecture (DICAr), University of Catania, Italy. He received his Ph.D. in "Architectural Engineering: design, production and renovation techniques" from the University of Palermo in 2000. His research interests include sustainable architecture, energy and seismic renovation, integration of renewable energy systems in the building envelope, innovation in building technologies, restoration of historical buildings, history of construction technologies. He is the author of 6 books and the author or co-author of over 60 papers published on national and international peer-reviewed journals or conference proceedings. He has a sound experience in the development and direction of national and international research projects and he is an independent expert of the EC for research and innovation programs. He is serving as guest editor, editorial board member and reviewer of over 10 international journals. As a licensed architectural engineer, he has over 25 years of work experience in detailed design, building refurbishment, and non-destructive tests on cultural assets.

Preface to "Energy and Seismic Renovation Strategies for Sustainable Cities"

Sustainability has become a fundamental requirement for the future of our cities.

This requirement is mostly associated with environmental issues, and a great effort has been made in the past years to build a low-carbon society. However, sustainability must also be associated with safety.

As a consequence, in seismic countries, sustainable cities must be not only low-carbon-emitting bust also earthquake-safe.

This concept represents the basic premise of this book.

According to this premise, in earthquake-prone nations like Italy—where most of the building stock is both highly earthquake-vulnerable and energy-consuming—energy renovation actions should be combined with seismic upgrades. Nevertheless, many barriers significantly limit the real possibility of undertaking combined retrofit measures, especially in the case of multi-owner housing and high-rise buildings. These barriers are of different kinds: economic/financial (high renovation costs, insufficient incentives and subsidies, landlord-tenant dilemmas, etc.), technical (ineffectiveness of conventional upgrade solutions, need of regulatory simplification, etc.), organizational (occupants' dislocation and disruption, consensus to the retrofit expenditure by condominium ownerships, excessive time for getting construction permits, etc.), and cultural/social (insufficient information and skills, lack of adequate policy measures for promoting renovation actions).

This book aims to overcome these barriers and to bridge the gap between sustainability and safety, so to conserve both human and environmental resources. It brings together 11 contributions on different seismic and energy renovation measures, proposing technical solutions at district, building, and component level, for both historic and modern case studies.

Finally, I would like to thank the editorial team of *Sustainability* for inviting me to guest-edit the Special Issue on "Energy and Seismic Renovation Strategies for Sustainable Cities" which has been transformed into this book. I also thank all the authors and reviewers for their fundamental contributions.

Giuseppe Margani
Special Issue Editor

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Article

Seismic and Energy Renovation Measures for Sustainable Cities: A Critical Analysis of the Italian Scenario

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Abstract: One of the main challenges of the twenty-first century is to increase the sustainability level of our cities. However, a town, to be considered sustainable, must, above all, be safe, particularly against natural hazards, which in Europe are mostly related to climate changes (e.g., hurricanes, floods, storms, and landslides) and seismic events (earthquakes). Unfortunately, sustainability is still not a prerogative of most European cities, especially those placed in seismic countries such as Italy, where at least 50% of the residential stock is earthquake-prone, while over 80% of the same stock is highly energy-consuming and carbon dioxide-emitting, thus contributing to trigger hazards related to climate changes. In this context, renovation actions, which combine both energy and seismic issues are strongly needed. Nevertheless, several technical, organizational and financial barriers considerably limit the real possibility to extensively undertake this kind of renovation. This study analyzes such barriers, with particular reference to the Italian scenario, suggesting and discussing possible solutions and underlining the advantages of increasing energy and seismic performances at the same time. The proposed solutions may be effectively extended to many other countries with similar socio-economic scenarios.

Keywords: seismic retrofit; energy retrofit; sustainability; safety; policy measures; apartment blocks

1. Introduction

Sustainability was not an explicit value until the last quarter of the 20th century; therefore, sustainability performances were not requested in the recent past.

The approach has changed in connection with the intensification of climate change, environmental degradation, overconsumption of natural resources, population growth and pursuit of incessant economic rise. Today, sustainability is instead considered a fundamental quality and a prerogative in any socio-economic context.

According to the definition of the 2005 United Nations World Summit, sustainability is based on three main pillars: environment, society and economy [1]. However, the social dimension, and in particular safety, has often been neglected, especially in relation to the vulnerability of the building stock.

In the last years, the EU has produced big financial efforts to increase the sustainability level of our cities and, in the 2014–2020 budget, over 5% of the European Regional Development Fund has been allocated to sustainable urban development [2–4].

These resources have mainly been driven towards energy efficiency and low-carbon measures, to reduce the energy bills and the hazard risks related to climate-change (e.g., hurricanes, floods, storms, landslides, desertification, melting of glaciers and sea level rise) that may cause significant damages and life losses. Special attention has been paid to existing buildings, which are responsible for about 40% of the final energy demand and therefore represent a great opportunity for energy saving and decarbonization [4–6]. In particular, renovation activities have been privileged over new constructions to limit urban-sprawl and soil consumption, according to the European aim to achieve no net land take by 2050 [7].

However, less effort has been made to reduce the seismic vulnerability of the existing real estate, mostly due to the high rate of European countries that are not listed as earthquake-prone (Figure 1). Consequently, the sustainability level of towns placed in seismic areas remains inadequate, since most buildings and infrastructures are unsafe, i.e., not sufficiently earthquake-resistant.

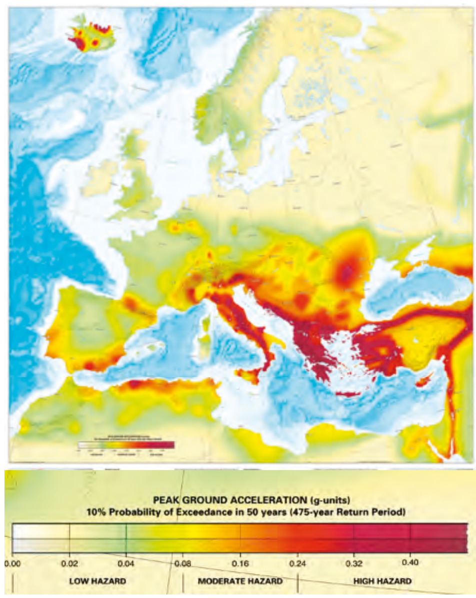

Figure 1. European-Mediterranean seismic hazard map [8].

In such areas, energy renovation actions must be synergistically combined with seismic retrofitting, for two main reasons: (a) to prevent life losses and damages caused by earthquakes; and (b) to avoid several costs otherwise duplicated, for instance those for building-site setup and scaffolds, as well as for cladding, plasters and other finishing [9]. As illustrated by Belleri and Marini, in the case of energy refurbishment only, the risk of a building located in seismic regions can be equalized to an additional annual embodied equivalent CO_2 that almost equals its annual operational CO_2 [10].

Nevertheless, several barriers considerably limit the real possibility to extensively undertake combined retrofit actions, especially for multi-owner housing and high-rise buildings. These barriers are of different kinds: (i) technical (e.g., unfeasibility and/or ineffectiveness of conventional retrofit solutions, and need of regulatory simplification); (ii) financial (e.g., high renovation costs, "split-incentive"/"landlord–tenant dilemma", and insufficient incentives and subsidies); (iii) organizational (e.g., temporary alternate accommodation for occupants, consensus to the retrofit expenditure by condominium ownerships, and excessive time to obtain building permits); and (iv) cultural/social (insufficient information and skills, and lack of adequate policy measures to promote renovation actions).

According to this general premise, this study intends to fill the gap existing in the scientific literature regarding combined seismic and energy renovation strategies and, in particular, aims to: (a) outline the scenario of seismic vulnerability and energy performance of the Italian residential building stock, with particular reference to that built during 1950–1990; (b) review and discuss the barriers which limit the concrete possibility to extensively undertake combined seismic and energy retrofitting interventions; and (c) suggest and discuss possible countermeasures to overcome such barriers and promote combined renovation actions.

The proposed countermeasures, which will be discussed with specific reference to the Italian reality, may be effectively applied also in other countries with similar hazard scenarios and socio-economic backgrounds, contributing to effectively enhance the sustainability level of their towns.

2. Seismic Vulnerability of the Italian Building Stock and Current Renovation Strategies

2.1. Seismic Vulnerability

Along with Greece, Turkey, Bulgaria, Romania, Iceland and most Balkan states, Italy is listed among the most earthquake-prone European nations (Figure 1). In these countries, the seismicity is not as high as in the Pacific coast of the Americas or in some Asian regions such as Japan, Indonesia, Philippines, Mongolia, Pakistan, Nepal, or China. Nevertheless, telluric shakes often produce in Europe significant damages for the high vulnerability of the building stock and the considerable value of that large portion classified as historic architectural heritage.

The seismicity of the Italian peninsula is due to its geographic position at the convergence of the Eurasian and African tectonic plates. The relative movement between these plates causes energy accumulation and deformations that are occasionally released in the form of earthquakes of different magnitude. The highest seismicity is concentrated in the central and southern part of the country, along the Apennine chain, in Calabria and Sicily, as well as in some northern regions, such as Friuli-Venezia Giulia.

Since 1974, Italy has been progressively classified into seismic zones, based on past earthquakes intensity and frequency. The last seismic classification map, updated in 2015, has catalogued 44% of the territory and 36% of the municipalities as highly hazardous, i.e., with a peak ground acceleration (PGA) value > 0.15 g (zones 1, 2, 2A, 2B of Figure 2) and a 10% chance of being exceeded in 50 years [11]. More in detail, nearly 3 million people live inside areas exposed to a very high-hazard level (zone 1; 0.25 g < PGA $\leq$ 0.35 g), while 18.8 million in areas exposed to a high-hazard level (zone 2, 2A, 2B; 0.15 g < PGA $\leq$ 0.25 g), i.e., globally 21.8 million people live in highly earthquake-prone municipalities, that is around 36% of the whole Italian population (Figure 3).

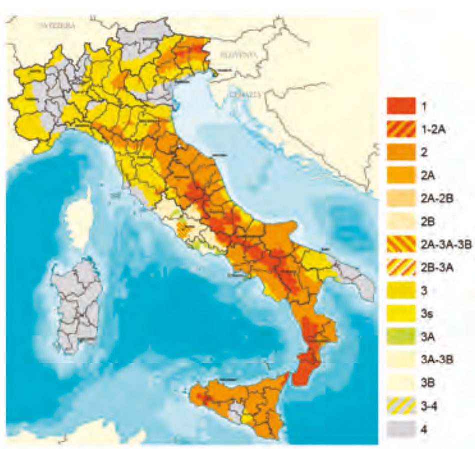

Figure 2. Seismic classification map of Italy (2015), with indication of seismic areas according to PGA values [12].

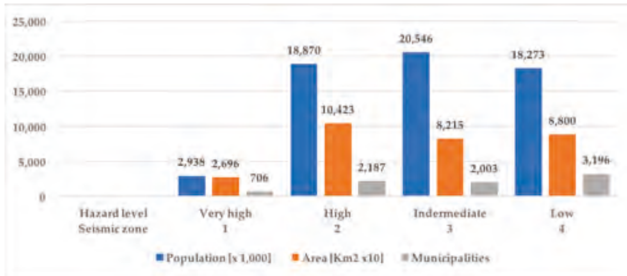

Figure 3. Distribution of the Italian population, area and municipalities over different hazard levels/seismic zones [11].

According to the 2011 census of the Italian national statistical institute (ISTAT), around 2/3 of the existing residential stock was built before 1974 (Figure 4), i.e., before the enforcement of Law 64/1974 [13], which represents the first specific and extensive code for earthquake-resistant buildings in Italy. This code applied only to new edifices included in the seismic classification map that has been progressively updated by releasing revised versions. Therefore, after 1974, a great number of Italian municipalities, now included in the map, were not yet classified as seismically vulnerable. Consequently, even after 1974, a significant number of edifices have been designed neglecting the above-mentioned code.

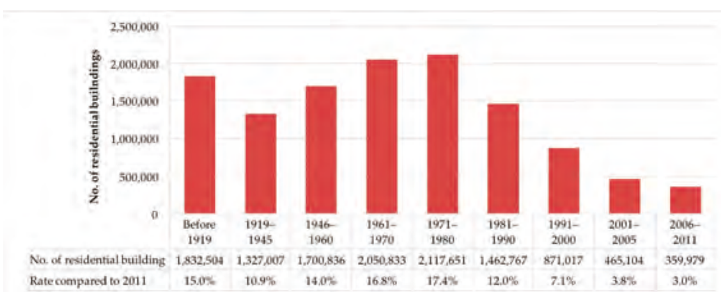

Figure 4. Historical growth of the residential building stock in Italy (data from 2011 ISTAT census [14]).

The same census also reported that nearly 1.8 million residential buildings erected before 1974 (i.e., 15% of the overall stock) lie in a poor or mediocre state of conservation, as shown in Table 1.

Table 1. Number of residential buildings by age and state of conservation (data from 2011 ISTAT census [14]).

	Poor	Mediocre	Good	Very Good	Total
Before 1919	74,561	441,737	896,196	420,010	1,832,504
1919–1945	53,159	348,766	672,771	252,311	1,327,007
1946–1960	36,389	375,174	940,919	348,354	1,700,836
1961–1970	20,126	320,106	1,209,616	500,985	2,050,833
1971–1980	11,533	221,145	1,254,545	630,428	2,117,651
1981–1990	5422	104,265	800,786	552,294	1,462,767
1991–2000	1743	25,896	334,992	508,386	871,017
2001–2005	542	6718	108,670	349,174	465,104
2005–2011	566	3960	46,791	308,662	359,979
Total	204,041	1,847,767	6,265,286	3,870,604	12,187,698

Based on this premise, estimating that at least 8% of the post-1974 building stock has been realized out of the seismic codes and considering that, according to Figure 3, around 70% of the Italian territory is included in areas exposed from a very high to an intermediate-hazard level (zones 1, 2 and 3), today over 50% of the Italian residential buildings (i.e., nearly 6.4 million) are not earthquake-safe and need urgent actions to improve their seismic resilience.

In the last 2500 years, Italy has been hit by over 30,000 earthquakes of medium-high intensity (>IV–V degree of the Mercalli scale), and approximately 560 of VIII intensity or more (nearly one every 4.5 years). The last century has witnessed seven earthquakes with a maximum Moment Magnitude Scale (MMS) greater than or equal to 6.5 (i.e., between X and XI degrees of the Mercalli scale) [15]. In comparison with other countries, in Italy, the ratio between the damage caused and the energy released by earthquakes is particularly high, due to the high population density and the vulnerability of the building stock.

To perceive the socio-economic consequences of the seismic vulnerability of Italian cities, it must be highlighted that, in the last 50 years, earthquakes have caused around 5000 deaths and over €150 billion damage [16]. To these figures, one should also add significant psychological consequences, whose effects might be overcome by the whole community only after several decades.

In this sense, the earthquake that struck the region of Abruzzo in April 2009 is emblematic: with a maximum MMS of 6.3, this earthquake caused 308 deaths, over 1500 injuries, nearly 70,000 homeless, and over €10 billion damages [17]. Today, seven years after, the beautiful and beloved historic center of L'Aquila—capital of the Abruzzo region—is still ruined, since both State and private investors have not yet found sufficient financial resources for its reconstruction. In similar conditions are many other neighboring towns that have been hit by the same earthquake. Recently, from August 2016 to January 2017, a new series of earthquakes with a maximum MMS between 6.0 and 6.5 hit several regions of central Italy, killing 333 people and devastating entire towns, with more than €23 billion damages [18].

Considering the priorities, it must be pointed out that the financial efforts for seismic retrofit interventions have to be primarily allocated to infrastructures and strategic public buildings, but it is also extremely important to upgrade the residential stock, because it is generally more continuously inhabited and, consequently, produces the highest number of deaths in case of seismic events.

According to this scenario and considering the high frequency of earthquakes in Italy, the seismic retrofit of the existing building stock represents an imperative, since it allows to consistently reduce the extent of damage and the number of victims.

2.2. Current Seismic Retrofit Strategies

Today, there are two main types of seismic retrofit strategies for edifices with reinforced concrete (RC) structure [19], which in Italy represents the building standard since the 1950s:

- strengthening of the existing structure with conventional techniques (jacketing with RC, steel, or fiber-reinforced polymers) and/or addition of extra structural members (pillars, shear walls, beams, foundations) [20,21]; and
- installation of base isolators and/or energy dissipation devices [22–25].

Another possible renovation measure consists in installing an external steel braced frame, which partially wraps the building and reduces its oscillations through energy dissipation devices applied between the nodes of the old and the new structure. Nevertheless, the adoption of this solution is restricted to limited cases, since it is mostly suitable for isolated edifices and generally requires a considerable strengthening of the existing RC frame too.

Historic and listed buildings, which in Europe account for around 30% of the current stock [4], need dedicated solutions, due to conservation issues and the variety of building fabric [26]. These edifices in Italy generally have unreinforced masonry bearing walls and, according to their fabric and their cultural value, they request different seismic-retrofit interventions, such as application of anchoring and tying devices, mortar injection, overlay of RC or fiber-reinforced polymer layers, bracing (e.g., steel sections, reinforced masonry, buttresses), insertion of internal or external frames, post-tensioning of unreinforced masonry walls.

A detailed overview and description of the above-mentioned strategies goes beyond the scope of this work.

3. Energy Performance of the Italian Building Stock and Current Renovation Interventions

3.1. Energy Performance

As for many other countries, in Italy, the household and tertiary sector is the most energy-consuming one, accounting for 37.7% of the overall demand (Figure 5). To reduce the energy need of this sector, in the last decade the Directive on the Energy Performance of Buildings (EPBD) has effectively promoted the increase of the energy performance especially for new buildings.

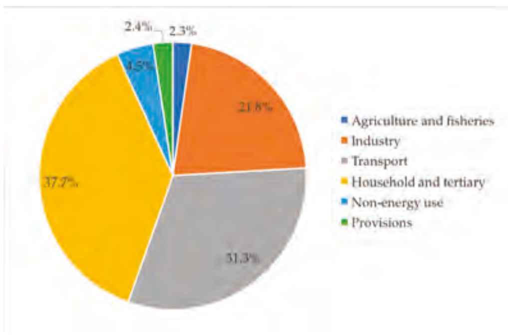

Figure 5. Final energy consumption by sector in Italy (Data from Italian Energy Balance 2016 [27]).

However, new buildings have little influence on the overall demand, since their incidence on the whole building stock is very low. Nowadays, new edifices increase the existing stock on average by less than 1.5% every year (Figure 6), while the demolition rate is estimated around 0.2–0.5% per year [4,28]. Therefore, nearly 85% of European building stock predicted for 2030 has already been built.

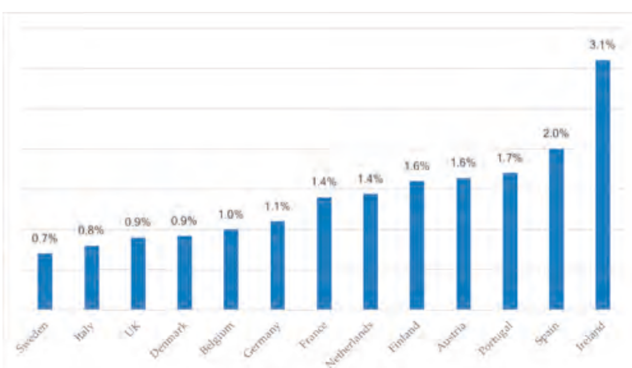

Figure 6. Annual growth rate of new buildings added to the existing stock by nation [28].

These data suggest the need to improve, above all, the performance of the existing building stock to reduce energy consumptions and greenhouse gas emissions. This applies particularly to Italy, whose edifices are, in general, performing badly. Indeed, here the first regulation concerning the reduction of energy consumption for buildings was issued in 1976 [29], but it was low-restrictive and often neglected, due to insufficient controls. The first effective and comprehensive legislation was only introduced in 1991 [30], when 86% of the current residential stock had been already built (Figure 4). For this reason, today, most Italian edifices are characterized by an annual heating demand ranging from 140 to 220 kWh/m^2 (Figure 7) [31–33], i.e., significantly over the limits set by current laws. Consequently, they need urgent energy retrofitting measures.

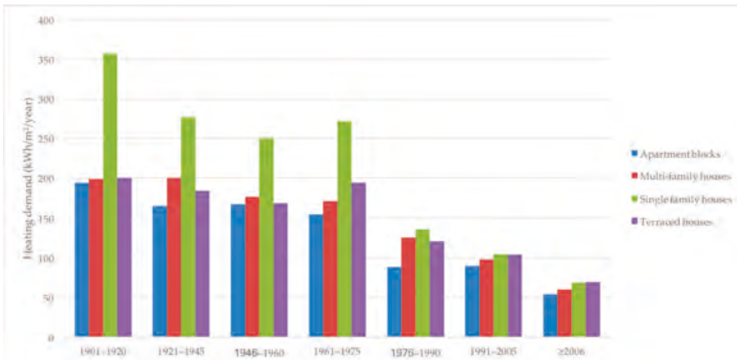

Figure 7. Heating demand by different building types and age groups in Italy (kWh/m^2/year) [33].

According to the National Energy Balance 2016, in Italy, 76% of the energy demand is covered by fossil fuels (Figure 8), which are mostly imported. This overdependence, along with bad energy performances, lead not only to high energy bills, but also to excessive greenhouse gas and pollutant emissions. Of course, excessive greenhouse gas emissions contribute to global warming and climate changes, which may cause the aforementioned hazardous events. These events, like earthquakes, may produce consistent damage and life losses, thus any effort to reduce their incidence should be promoted.

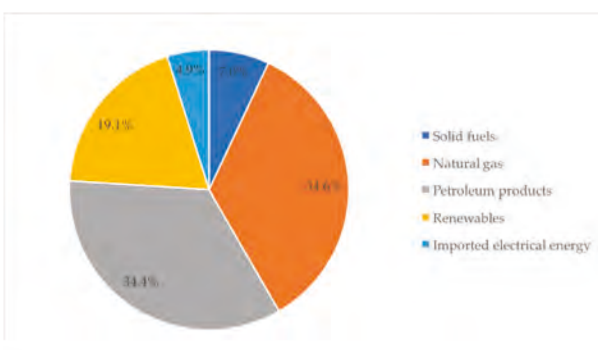

Figure 8. Energy mix in Italy (data from Italian Energy Balance 2016 [27]).

The decarbonization potentiality of energy retrofitting is undoubtedly relevant, both in Italy and in Europe, as highlighted by studies of the Fraunhofer ISI, which have predicted that energy-upgrade measures in the household and tertiary sector might reduce the overall final energy demand by 25% in the year 2050 [34–36].

Apart from environmental issues, the inability of households to adequately heat or cool their homes, due to continuously rising energy costs, may also produce significant social consequences. Houses with poor thermal comfort have a strong impact on health and consequently on healthcare expenditure. Hence, the social return on investment from energy retrofitting can be relevant too.

Energy improvements are today mandatory in Italy when major renovations are made. In particular, when refurbishment activities involve more than 25% of the building envelope, the thermal transmittance (U) of the envelope and the efficiency of the heating and cooling system must be considerably improved [37]. If the retrofitting involves the entire building envelope, the current regulation also imposes the installation of renewable energy source (RES) systems [38]. Anyway, it is necessary to respect specific U-values of the envelope components in order to take advantage of the actual fiscal incentives [39].

3.2. Current Energy Retrofit Interventions

Nowadays, there are two main solutions for enhancing the energy performances of buildings [40]:

- to reduce energy consumptions; and
- to promote the energy production on site through Renewable Energy Source (RES) systems.

The first solution is generally addressed by increasing the thermal resistance of the building envelope (e.g., application of insulating layers on walls and roofs, and replacement of the existing windows with high-performing ones), by providing sun shading devices, by improving the air-sealing (in particular for cold climates), by exploiting bioclimatic resources (solar radiation, night ventilation, etc.), by improving the efficiency of Heating, Ventilating and Air Conditioning (HVAC) equipment, and by changing operational schedules.

The second strategy, which is often combined with the former one, is mainly accomplished by installing solar panels (photovoltaic, PV, and/or solar thermal, ST), which today represent one of the most cost-effective solutions for energy production on site, especially in southern and central Europe, where sun-based RES systems turn out to be quite efficient [41–43].

Both strategies may also be optimized and interconnected by a Building Energy Management System (BEMS), i.e., a computer-based control device that supervises and monitors the mechanical and electrical equipment of the building (e.g., HVAC, RES, lighting and power systems), according to comfort requirements and occupancy regimes. BEMS are currently used mostly for commercial and industrial buildings, but they may be effectively installed also in residential ones.

In addition, in this case, specific solutions should be considered for historic or listed edifices, which present valuable facades not suitable for external insulation application or conventional RES system installation [44,45]. These buildings generally need non-invasive retrofit techniques, such as insulating and/or phase-change-material plasters, internal wall insulation [46–51], specific solutions for PV or ST integration, etc.

As in Section 2.2, a detailed analysis of the energy retrofit strategies is here omitted.

4. Barriers to the Seismic and Energy Renovation of Residential Buildings

This section will now consider the technical, financial, bureaucratic, cultural and organizational barriers that might affect combined seismic and energy retrofitting strategies.

The analysis will focus on the Italian residential stock realized from the 1950s to the 1980s, which accounts for around 60% of the current real estate (Figure 4). Historic or listed edifices are here not included, since for them the retrofit interventions are too closely connected to each specific case and the relative costs are hardly predictable and generalizable.

The principal potential obstacles that may affect this kind of strategies are listed and discussed below.

4.1. Technical Feasibility of Renovation Interventions

The principle of sustainability generally leads to prefer renovation activities over demolition and reconstruction practices [52–55], since renovation may keep and reuse many building components (e.g., foundations, structural frame, walls, floor slabs, etc.)—saving resources and reducing waste—and limit urban-sprawl and soil consumption.

However, in particular, seismic renovation can sometimes be technically unfeasible or not recommendable. This applies especially to the edifices in a very poor state of conservation, with weak and carbonated RC and/or affected by significant design or construction errors (e.g., inadequate load-bearing structure, faulty concrete composition and/or compaction). For such buildings, any retrofitting measure may turn out to be ineffective, both from the technical and the economic point of view. In this case, the most sensible solution would be to demolish and reconstruct the edifice.

4.2. Cost of Seismic and Energy Renovation

Costs have usually a key role in undertaking renovation actions. Retrofitting expenditures strongly depend on many variables, such as state of conservation, type of selected intervention, number of stories, total floor area, plan irregularities, presence of adjacent buildings, local seismicity, soil type, local prices for materials and labor, etc.

Recent studies have calculated the costs for the combined energy and seismic retrofit of apartment blocks, which represent one of the most frequent building types constructed in Italian urban areas in the considered period (1950–1990) and, above all, the most inhabited one [33]. With reference to the renovation strategies described in Sections 2.2 and 3.2, this cost currently ranges from 100 to 230 €/m^3, i.e., between 30,000 and 70,000 € for a 100-m^2 apartment [56–60].

The main contribution to these renovation costs is due to the seismic component that ranges from about 50 to 150 €/m^3. High expenditures, along with a difficult access to capital and an unwillingness to incur debt, often discourage building owners from supporting seismic renovation practices, especially taking into account that it is uncertain when and where telluric shakes will occur. Therefore, owners might tend to believe that earthquakes will spare their families and properties and consequently to repress eventual prevention activities.

Moreover, families with low incomes have often dwellings with poor seismic and energy performance. This circumstance reduces the opportunity of undertaking renovation actions even for the buildings with the highest seismic vulnerability and decarbonization potential.

4.3. Temporary Alternate Accommodation for Occupants

In many cases, renovation activities imply the necessity of emptying and leaving the housing during retrofitting works, which may last for several months. This entails a relevant disruption to the occupants, additional rental costs for an alternate accommodation, a stressful interruption of everyday routines (especially for elderly and disabled people), as well as psychological concerns about the real and timely conclusion of the refurbishment works.

4.4. Insufficient Awareness and Skills

Building owners are often unaware of the real seismic vulnerability and energy performance of their dwellings.

In particular, with specific reference to the seismic vulnerability, as stated before, they might tend to assume that earthquakes are unlikely events, which will occur in a distant future, after their death. Therefore, unless they are driven by the emotional push of a recent devastating seismic event, they are often inclined to neglect the relevant efforts necessary for a seismic renovation. In addition, energy performance issues are also usually ignored by building owners, who often do not monitor their energy consumption and costs, do not fully comprehend the effectiveness of specific retrofitting technologies, and might not be keen in learning about renovation options.

Moreover, seismic and energy retrofitting works and related financial or fiscal incentives require a specific knowledge and expertise, while there is a lack of advice agencies, skilled professionals (architects, engineers, auditors) and qualified constructors [61,62].

There is also a strong need of simple and reliable decision-making tools to compare different seismic and energy retrofitting scenarios and select the best option in terms of costs, available incentives and financial aids, improved seismic and energy performance, thermal comfort, increased property value, and reduced disruption to the residents.

4.5. Consensus to Retrofit Expenditure by Condominium Ownership

This barrier may represent the most relevant one, particularly in countries like Italy, where the property of multifamily buildings is largely fractioned. In this case, it will be difficult to find a consensus for expensive and demanding renovation initiatives among all the owners, especially for demolition and reconstruction scenarios, which entail risks and concerns in switching to a new solution. In addition, personal dislikes related to past disputes may further complicate decision making.

This issue becomes even more relevant when buildings involve different occupant typologies, i.e., both owner-occupants and tenants.

Moreover, in the case of a short decision time-frame, owners might neglect the best choice for the building performance and instead opt for solutions that suit their personal situation. For instance, elderly people are often not willing to engage in renovations, and the same may occur to tenants or owners who expect to move soon elsewhere [63].

Even if the approval of renovation works in Italy is legally insured by absolute majority (i.e., >50%, see Table 2), substantial practical difficulties arise every time that one or more owners dissent, especially if they do not have sufficient financial resources. Dissenters may severely delay decision making or even jeopardize technically necessary retrofitting activities.

Table 2. Share of required majorities for decisions on renovations [63].

	Austria	Bulgaria	Czech Republic	Germany	Finland	France	Italy	Romania	Spain
Required majority for decision on renovation	>50% of share, but minority rules	>67% of area	>75% of votes	>75% of shares	>50% of shares	>50% of shares	>50% of shares	>67%	>50% of shares

Far easier is the circumstance of single-owned multifamily buildings, which do not present consensus concerns.

4.6. "Split-Incentive Barrier"

In the case of rented properties, the most relevant issue is represented by the so-called "split-incentive barrier" or "landlord–tenant dilemma": energy costs are paid directly by tenants and landlords are not driven to invest in efficient building systems; conversely, if landlords pay energy expenses (gross leases), tenants will have little incentive to save energy in their leased space [32,63–65]. Moreover, if the building is rented out, also specific seismic renovation interventions will often be neglected, since landlords are not driven to invest money for supporting tenants' safety. In this case, the government, which is responsible for financing healthcare and reconstruction activities due to catastrophic events, is the subject that mostly benefits from preventing and limiting earthquake consequences.

However, in countries such as Italy, Spain, Romania and Bulgaria, where more than 70% of the families live in property homes (Table 3), "split-incentive" issues are less relevant in comparison with countries such as Austria or Germany, whose share of owner-occupancy in multifamily housing is below 25%.

Table 3. Share of owner-occupancy in multifamily housing by nation [62,66].

Austria	Bulgaria	Czech Republic	Germany	Finland	France	Italy	Romania	Spain
23%	90%	79%	24%	50%	26%	72%	96%	86%

4.7. Bureaucratic Obstacles

Italian building owners and professionals also have to face an endemic and structural problem: bureaucratic obstacles. Several months frequently elapse to obtain a building permit, especially for renovating protected or listed edifices. This is mostly due to confusing regulations, which often overcomplicate the procedure, to the fragmentation of competences among many different agencies (responsible for architectural design, structures, listed buildings, etc.), and to the inertia of the offices in charge of releasing permits.

Moreover, the access to fiscal incentives, which will be illustrated in Section 5.1, is for some aspects complicated. For instance, it is now necessary to follow two distinct and parallel procedures for seismic and energy renovation, increasing the likelihood of making mistakes and consequently of missing the incentives.

Over the last years, some simplifications have been adopted to accelerate procedures, but the results are still unsatisfactory.

5. Possible Countermeasures and Discussion

In this paragraph, possible solutions for overcoming the barriers considered in the previous section will be reviewed (in case of existing measures), suggested (in case of novel ones) and discussed.

5.1. Financial and Fiscal Incentives

According to the prices previously indicated, nowadays the combined seismic and energy retrofitting of a standard 100-m^2 apartment in Italy costs on average around 50,000 € (i.e., about 165 €/m^3). This is a relevant amount that turns out to be unaffordable for most people; thus, costs often represent the most relevant barrier. Hence, a solution that in the past years has shown satisfactory results in Italy consists in granting fiscal incentives, such as tax credit and VAT reduction. These incentives represent supporting measures, which are usually preferable and more effective than coercive regulations that would impose renovation actions without meeting the real needs and the public acceptance.

In particular, in Italy, since 1998, the government has been offering tax credits, allowing subtracting 36–65% (with a gradual increase over the years) of refurbishment costs (project management included) from the tax due, with deductions equally distributed over 5 or 10 years (according to the beneficiary's age) [67–70]. In 2017, these shares have been consistently enhanced until 2021, especially for apartment blocks: 75–85% for seismic upgrades (according to the reached seismic vulnerability), with deductions distributed over five years [71], and 70–75% for energy upgrades (according to the reached energy performance), with deductions distributed over 10 years [69]. For all these costs, the current regulation also allows reducing VAT from 22% to 10% [72].

Moreover, the Italian government has recently introduced a further useful incentive: if a beneficiary has a low income and consequently his tax credit turns out to be higher than the tax due, he will able to transfer this credit to third parties, such as construction companies or banks. Actually, with the introduction of this incentive, it is advisable that the deductions will always be distributed over 5 years, instead of 10, avoiding to penalize the assignee. Furthermore, it is desirable that all the fiscal incentives will be extended sine die, confirming the current highest shares (70–85%).

As an alternative to the tax credit and only for energy retrofitting, it is possible to benefit from subsidies to produce thermal energy from RES and to increase the energy efficiency [73]. These subsidies cover 40% of the eligible expenditure, with specific limits for the unit and total costs of each type of intervention. For private buildings, the eligible costs will be refunded in five annual rates.

Taking advantage of these incentives, in particular the tax credit, as well as the reduced energy bill after renovation, the investment for combined seismic and energy retrofitting may be repaid within 10–11 years, as highlighted in previous studies [60]. The investment cost will considerably increase if the installation of RES systems is considered, but according to recent investigations, in mild climates the PBT may reach similar values [74].

A simple PBT of 11 years could be sufficiently attractive from an economic point of view. Anyway, due to the relevant cost of the initial investment, these fiscal incentives alone are often not sufficient to concretely promote both energy and seismic retrofits.

Consequently, public-supported financial measures should also be fostered for low-income people, such as subsidies and/or long-term and low-interest loans. To grant these loans easily, the energy cost savings generated by the energy renovation could also be accepted as a form of collateral [62]. Another financial incentive is represented by feed-in tariffs, which should be further fostered in case of refurbishments that include electricity production from RES.

Nevertheless, it is important to underline that although governments should underpin and stimulate renovation with financial incentives, public funds can only cover a small part of the necessary investment. Therefore, it is necessary to develop sustainable, income-based and attractive schemes to facilitate the engagement of building owners in retrofitting activities, without flooding the market with subsidies.

5.2. Reconstruction Scenarios for Buildings in Poor Conditions

Another significant obstacle concerns the ineffectiveness of any seismic retrofit intervention for buildings in poor conditions. As mentioned in Section 4.1, in such cases the only possible solution would be to demolish and reconstruct the edifice, facing costs that in Italy account for around 400 €/m^3 for apartment blocks, i.e., nearly 2.5 times more than those necessary for refurbishment solutions. Hence, high costs and the necessity of a temporary alternate accommodation for occupants represent here the trickiest issue.

Regarding the alternate accommodation, householders without personal opportunities (second homes, accommodation by relatives or friends) could benefit from public vacant buildings, which should be refurbished (if necessary) and cheaply leased for this purpose. Once this cycle has been concluded, these buildings could be allocated to social housing. Of course, specific guarantees should be promoted to safeguard property owners against unsuccessful or delayed delivery of their dwellings. Otherwise, if the occupants do not request to live in the same building, it is possible to move them into a new one specifically built in another plot, possibly made available from the government, while the degraded one will be demolished and reconstructed on site for the same purpose, triggering a virtuous rotating process that leads the progressive renovation of the building stock.

With reference to the high investment costs, a possible solution consists in creating surplus apartments, whose sale may considerably reduce the final expenditure. For example, it may be destined for sale 30% of the built volume that can be obtained as follows: (a) each owner renounces to 10% of the net surface of his property; (b) the government allows increasing the building volume, for instance by 10%; and (c) the story height is decreased by 10% (in Italy, apartments built during 1950–1990 often have a net floor height of 3 m or even higher, which can be reduced to 2.7 m according to the current regulations). Such measures may contribute to enhance the economic appeal of the operation, to reach consensus in case of multi-owner housing, and to encourage an active involvement of general contractors.

An increase of the building volume, namely a volumetric bonus, is currently allowed under specific circumstances by many Italian municipalities in case of demolition and reconstruction activities that address explicit sustainability targets [75]. An interesting further option consists in the possibility to sell the volumetric bonus to third parties, such as building contractors and construction companies. Moreover, in Italy, the reconstruction of an earthquake-prone building in seismic zone 1 recently benefits also from tax credits, namely 75–85% (according to the reached seismic safety) calculated over a maximum investment of 96,000 € [76]. Nevertheless, negative consequences may arise from the resulting increase of urban density; therefore, municipalities should provide new areas for complementary urban services (schools, parking lots, green areas, etc.).

5.3. Information and Engagement Campaigns

Information and engagement campaigns are recommended to achieve a behavioral inclination towards more sustainable choices and decisional strategies for energy efficiency and seismic safety. These campaigns should be encouraged by municipalities and involve housing associations and administrators, which require a preliminary support and training for suggesting appropriate retrofit scenarios for the buildings they represent or manage. Schools also play a relevant role in creating safer environment and should be actively involved to obtain an effective and widespread educational and awareness process.

Another useful information and engagement tool consists in promoting free visits of demonstration buildings (e.g., through guided tours or open-door days), which can play as a virtuous model for a seismic and energy renovation.

As an alternative to public actions, contractors could directly include a decision-support package in their service, even if they might not be perceived as impartial and clients could be unwilling to pay for this extra assistance.

It is also crucial to develop simplified and user-friendly decision-support tools for assessing the seismic vulnerability and the energy performance of buildings and for choosing the best alternative, as already specified in Section 4.4. To this purpose, the EU has already promoted several calls for proposals within the Horizon 2020 funding initiative, while, in some countries (e.g., Finland, Germany, France, and Switzerland), financial aids have been specifically offered for supporting energy audits [61].

5.4. Regulatory Instruments

An effective way for promoting building renovation is the imposition of a seismic label to rate the seismic safety of an edifice. This label has been recently adopted in Italy [71] and works likewise the energy one, which has been already imposed by the EPBD to rate the energy performance.

However, thus far, the energy performance certificate for the sale or rental of buildings has still had little effect on the market price of the real estate [77]. To increase the value of the renovated stock, the seismic and energy label should also be supported by a new taxation for real estate transactions, which should be indexed according to the reached performance.

Moreover, governments should promote mandatory insurances to cover damage from natural hazards, with premiums based again on the same label. Considering the recent history, natural hazards are not extraordinary events (see Section 2.1) and they must be insured, like usual accidents. The risks faced by the insurance company in case of earthquakes or other natural hazards can be opportunely alleviated through new security tools, like the catastrophe bonds (namely "cat bonds"), which allow transferring some of these risk from the insurance company to investors [78]. More in detail, an insurance company issues bonds and sell them to investors through an investment bank. If no catastrophe occurs, the company will pay a coupon to the investors. On the contrary, if a catastrophe does occur, then the investors will lose part or all of their principal, which is used to pay the claim-holders.

An additional useful measure is represented by a compulsory establishment of a renovation fund, in order to collect money for future retrofitting activities. In Germany, a renovation fund as high as 1% of the building value has been already activated [62], but this rate is usually too little to cover expensive interventions like seismic upgrades. Fund rates should be determined according to the seismic vulnerability and energy performance of the considered edifice.

Finally, particularly in Italy, a substantial regulatory simplification, both for seismic and energy renovation actions, is necessary to avoid bureaucratic trammels and to accelerate the procedure to obtain the building permit. In the light of this simplification, also the access to fiscal incentives has to be streamlined, developing a unified procedure for combined seismic and energy renovations.

5.5. Consensus to the Retrofit Expenditure for Multi-Owner Housing

As indicated in Section 4.5, for multi-owner housing, it is often difficult to find consensus for renovation works, since many residents are not well informed, do not attend assemblies regularly and have conflicting interests. Moreover, condominium assemblies do not only involve financial, technical and legal issues, but also imply interpersonal and psychological problems.

In such uncertain situations, a possible solution may consist in engaging external parties—such as municipal agencies, housing associations, structural and energy consultants—to support and speed up decision making. In fact, condominiums may take advantage of a step-by-step technical and organizational supporting process, which can be moderated by external and impartial professionals.

To reach consensus, a useful contribution can be given by solutions that minimize the disruption to the occupants during the renovation works. This may be achieved trying to operate mainly from the outside of the building, promoting the use of prefabricated components [79], and concentrating the inner interventions in a short period. The works must be organized by proceeding from the foundation level to the top of the edifice, operating progressively floor by floor.

5.6. "Split-Incentive Barrier"

In the case of both renovation and reconstruction, the "split-incentive barrier" plays a significant role, as illustrated in Section 4.6. A possible countermeasure to this problem consists in revising contracts to permit landlords to raise the rent of the retrofitted or rebuilt property, with an increase commensurate with the reduced energy bill paid by tenants and the enhanced seismic performance.

Anyway, apart from a possible contract review, it should be underlined that, due to the renovation activities, landlords will nevertheless benefit from an asset of greater value and able to survive catastrophic events, as well as from the possible exploitation of tax incentives. Moreover, the money saved by tenants on energy costs will leave more money left over for rent, reducing defaulting circumstances. Finally, especially in a competitive rental market, a seismic-safe, low-energy and thermally-comfortable building will have better chances to be well rented or sold.

Consequently, the "split-incentive barrier" might be overcome simply through appropriate and accurate information campaigns, which illustrate all the benefits related to seismic and energy renovation actions.

6. Conclusions

Seismic and energy renovation of buildings represents today a prevention action that is becoming more and more necessary to increase the sustainability level of our towns. It will allow reaching very relevant benefits, at environmental, social and economic levels. In particular, in the case of earthquakes or natural hazards related to climate change, this action will decrease the number of deaths, injuries, and disabilities, as well as the tragic social and psychological consequences for those who will lose their beloved ones; it will also consistently reduce damages and the related economic efforts for repair and reconstruction activities. Furthermore, it will contribute to lower the carbon dioxide emissions, increase the property value, decrease the energy bill, improve the dwelling comfort and healthiness, refresh the architectural image of towns, boost the building market and the employment rate, and consequently increase consumption, gross national product and tax revenue. A positive psychological sensation of life security and welfare may also be taken into account.

Nevertheless, today private owners are often not sufficiently motivated to undertake seismic and energy renovations, mostly due to the significant economic effort, occupants' disruption, and problematic decision-making that this kind of intervention usually implies. Hence, national governments must directly intervene, especially with specific supporting measures, which are generally more preferable than coercive ones.

First, national governments must lead by example upgrading public buildings, adopting state-of-the-practice standards that safeguard the edifices as well as the environment, and providing substantive, performance-based guidelines. Moreover, several further measures have here been suggested, which can be summarized as follows:

- Extend sine die the fiscal incentives (tax credit, VAT reduction, and feed-in tariffs), with the current highest shares (70–85%) and with transferable deductions distributed over five years;
- Foster long-term, low-interest loans and subsidizes for low-income people.
- Grant transferable volumetric bonuses and fiscal incentives, in case of demolition and reconstruction actions, extending these benefits also to other seismic zones.
- Provide permanent or temporary public alternate accommodations in case of demolition and reconstruction.
- Develop easily accessible information about seismic vulnerability and energy performance of buildings, as well as user-friendly decision-support tools to select the best renovation option.
- Index the taxation of the real estate market according to the seismic and energy label.
- Promote mandatory insurances for covering damage from natural hazards, with premiums based on the previous label.
- Establish a reserve fund for renovation.
- Simplify regulations to accelerate the implementation of renovation activities.
- Develop a single procedure to access fiscal incentives for combined seismic and energy upgrades.
- Engage external parties to support and speed up decision making for the refurbishment of multi-owner housing.
- Develop renovation techniques and methods that minimize occupants' disruption.

Prevention is essentially a matter of mindset and culture [80]. Since European countries have a great tradition and culture, the basic premises for developing a prevention attitude and reaching proper economic and technical solutions are all there.

However, wide engagement actions, at both local and European level, are fundamental to raise awareness of the social, environmental and cultural relevance of prevention actions, and to achieve consensus and behavioral change towards decisional strategies for both energy efficiency and seismic safety.

In this context, schools, universities and research institutes play a crucial role, stimulating institutions and political forces to strongly promote and encourage the upgrade of the building stock.

This virtuous circle is possible, as well shown by the movement for the restoration of historic cities that has originated in Europe and afterwards has reached a correct conservative profile, producing brilliant results of urban rebirth, which are clearly evident in Italy as well as in many other countries.

Today, similar results could also be obtained for the renovation of modern buildings, without aggravating the public debt that has now reached unsustainable levels, not only in Italy but also in Europe and in most other developed countries. Hence, it will also be essential that private householders invest personal capital and that the Government act as guarantor, regulating the subject and, as mentioned above, granting substantial financial and fiscal incentives.

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Review

Seismic and Energy Renovation: A Review of the Code Requirements and Solutions in Italy and Romania

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Abstract: Most European cities are characterized by very large areas, often formed by buildings of low quality, from a series of perspectives (architectural, technological, materials, technical systems, etc.). The possibility of renovating them is strategic to improve both the quality of life and to the possibility of economic recovery for building companies. In the last decades, the attention of the scientific community has been addressed to the energy renovation, thanks to the strong activities of the European Community in this field. However, since a relevant part of the EC territory is at risk of earthquake, the possibility to combine both energy and seismic renovation actions may be strategic for many countries. In particular, Italy and Romania are linked by a common social tradition that springs from the Roman Empire. Nowadays, this link is stronger, thanks to common interests in social, cultural and business fields. Therefore, the investigation of possible synergies for seismic and energy renovation strategies may be really interesting for both countries. In this paper, after an overview of regulations and common practices for buildings with reinforced concrete structures, in both states, some key combined renovation interventions will be described and discussed, as well as advantages and perspectives of integrated renovation approaches. The outcomes of this work are to show the way to transform existing energy-consuming and seismic-prone buildings into energy-efficient and seismic-resistant ones.

Keywords: building rehabilitation; energy efficiency; seismic reinforcement

1. Introduction

Most European cities are characterized by large urban areas, built after the II World War and formed by edifices that often show low standards of quality. The renovation of these districts represents a strategic issue to improve the quality of life and to foster the recovery of the building sector.

In the last decades, the attention of the scientific community has been driven mainly to energy retrofitting, thanks to the strong activities of the European Community in this field. However, a significant number of EU regions is earthquake-prone, as it has been unfortunately shown even in recent time in Greece (2008, 6.4 Mw and 2015, 6.5 Mw), in Serbia (2010, 5.3Mw) and in Spain (2011, 5.1 Mw) [1], as well as in Italy and Romania, as described in detail in Section 2. So, the opportunity to combine energy and seismic renovation turns out to be crucial for many countries.

Italy and Romania, whose real estate is highly energy-consuming [2] and seismically vulnerable [3], may play a breakthrough role.

This paper will review both traditional and innovative renovation interventions devoted in Italy and Romania to enhance the seismic and energy performance of recent buildings, that is, erected from the 1950s through the 1980s, which are generally characterized by reinforced concrete (RC) or steel load bearing structures. The goal is to show the way to transform existing energy-consuming and seismic-prone buildings into energy-efficient and seismic-resistant ones.

Historic edifices [4], that is, built before 1950, need specific measures [5–7] and are not considered in this paper.

2. State of Art

2.1. Overview of Technical Regulations in Italy in Relationship with Earthquake Vulnerability

The classification of the Italian territory in areas with different levels of seismic hazard started in 1909, after the devastating earthquake that hit the cities of Messina and Reggio Calabria in 1908. The district of Messina and the whole Calabria region were classified as earthquake prone areas and the explicit consideration of the seismic excitation in the design of buildings located in these areas became mandatory [8]. The effect of the earthquake was simulated by equivalent horizontal forces [9]. The level of seismic resistance to be provided to the structure was set to avoid the collapse on the occurrence strong ground motions but damage of structural members caused by such extreme events was admitted. The classification of new seismic areas generally followed the catastrophic events that struck the country over time; for instance, after the Avezzano earthquake in 1915, a portion of the central area in Italy was classified as earthquake prone [10]. Other important seismic events that anticipated the classification of new seismic areas are those that occurred in Abruzzo and the southern area of Marche (1943), the central area of Calabria (1947), Carnia (1959), Velina valley (1961), Irpinia (1962), Monti Nebrodi (1967), Belice valley (1968), Tuscania (1971), Friuli (1976), the southern area of Calabria, Patti gulf (1978), Valnerina (1979) and Irpinia-Basilicata (1980). Today, the whole country is considered earthquake prone and the expected level of seismic excitation is given based on the geographic location of the site (Figure 1). Unfortunately, the most considerable growth of the building stock in Italy took place in seventies when the application of seismic provisions was not mandatory in most of the country. As a consequence, most of the existing buildings supported by a RC frame, which represents the most common technology in Italy [11], have been designed without considering seismic provisions and are affected by important structural deficiencies. In these buildings, resisting elements are mainly arranged in one direction, which makes the structure weak and flexible in the orthogonal direction. Furthermore, the structure if often low ductile at both global and local level, because it tends to form story collapse mechanism and ductile detailings of structural members are missing. Finally, the situation may be aggravated by the use of low quality or time degradation of materials. The seismic upgrading of these buildings is of paramount importance for the safety of the population and the resilience against earthquakes [11].

The Italian Building code provides specific sections for existing buildings. More in detail, provisions for seismic assessment and retrofitting of existing buildings are reported in Section 8 of the "Norme Tecniche per le Costruzioni" (Technical rules for constructions, NTC08) enforced in 2008 [12] and in the relevant section of the associated Commentary [13]. In addition, Section 11 of the Ordinance n. 3431 [14] emanated in 2005 still applies when not in contrast with NTC08. The Italian code is fully consistent with the European building code, which provides the regulations on existing buildings in Eurocode 8 part 3 (EN 1998-3) [15]. Finally, EN 1998 as implemented by means of the relevant National Annexes [16] is also applicable in Italy. The code provisions for existing buildings in force in Italy (i) regulate the procedure for the identification of the structural system and its geometric/mechanical features, (ii) define the methods of analysis and their limits of application and (iii) provide instructions for the execution of the safety verifications.

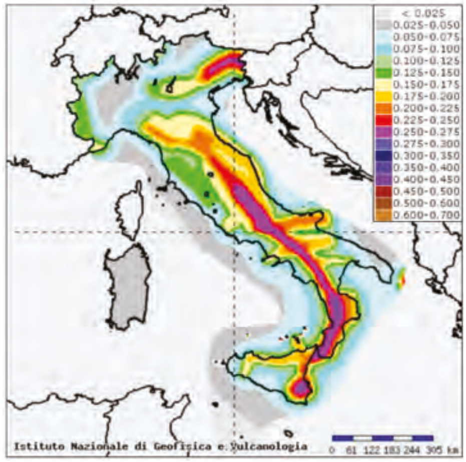

Figure 1. Italian seismic hazard map for probability of exceedance of 10% in 50 years, Peak Ground Acceleration (PGA) in g.

2.2. Overview of Technical Regulations in Italy in Relationship with Energy Performance Requirements

In Italy, the firs regulation for the reduction of the energy consumption in buildings was issued in 1976 (Law 373/1976) [17] but it was low-restrictive an often unattended, due to inadequate controls. The first effective code addressing thermal performance criteria was issued only in 1991 (Law 10/1991) [18], when over 80% of the current residential stock had been already built [19]. Consequently, most of the Italian real estate is highly energy-consuming [20].

According with its geographic characteristics, Italy has a large variety of climatic conditions (Figure 2) and so, the approach to the energy renovation problems, is very different, along the peninsula. As a simplification, in the northern regions, where the heating demand is prevailing, it is necessary to highly insulate the building envelope [21], while in the southern ones, where conversely the cooling demand is predominant, it is important to take advantage of natural ventilation, external sun-shading devices and massive walls [22,23].

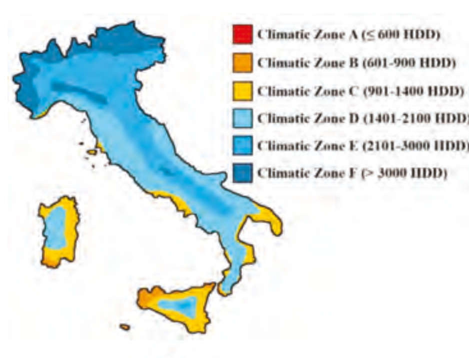

Figure 2. Italian climatic zones, according to the heating degree-days (HDD).

Today, a recent directive regulates the energy efficiency of new and existing buildings: the Inter-ministerial Decree 26/6/2015 [24].

With particular reference to renovation actions, this directive classifies three levels of interventions:

a. *relevant renovations of first level*, which involves more than 50% of the building envelope, as well as the upgrade of the heating and/or cooling system;
b. *relevant renovations of second level,* which involves 25/50% of the building envelope and may involve also the heating and/or cooling system;
c. *energy requalification*, which involves less than 25% of the building envelope and/or the upgrade of the heating and/or cooling system.

In case of interventions (a), the renovated building must have the same energy performance of a new building. In particular, the energy performance must be higher than that of a theoretical so-called "reference building" that has the same location, orientation, use and geometry (shape, volume, surfaces, etc.) of the real building but is characterized by the following U-values for each envelope component (Tables 1 and 2):

Table 1. Thermal transmittance values [W/m^{2}K] for the envelope components of the "reference building," currently in force.

Building Components	Climatic Zone				
	A, B	C	D	E	F
Exterior walls	0.45	0.38	0.34	0.30	0.28
Windows	3.20	2.40	2.00	1.80	1.50
Roofs	0.38	0.36	0.30	0.25	0.23
Ground slab	0.46	0.40	0.32	0.30	0.28

Table 2. Thermal transmittance values [W/m^{2}K] for the envelope components of the "reference building," in force from 1 January 2019 for public buildings and from 1 January 2021 for all the other buildings.

Building Components	Climatic Zone				
	A, B	C	D	E	F
Exterior walls	0.43	0.34	0.29	0.26	0.24
Windows	3.00	2.20	1.80	1.40	1.10
Roofs	0.35	0.33	0.26	0.22	0.20
Ground slab	0.44	0.38	0.29	0.26	0.24

For interventions (b) and (c) the energy performance requirements to be verified regard mainly the thermal characteristics of the portion of the building envelope interested by the renovation works and/or the efficiency of the upgraded systems.

In particular, for (c), the g-values of the windows oriented from East to West (passing through South) must be not higher than 0.35, while thermal transmittance of the renovated components of the building envelope must be not higher than the following values (Tables 3 and 4):

Table 3. Maximum values of the thermal transmittance [W/m^{2}K] of the building envelope components, currently in force.

Building Components	Climatic Zone				
	A, B	C	D	E	F
Exterior walls	0.45	0.40	0.36	0.30	0.28
Windows	3.20	2.40	2.10	1.90	1.70
Roofs	0.34	0.34	0.28	0.26	0.24
Ground slab	0.48	0.42	0.36	0.31	0.30

Table 4. Maximum values of the thermal transmittance [W/m^{2}K] of the building envelope components, in force from 1 January 2019.

Building Components	Climatic Zone				
	A, B	C	D	E	F
Exterior walls	0.40	0.36	0.32	0.28	0.26
Windows	3.00	2.00	1.80	1.40	1.00
Roofs	0.32	0.32	0.26	0.24	0.22
Ground slab	0.42	0.38	0.32	0.29	0.28

For (b), it is necessary to address the limits set for (c) and, in addition, the transmission heat loss coefficient H'_T of the renovated portion of the building envelope must be not higher than the following values (Table 5):

Table 5. Maximum values of the transmission heat loss coefficient H'_T [W/m^{2}K].

Climatic Zone				
A, B	C	D	E	F
0.73	0.70	0.68	0.65	0.62

Moreover, according to the Legislative Decree 28/2011 [25], if the energy renovation involves the entire envelope (external walls, windows, roofs and ground slab) of buildings with a net floor area over 1000 m^2, at least 50% of the energy demand for heating, cooling, Domestic Hot Water (DHW) and electricity must be covered by Renewable Energy Sources (RES).

Finally, according to Law 90/2013 [26], from 2019 all new public buildings and from 2021 all new buildings must reach the nearly Zero Energy Building (nZEB) standard. Of course, this applies also to relevant renovations of first level (a).

2.3. Overview of Technical Regulations in Romania in Relationship with Earthquake Vulnerability

The seismic hazard of Romania (Figure 3) is dominated by the Vrancea intermediate depth earthquakes in south-east of the country. This source affects with high intensities ca. 50% of the territory and is felt with quite important damaging effect on very large areas in neighbouring countries, at each strong event. Romania is a country that is periodically subject to such destructive Vrancea earthquakes, as most recently in 1940 and 1977 [27]. Other crustal (shallow) earthquakes can generate locally very high intensities, with a strong tendency of concentration in west and north.

The November 10, 1940 Vrancea earthquake had a magnitude $M_{G\text{–}R}$ = 7.4 (converted at present at M_w = 7.6–7.7) with an epicentral intensity assessed as 10 MCS. The March 4, 1977 Vrancea earthquake had a magnitude $M_{G\text{–}R}$ = 7.2 (converted at present at M_w = 7.5) and caused damage to a large area and to a variety of buildings. The Building Research Institute (INCERC) seismic record of 4 March 1977 pointed out, for the first time, the spectral content of long period seismic motions of Vrancea earthquakes, the duration, cycle number and higher values of actual accelerations versus code ones, with important effects of overloading upon flexible structures [27–30]. As a consequence of the INCERC record, the spectral curve (the dynamic coefficient β_r), from the P13-1970 Code (which became P100-78), as well as the seismic zonation map of Romanian Standard STAS 2923-63 have been radically changed, with increase of base shear forces. Since then, all areas are seismic.

The new seismic design codes P100-1991, revised 1992, introduced a seismic zonation with two maps, one in terms of seismic coefficient (related to PGA) and another in terms of corner period of the design spectrum, with 3 values. The return period of the map was different in function of the source type.

The procedures for the harmonization between national and European regulations in the field of civil engineering started in Romania in the mid-1990s. Prior to its accession to the European Union (on 1 January 2007), Romania has also followed tightly the programme for the adoption of Eurocodes as national standards [31–33]. The Romanian Seismic Design Code P100-1/2006 has prepared the adoption, starting from 2011, of the homologous EN 1998-1, as the Romanian standard SR EN 1998-1, together with its National Annex for Romania and has represented an essential factor in the transition to European norms. The P100-1/2006 Code implements important elements of progress with respect to its previous version, P100-92. The zoning map was set with a return periods of 100 years [31]. The P100-1/2013 Code, introduced a map with 225 years return period. Currently Peak Ground Acceleration (PGA) from 0.10 g to 0.40 g are compulsory by the zonation map (Figure 3) [32]. A zonation map with 475 years return period map (EC 8 level) was not yet endorsed, being considered necessary an interval for stakeholders' adaptation.

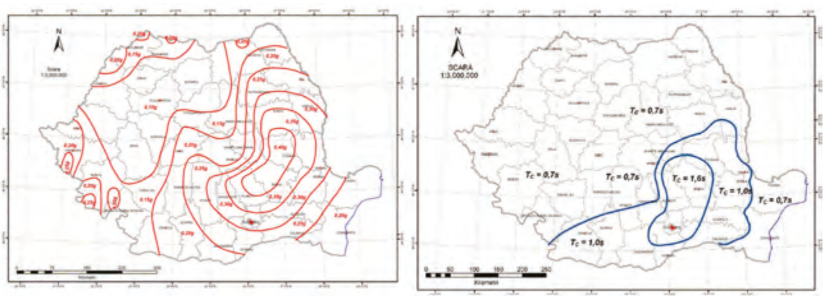

Figure 3. Left: The seismic zoning map of Romania (PGA) for a mean recurrence interval of 225 years and 20% exceedance probability in 50 years. **Right**: The seismic zoning map of Romania in terms of Tc—corner periods of the response spectrum (Code P100-1/2013, UTCB [32]).

The Romanian code for the seismic assessment of existing buildings, P100-3/2008, includes several notions and concepts from its European homologue, EN 1998-3. However, Code P100-3 preserves a quantitative approach, based on seismic risk indices, as in code, P100-92 (chapters 11 and 12) and is based on a three-tier approach, similar to that of the ASCE standards [33,34]. The relevant chapters of this code [35] are:

- Generalities; Performance requirements and qualifying criteria;
- Seismic assessment of structures and Non-Structural Components (NSC);
- Collecting the information for structural assessment; Levels of Knowledge (KL1, KL 2, KL3);
- Qualitative assessment; Assessment by calculation (Level 1, 2, 3); Assessment of foundations;
- Final assessment and conclusions;
- Annex A—Performance based seismic assessment of existing buildings;
- Annex B—Reinforced concrete structures; Annex C—Steel structures; Annex D—Masonry structures; Annex E—non-structural components (NSC);
- Annex F (informative)—Guide for seismic rehabilitation of existing buildings (for different materials, energy dissipation systems and base isolation).

2.4. Overview of Technical Regulations in Romania in Relationship with Energy Performance Requirements

Technical regulations for the calculation of the thermal protection of the building envelope have been developed since 1961, with standard STAS 6472-61, revised in 1968, 1973, 1975, 1984 (when there is a major change in the insulation requirements of envelope elements—by normative NP-84), 1989.

In 1997, the technical regulation C107-1997 was developed, based on the European and International CEN ISO standards, revised afterwards [36–38]. It introduced the calculation of the thermal resistance values of the envelope elements (1) taking into account the correction due to the effect of thermal bridges (R′, which is the inverse thermal transmittance, U-value, of a building element), evaluated by the linear thermal transmittance ψ and point thermal transmittance χ (Figure 4). R is the thermal resistance of flat, unlimited elements and A is the area of the considered building element.

$$R' = \frac{1}{U'} = \frac{1}{\frac{1}{R} + \frac{\sum \psi \cdot \ell}{A} + \frac{\sum \chi}{A}} \quad (1)$$

The calculation of a global heat loss coefficient G of buildings has been introduced, whereby the thermal performance of a building envelope can be assessed by imposing a GN norm ($G \leq GN$). The heating energy requirement for buildings in Romania can be judged by the global thermal insulation coefficient G and the average G, as follows:

- 1950–1985—1.00 W/m^3K
- 1986–1997—0.80 W/m^3K
- 1998–2010—0.55 W/m^3K

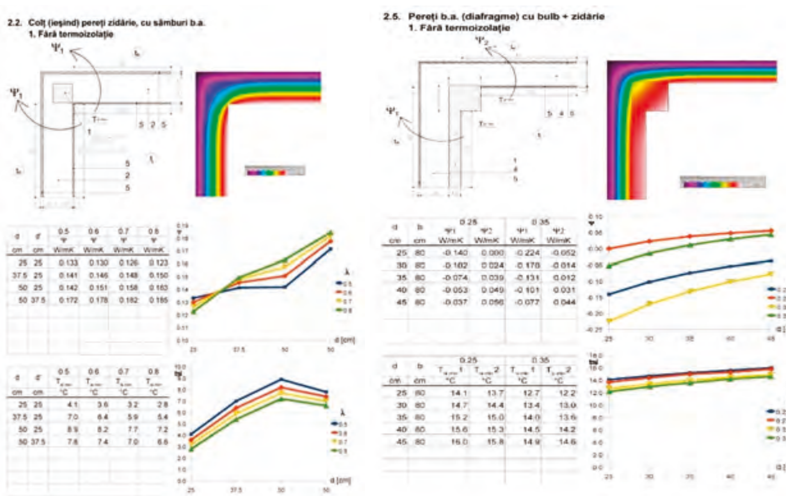

Figure 4. Extract of a thermal bridges catalogue, showing the linear thermal transmittances ψ of a corner with an embedded, uninsulated reinforced concrete (RC) member (column or shear wall) [39].

The climate zonation map in force has 5 zones with design temperatures for Winter (from −12 °C to −24 °C) (Figure 5 [40]).

According to 2011 Census, the existing buildings stock of Romania has some 5.3 million buildings, including 8.7 million conventional dwellings. Standardized apartment blocks have a share of up to 70% of the existing housing stock in some urban areas.

Existing apartment blocks with large panel structure (over 35% of the total number of blocks until the 1990s) that according to the level of the achieved thermal protection are divided into two categories:

- apartment blocks built according to standard projects until 1985 (approximately 30% of the built stock) mostly with 5 or 9 stories, having an average G-coefficient of about 1 W/(m^3K)/average thermal resistances of only 0.6–0.5 m^2K/W, which have to be thermally insulated as first measure in energy renovation;
- apartment blocks with 5 stories and 9 stories erected after 1985 according to standard projects (about 7% of the total built stock) based on the provisions of Decree 256 and NP 15 Normative with a medium thermal resistance increased to about 0.9 m^2K/W, characterized by an average global thermal insulation coefficient G of about 0.8 W/m^3K.

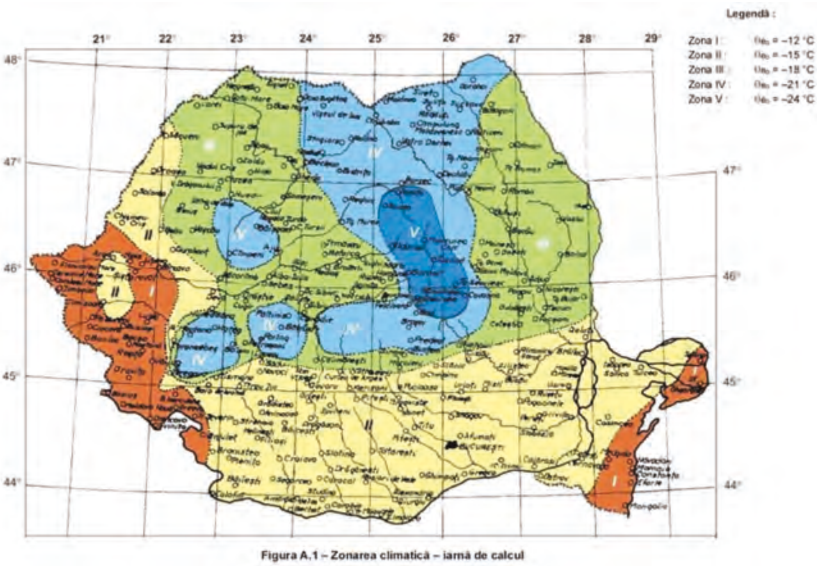

Figure 5. Climatic zonation map of Romania—Winter design temperatures [40].

Structures made of masonry predominate numerically in the dwelling buildings; even in Bucharest. Meanwhile, their number has increased throughout the country.

The level of thermal protection of buildings from the existing building stock corresponds, independently of the structural system used, to the specifications and exigencies imposed during each period, by the technical regulations for the calculation of the thermal performance of the envelope elements. According to each generation of the technical regulations, as well as to the technological level specific to the period, there are groups of buildings with the same level of thermal protection, regardless of the materials used to build the building envelope.

The share of energy consumption in the annual energy balance of an average apartment built between 1970 and 1985 is: heating energy 55.5%; DHW 9.5%; drinking water 1.4%; consumption of natural gas for the preparation of food 9.7%; electricity consumption for lighting 13.9%. Out of the annual energy consumption of a building irrespective of its destination, the heating energy and DHW production represents the main annual energy consumption of about 75% [40].

The implementation of the European Parliament's Energy Performance of Buildings Directive (EPBD 2002/29/EC, EPBD 2010/31/EC) is also being carried out in Romania in compliance with the provisions of Law no. 372/2005 modified and completed later. A calculation methodology for energy performance of buildings (including the energy certification of buildings and energy audit) was initially based on several norms (2001), later on incorporated in a comprehensive one 2006 [41] and is currently under review. Some other technical guidelines for buildings thermal rehabilitation have been developed, as well as a Catalogue of thermal bridges [39].

For all new buildings it is already mandatory, since 2007, to present the energy performance certificate at the reception of the executed work. For existing buildings that are being rehabilitated, expanded or upgraded, such a certificate must be drawn up. For apartments in residential buildings, the energy performance certificate of the building is mandatory for sale-purchase or lease, from 2010. For public buildings, the energy performance certificate must be exposed at the entrance.

The minimum thermal resistance—R'_{min} and thermal transmissions—U'_{max} of the building envelope elements (taking into account the effect of thermal bridges), on the whole of the dwelling buildings, designed on the basis of the design contracts concluded after 1 January 2011 [42] is presented in Table 6.

Table 6. The minimum thermal resistance—R'_{min} and thermal transmissions—U'_{max} of the building elements, on the whole of the dwelling buildings, designed on the basis of the design contracts concluded after 1 January 2011 [42].

Nr. Crt.	Building Components	Residential Buildings	
		R'_{min} [m^2K/W]	U'_{max} [W/m^2K]
1	Exterior walls (excluding glazed surfaces, including adjoining walls of open joints)	1.80	0.56
2	Windows	0.77	1.30
3	Top slabs above the last level, under terraces or attics	5.00	0.20
4	Bottom slab over unheated basements and cellars	2.90	0.35
5	Walls adjacent to closed joints	1.10	0.90
6	Slabs that delimit the building at the bottom, from the outside (in the bow-windows, passage gangs, etc.)	4.50	0.22
7	Slabs on the ground (over ground level)	4.50	0.22
8	Slabs at the bottom of heated semi-basement or basements (under ground level)	4.80	0.21
9	External walls, under ground level, of heated semi-basement or basements (under ground level)	2.90	0.35

The Energy Performance of Buildings Directive, issued in 2002 and revised in 2010 (EPBD 2010/31/EC) and the European Directive on the use of RES (RESD 2009/28/EC), were the basis for the drafting of country strategies and government policies, transposed into national laws. The National Plan [43,44] includes the long-term energy efficiency strategy at national level, based on existing legal framework and programs establishing the contribution of the state, the local administration and the owners and specifies the necessary documentation and eligible type of actions. The definition of nZEB in Romania was detailed by the MDRAP Order 386/2016 by officially specifying the performance levels in terms of the maximum admissible level of primary energy from fossil sources and of CO_2 emissions resulting from the operation of buildings—by building types and winter climate zones in Romania (Figure 5). The levels will be applied mandatory for all new buildings starting from 2021. The maximum allowed value of the primary energy use (thermal and electric energy supply processes), determined by cost optimal calculations based on reference buildings vary according to the winter climate zoning of Romania (values between brackets correspond to the average climate zone for Romania): 98 to 217 (111) kWh/m^2yr for single-family residential buildings, 93 to 135 (100) kWh/m^2yr for multi-family apartment buildings, 45 to 89 (57) kWh/m^2yr for office buildings. In order to ensure the total energy use of a nZEB, energy from RES shall account for at least 10% of the total calculated primary energy of the building.

As intermediary performance values until the enforcement of nZEB obligations for new buildings, the MDRAPFE Order No. 2641/2017 recently established (for the first time in Romania) minimum requirements in terms of maximum primary energy consumption for heating (only). The limits (max primary energy for heating in kWh/m^2yr) vary from 60 for office buildings to 117 (large residential), 149 (hospital) and 153 (small residential). This time, the requirements are applied both for newly built and existing buildings undergoing major renovation.

3. Seismic Resistance Assessment and Structural Strengthening

3.1. Italian Relevant Seismic Codes and Expertise on Seismic Strengthening of the Existing Building Stock

The identification of the structural system is of paramount importance for a proper assessment of the structure and for the design of retrofit interventions. In fact, usually designers do not know the mechanical features of the materials, size and arrangement of the structural members and quality of structural detailing. Hence, information on these aspects have to be collected from the available documentation, analysis of the codes in force at the time of construction, field investigations and in-situ and/or laboratory measurements. Based on the completeness and reliability of the collected information, the structure is assigned to one of three "knowledge levels": limited knowledge (KL1), normal knowledge (KL2) and full knowledge (KL3). The knowledge level of the structure determines method of analysis and numerical model that can be used for the evaluation of the structural response and the values to be adopted for the confidence factors [45] in the safety verifications.

Linear or nonlinear methods of analysis and modelling can be used for the evaluation of the seismic response of the structure. The choice depends on the achieved knowledge level of the structure. Linear structural analysis model (Linear numerical Model analysed by Lateral Force Analysis or Multi-modal Response Spectrum Analysis [46,47]) must be used for knowledge level KL1, while nonlinear structural analysis model (Nonlinear numerical Model analysed by Nonlinear Static Analysis [48,49] or Nonlinear Time-History Analysis [50–52]) may be used if the knowledge level achieved by means of the preliminarily inspection of the structure is KL2 or KL3. Since the collapse mechanism of an existing structure is not known a priori, any member may yield and there is no distinction between dissipative and non-dissipative members. Hence, nonlinear models and methods of analysis, which are able to detect the collapse mechanism and predict the inelastic demand of the members explicitly, should be preferred to the linear ones when applicable.

Criteria for safety verification are given separately for RC, steel, composite and masonry structures. Furthermore, for each type of structure, the Italian code provides two sets of criteria: the first set applies if the seismic response to be assessed has been determined by linear methods of analysis, whereas the second one is used in combination with nonlinear methods of analysis. Criteria for linear methods of analysis are rather conservative to compensate for the low level of accuracy of these methods. Furthermore, the conservativism of the criteria for safety verification is also controlled by the values of the confidence factors, which modify the strength of the members to be considered in the verification. A lower knowledge level means a higher degree of uncertainty of the features of the structure, which is compensated by the use of larger values of confidence factors.

If the seismic response of the structure does not fulfil the standard required by the code, the gap should be filled by seismic upgrading [53]. Increasing the safety level of the building against collapse is the primary goal of retrofit interventions. However, a reduced damage of structural and non-structural elements in the occurrence of moderate earthquakes and a limited disturbance to the occupants of the building during the realization of the retrofit interventions should be considered as further important goals in the choice and application of the retrofit technique. Many strategies may be embraced to pursue these objectives. The most classical way is to increase the strength and/or ductility capacity of the structure at global or local level. For instance, the (global) lateral strength of the structure can be increased by adding new seismic-resistant elements, for example, RC shear walls or steel braced frames. The new resisting elements should be properly connected to the existing structure and stiff enough to draw part of the seismic force. Alternatively, the strength can be increased locally by interventions on individual structural elements; for example, concrete or steel jacketing [54] as well as Fibre Reinforced Polymer (FRP) plating and wrapping [55] can be used to improve the flexural and/or shear strength of RC members. Furthermore, these interventions also allow the enhancement of the ductility capacity of RC members through the confinement of concrete.

An alternative retrofitting solution is to reduce the seismic demand of the structure by base isolation [56–59]. First, columns are cut off from foundation; then isolators are installed between column bases and foundation. These measures elongate the fundamental period of the structure and thus drastically reduce the seismic force on the structure. This strategy is very effective but cannot be used when the building to be upgraded is contiguous with other buildings. Furthermore, its effectiveness decreases with the aspect ratio. Seismic demand can also be reduced by using dampers [60]. Many kinds of dampers (hysteretic, viscous, viscoelastic, etc.) [61–65] are available on the market and can be embedded in the structure [66–68] or inserted between the structure to be retrofitted and an external reaction structure [69]. Dampers dissipate part of the input energy provided by the earthquake, thereby reducing the displacement demand of the structure. As an example, Figures 6 and 7 show two retrofit interventions on schools in Italy. In particular, Figure 6 shows the retrofit intervention carried out at the school Cappuccini located in Ramacca at about 50 km from Catania by means of Buckling Restrained Braces (BRBs). The school was condemned owing to a severe crack pattern present in the non-structural elements after the earthquake that stroke the eastern part of Sicily in 2002. The building was built in the 1970s and endowed with RC moment resisting frames designed for gravity loads only. The BRBs were inserted in the early 2000s to reduce the seismic action effects on the existing structure and dissipate part of the input seismic energy. The BRBs were inserted within some frames located in the central part of the building [70]. Figure 7 instead shows the retrofit intervention carried out at the school Gentile-Fermi located in Fabriano at about 70 km from Ancona by means of viscoelastic dampers [71]. The building was built in the 1950s and endowed with RC moment resisting frames designed for gravity loads only. The school was condemned after an earthquake occurred in 1997. Like the previous structure, that of the school Gentile-Fermi had insufficient resistance to seismic actions and insufficient local and global ductility. Viscoelastic dampers were chosen to dissipate part of the seismic input energy and limit the increase of the lateral stiffness consequent to the introduction of braces. To reduce the interruption of the functionality of the construction, the viscoelastic dampers were inserted within some frames located on the perimeter of the building.

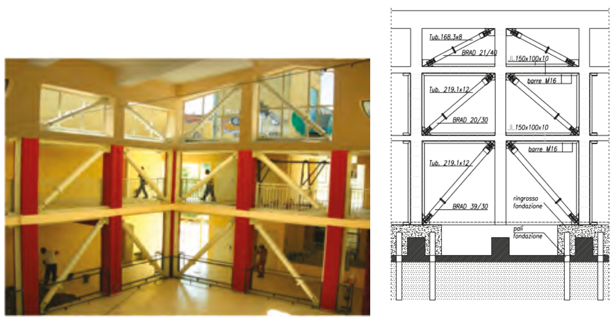

Figure 6. Retrofit intervention by means of buckling restrained braces (BRBs) in the school Cappuccini in Ramacca (Catania).

Figure 7. Retrofit intervention by means of viscoelastic dampers in the school Gentile-Fermi in Fabriano (Ancona) [71].

The retrofit intervention is selected based on the analysis of the structural deficiencies. Often, two or more techniques are combined together to achieve the seismic upgrading of the building [72–79]. The great variety of techniques and the need to combine them together represent a further source of difficulty with respect to the case of new structures, for which the designer needs to select just one structural type among a limited number. As an example of a retrofit intervention in which more techniques are combined, Figure 8 shows the retrofit intervention carried out at the school Varano located in Camerino at about 30 km from Macerata by means of rigid rocking towers and viscous dampers patented by Alessandro Balducci [80]. The school was built in the 1960s and consists of two separate constructions. Both are endowed of RC framed structures. The retrofit intervention was completed in 2012 (in about 7 months) without interruption of the school activities. The intervention aimed at dissipating a large amount of energy by means of the viscous dampers at the base of the towers and leave the RC structural elements to be elastic under moderate intensity earthquakes. The two steel braced towers were connected to the decks by means of steel trusses.

Figure 8. Retrofit intervention by means of dissipative towers and viscous dampers in Camerino (Macerata) [80].

The regulations given in the code are mostly for traditional retrofit interventions, while innovative techniques are not covered by code provisions. This is a gap in the code that will be hopefully filled in the future. Research devoted to standardizing the method of application of these techniques for the seismic upgrading of structures and to formulate design methods for retrofitting interventions able to achieve the performance objectives stipulated in the Italian code are of paramount importance. This research activity could create the background for the new generation of building codes and make innovative technique immediately available. In fact, the Italian building code has been developed in a performance-based framework. The performance objectives are defined through three limit states, namely Near Collapse (NC), Significant Damage (SD) and Damage Limitation (DL). Details on the seismic excitation level that should be considered for the verification of each limit state and acceptance criteria may be found in the relevant part of the Italian building code [13,14] and EN 1998 Part 3 [15]. This allows the use of techniques and design methods that ensure the minimum level of structural safety required by the code, even if these techniques are not explicitly considered in the code.

3.2. Romanian Relevant Seismic Codes and Expertise on Seismic Strengthening of the Existing Building Stock

The experience of 1977 Vrancea earthquake is relevant for the situation of existing built stock in terms of features, vulnerability and risk. The most heavily affected category in 1977 was that of the old tall buildings. This situation may be understood mainly in connection with some features of their structural design, which was without or with reduced seismic requirements. Some urban and architectural planning patterns played a role (irregular shape in plane and on vertical). The damage of 1940 earthquake were not repaired, while from 1940 to 1977 the buildings maintenance was neglected. The old, relatively low and stiff, bearing masonry buildings (Figure 9) have shown, as a rule, a better performance, especially in Bucharest and collapses were noticed in isolated cases. The spectral specific of strong motion was an important factor of overloading or reduced loading [27,28].

Figure 9. Low-rise and mid-rise masonry buildings, after some 80–100 years.

The new apartment buildings, built after 1950, present a wide diversity of architectural planning and of structural solutions, with many solutions used in standardized design for low-rise buildings (up to 5 stories) and high-rise buildings (8 to 18 stories, the most frequent being that of 10–11 stories).

Before 1990, various construction technologies and structural systems, included prefabrication and industrialized forms for cast-in-place concrete. The large panel standardized apartment blocks represented an increasingly important share of the new construction. The performance of these buildings was good or fair in almost all zones for five-story as well as for eight- or nine-story buildings. It is important to say that most of IPCT solutions were tested in INCERC.

The cast-in-place, RC shear wall buildings that present the greatest share among the structural solutions in seismic zones, especially for high-rise buildings, have shown various behaviour patterns, depending on their overall number of stories, on the quality of workmanship and structural solution, as well as on the intensity of shaking. Under such circumstances, five-story buildings have shown a good or fair behaviour, independent of the structural solution adopted (smaller or large intervals between shear walls).

The new RC framed structures, with five or eleven to twelve stories, for which a regular pattern of columns and beams has been provided, have shown generally a much better performance than old buildings (pre-1940) with RC framed structures, for which the place of columns has been an irregular one.

After 4 March 1977, the specialists of INCERC, as well as the great number of civil engineers existing in 1977 in numerous design institutes provided immediate technical guidelines for repair and strengthening. From structural point of view, the most damaged were pre-1940 structures with columns and beams but not moment resisting frames and all other structures designed after 1940's with some seismic code but at more reduced base shear force, as it was the knowledge for each period. But on 30 March 1977 the Government of that time ordered that the existing structures shall be maintained or rehabilitated, nominally, at the initial strength level. On 4 July 1977, it was ordered to make only local repairs. Thus, political orders left Bucharest with a large stock of high-occupancy, high-rise residential buildings that have been damaged by the 1977 (and possibly the 1940) Vrancea earthquake. Most of these buildings, still in use, are at significant risk from future Vrancea earthquakes [30].

The new seismic design codes P100-1991, revised 1992 and 1997, introduced in chapters 11 and 12 the obligation to evaluate buildings and indicate classes of risk, as it is also in Code P100-3/2008, in force, and, if required, to rehabilitate the existing buildings, with some public financing. Buildings of the first class of risk are labelled with a red dot.

By Law, that is, Government Ordinance on Existing Buildings Risk Reduction [81], evaluation of residential buildings resistance (in terms of Code P100-92, later on in Code P100-3/2008) was provided for free, while for design and strengthening works the owner may receive a bank credit at 5% interest up to 20 years, paid by Government; the apartment owners in buildings of first class of risk, with an income under the country average, may receive full subsidies.

For high-rise buildings erected before 1940 (Figure 10), conceived without seismic design, the strengthening means a rather general jacketing of existing frames, from foundations to the top, to become moment-resisting ones, ductile and able to withstand lateral forces. This implies local or general evacuation and relocation of occupants for 1 to 2 years. For other 1950–1977 (Figure 11) structural types, designed for lower seismic loads, interventions may be on some specific members or zones, or on several stories. In such cases, some advanced techniques, as frame bracing could be applied, with less need of evacuation.

Figure 10. High-rise apartment building, with RC columns and beams, infilled with masonry, erected before 1940. **Left side**: a building without visible strengthening or renovation. **Right side**: with local repair, that is, limited and inadequate jacketing of columns, after 4 March 1977 earthquake.

Figure 11. High-rise apartment building erected in the 1970s, having commercial spaces at ground-floor, with visible damages from 4 March 1977 earthquake, before renovation.

4. Current Technologies for Energy Efficiency

4.1. Current Technologies for Energy Efficiency

The current retrofit technologies used in Italy for enhancing the energy efficiency of buildings can be categorized into three main categories:

(i) heating and cooling demand reduction;
(ii) upgrade of the Heating, Ventilating and Air Conditioning (HVAC) equipment;
(iii) installation of RES technologies.

To category (i) belong all the interventions that involve the building fabric: envelope insulation (roof, wall, ground floor) [82], windows retrofits (thermal-break frames, multiple glazing, inert gas filling, low-emission coatings, external sun-shading systems, etc.), cool roofs and coating and increased air tightness. To this group one may also add bioclimatic technologies for exploiting natural resources: solar radiation, natural ventilation, evaporative cooling, etc.

Category (ii) includes mostly the improvement of the heating and cooling systems, for example, by installing high efficiency heat pumps, biomass boilers, geothermal power systems, etc.

Finally, category (iii) embraces the integration of different RES systems, such as solar thermal (ST) collectors, PhotoVoltaic (PV) or hybrid PhotoVoltaic and Thermal (PV/T) panels, wind power micro-turbines, etc. [83–86].

In case of relevant renovations of first level (see (a) in Section 2.2.), in Italy, from 2019 (for public buildings) or 2021 (for all other buildings), it will be mandatory to reach the nZEB standard. In this case further strategies should be necessary in some cases, such as the integration into the building envelope of Phase Change Materials (PCM), the use of low conductivity insulation materials (e.g., aerogel, vacuum insulated panels), as well as the use of Building Energy Management Systems (BEMS) [87–90], that is, computer-based control devices that supervise and monitor the mechanical and electrical equipment (e.g., HVAC, RES, household appliances, lighting and power systems) [91,92], according to comfort requirements, occupancy regimes, energy demand and current electricity price.

For each renovation intervention, the implementation cost and the potential benefits are different. Figure 12 shows the intervention costs versus environmental benefits (reduction of CO_2 emission). It can be observed, that the installation of RES systems may require high investment costs and low environmental benefits. This is mostly due to the high environmental impact of the disposal of some RES systems (e.g., PV, PV/T) [93].

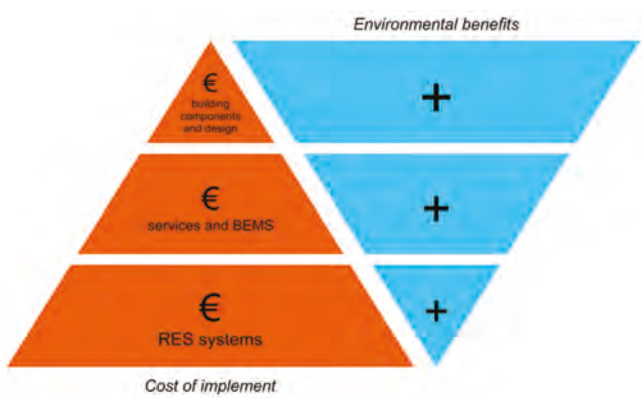

Figure 12. Intervention cost versus environmental benefits.

In Romania, the insufficient thermal insulation of the existing buildings compared to the requirements stipulated in the current thermal regulations is added to the limited seismic resistance of some structural types, as well as a state of degradation of the built part or an advanced wear of the installations. Therefore, many of the buildings requiring energy rehabilitation also need the assessment of the structural resistance and of strengthening scenarios.

The implementation of the Energy Performance Building Directive (2002/91/CE followed by the recast version 2010/31/UE) in Romania, has determined an upgrading of the minimum standards of energy performance of the buildings. It was introduced a methodology for energy balance calculation and an energy performance certificate, both for new and for existing buildings at their rehabilitation moment (Figure 13). Special norms for the inspection of the heating, cooling and ventilation devices were elaborated. Several successive National Programs for the rehabilitation/modernization of the multi-story residential buildings were applied in the last decades. Currently, the attention is directed to public buildings rehabilitation and certification.

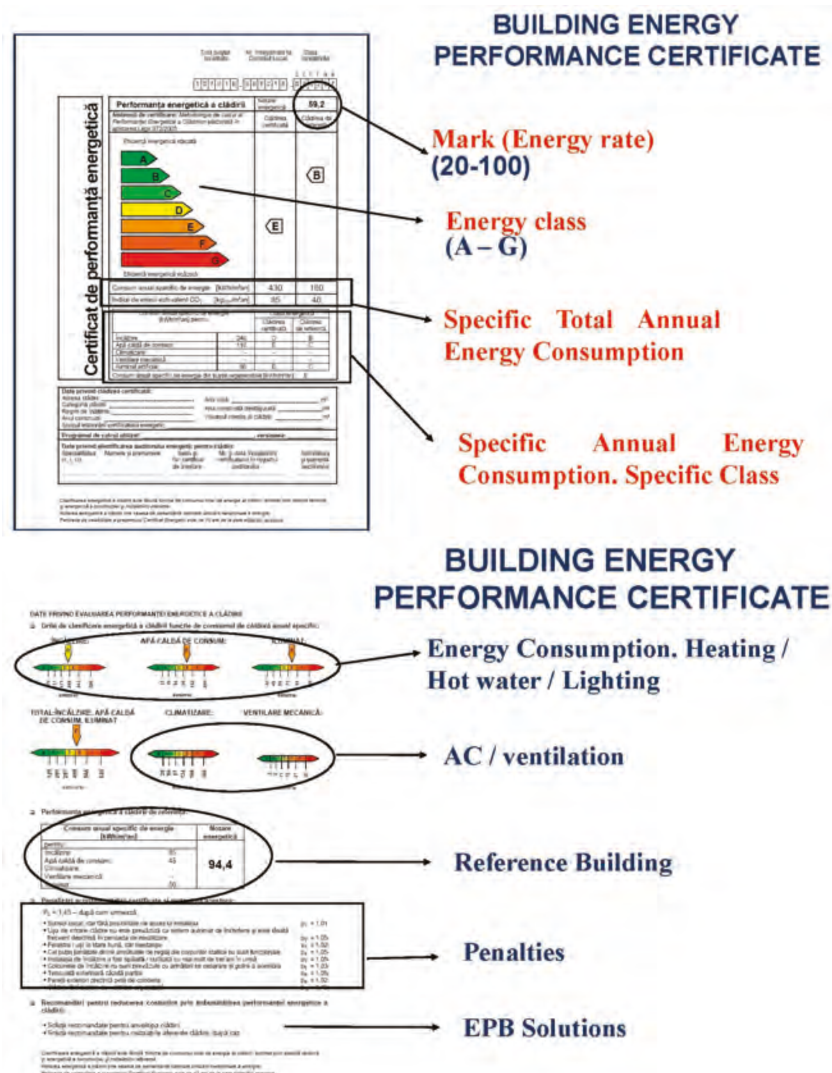

Figure 13. Content of the Romanian Building Energy Performance Certificate [42].

As for the building envelope (opaque components and fenestration), till now, it was applied additional thermal insulation layers using polystyrene or mineral wool plates with thermal conductivity (λ) between 0.030 and 0.045 W/mK (on external walls, roofs, ground slab), in many apartment blocks built during 1950–1990. Maximal values of the thermal transmittance U, for external walls, were U′ = 0.70 W/m^{2}K till 2010 and then U′ = 0.55 W/m^{2}K, taking into account the effect of thermal bridges for each envelope element.

The old types of windows (with wood frames and double glass without any coating) were replaced, in retrofitting programs, with high efficiency double glazing windows with low emissivity coatings, tinted and/or gas filled, having especially PVC frames (U = 2 W/m^{2}K till 2010 and since 2011 U = 1.3 W/m^{2}K). In the last 2–3 windows with triple glazing and low emissivity coatings are provided, having U = 1.1 W/m^{2}K. In general, thermal bridges are taken into account in the calculations and in designing the renovation measures. However, sensitive connections remain with high values of the thermal bridge coefficient, in particular remaining penetration of RC elements in the insulation layer at basement or building foundation and installation of insulating windows in the structural layer (rather than in line with the insulation layer).

With the implementation of the first projects under the National Rehabilitation Program of the Housing Blocks—Condominiums, coordinated and funded by MDRAPFE and the Local Councils of City Halls, a number of new issues emerged.

The choice of technical and architectural solutions to improve the thermal performance of vertical envelopes must be done, in the future, using the optimal cost method and taking into account and controlling all important aspects.

The new approaches, which can be effectively adopted both in Italy and in Romania, are indicated in the following list:

- Ventilated facades (opaque ventilated façades, double skin glass façades, hybrid façades—wall/glass) were provided only for special buildings (offices, hospitals, public buildings, etc.) due to their initial high cost. The curtain walls using special glass were used for office buildings.
- Green walls and green roofs were used sometimes. Solar shading devices—external or internal, were provided without a detailed analysis. Passive solar energy systems like solar greenhouse were studied and provided in some cases.
- Active solar energy systems as PV panels, ST collectors and mixed systems were provided on some demonstration buildings but Building Integrated Photovoltaics (BIPV) in building envelopes are not usual, although used in pilot buildings.

Acoustic performance for the external thermal insulating systems is under study.

For roofs (flat or sloped), technologies to improve ventilation (single or double ventilation layers for sloped roofs), passive cooling (cool roofs), thermal inertia and waterproof (green roofs or cool roofs), RES use, etc., must be provided.

In Figures 14 and 15 some of the main solutions for thermal energy renovation are presented. The legend is common for the 3 figures and the relative numbers indicate: 1—external wall, possibly plastered; 2—efficient thermal insulation layer (EPS, mineral wool, etc.); 3—insulation protection layer (mineral additives mortar, with fibre glass reinforcement); 4—thin external finishing; 5—protective layer against wind; 6—ventilated layer; 7—external cladding with closed joints; 8—damp-proof course; 9—interior gypsum boards/dry plastering.

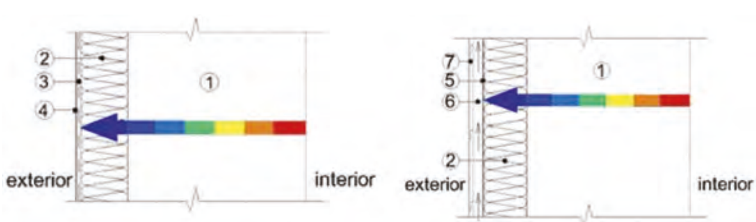

Figure 14. Main solutions for thermal energy renovation of external walls in current field, with external insulation. **Left**: External Thermal Insulation Composite System (ETICS) composite compact structure with protection layer of thin rendering with fiberglass reinforcement. **Right**: ventilated layer structure with protection layer and external cladding fixed trough a metallic frame [39].

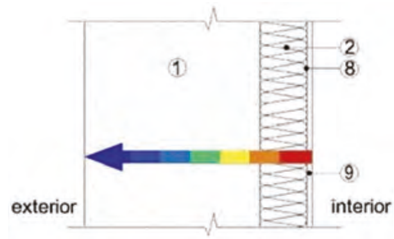

Figure 15. Main solutions for thermal energy renovation of external walls in current field, with internal insulation and finishing of gypsum boards [39].

For the future buildings (nZEB), the most promising and interesting insulating materials are: Aerogel, PCM, Transparent Insulation Materials (TIM), Vacuum Insulating Panels (VIP), organic materials (cork, sheep-wool, etc.), high efficiency windows.

In Romania, the nZEB concept does not seem to be easily applicable yet, in particular in the case of the renovation of existing buildings [94]. Besides the required investments and optimal integration of the technologies suitable for the construction and/or renovation of buildings at nZEB level, one of the main barriers for this consists in the skills gaps experienced by the building sector.

Some projects [95–98] approach this barrier by developing a roadmap for construction workforce qualification to achieve the sustainable energy policy objectives set for Romania for 2020. Thanks to them, mechanisms to supporting the national implementation of large-scale and long-term qualification schemes for thermal insulation systems and high thermal performances windows installers are defined (Figure 16).

Aspects such as the arrangement of the ventilation of the spaces in order to obtain adequate indoor air quality, the repair of the sidewalks, the removal of moisture and mould, the rehabilitation of the waterproofing, the modernization of the balconies and loggias were subsequently explicitly included in the current legislation. The arrangement of extensions and mansard spaces is of interest to a number of investors. The approach aims to provide RES, in order to achieve the cost-optimal energy performance of a building or, rather, of a district of buildings and also the highest indoor comfort by a good thermal insulation, restricting the heating load, the use of air conditioning units and artificial lights.

Figure 16. Practical training facility for nearly Zero Energy Building (nZEB) in the Building Knowledge Hub (Bucharest).

4.2. Common Practice and Current Projects of Energy Renovation in Romania

The compound Prietenia of Sfantu Gheorghe City, consisting of 18 apartment buildings of five stories made of large panels, with 410 apartments, was under energy renovation from 2008 to 2009 (Figures 17–20). The project was done with the consultancy of UAUIM and IPCT Instalatii, in an integrated approach, to address also the architectural and landscape image as local urban issues.

The Prietenia Project allowed an energy reduction of ca. 60% and for this goal the following solutions and technologies have been applied:

- for terrace—EPS 120 of 16 cm thickness;
- for external walls—EPS 80 of 10 cm thickness (XPS 8 cm at socle);
- for slab over basement—EPS 70 of 8 cm thickness;
- for internal walls and slabs of entrance hall EPS 80 of 10 cm thickness;
- thermostatic valves and mixing water faucets, with reduced consumption.

Figure 17. The apartment buildings before renovation, Prietenia compound, Sfantu Gheorghe.

Figure 18. The apartment buildings under renovation, Prietenia compound, Sfantu Gheorghe.

Figure 19. The apartment buildings under renovation, Prietenia compound, Sfantu Gheorghe. Community members were able to choose the colours of renovated facades.

Figure 20. The apartment buildings and adjacent spaces, including playing grounds for children, at the end of renovation, Prietenia compound, Sfantu Gheorghe.

The mass renovation programs in Bucharest (Figures 21–24) and other large cities were quite successful and popular in the view of communities, especially because and when the cost was fully supported by local authorities or from European funds. However, from the point of view of architectural and technical quality the high speed of works and the lack of workers training caused some critics.

Figure 21. Large high-rise apartment buildings in Bucharest, erected in the 1970s, before and after energy renovation.

It is worth to mention that the shear wall structural types of 1970s, although designed to forces lower than current code, behaved satisfactorily in 1977 earthquake and thus they were included in energy renovation projects without other structural upgrading.

Figure 22. Large high-rise apartment building in Bucharest, erected in the 1970s, during energy renovation.

Figure 23. Large high-rise apartment building in Bucharest, erected in the 1970s, after energy renovation.

Figure 24. The UTCB Lacul Tei Students Dormitory building after energy renovation (2007). The first public building with displayed Energy Performance Certificate.

The IR images presented in Figure 25 illustrate the qualitative impact of applying external insulation to the Students Dormitory building, while the previously replaced windows (double glazing aluminium profile, moderate thermal performance) were not improved in the energy renovation.

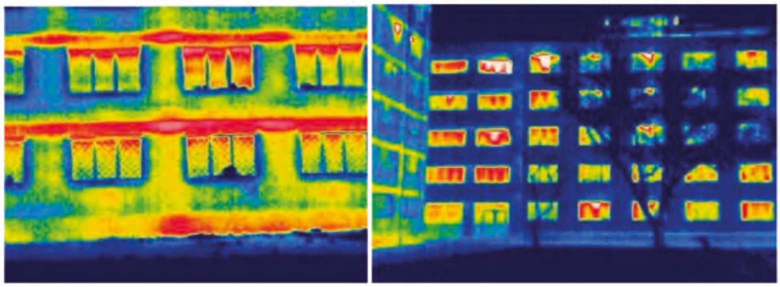

Figure 25. The UTCB Lacul Tei Students Dormitory building. IR thermography images before and after energy renovation (2007).

Based on the JRC study, Romania has one of the 10 exemplary Renovation Strategies (as required art. 4 of the Directive 2012/27/EU), ranked the 3rd at EU level, mainly for having detailed estimations, 4 scenarios, multiple benefits assessed, cost benefit analysis. The biggest source of funding for energy efficiency comes from EU Cohesion Policy Funds, while between 2014 and 2020, Romania intends to allocate more than €1.25 billion to building renovation of residential and public building. The majority of the funds will be used as grants for the building owner/association, covering (some of) the cost of the thermal renovations. However, deep renovations rate remains among the lowest in Europe, while the energy renovation of individual houses is not effectively supported by public funding nor stimulated by actual incentives. Moreover, the energy performance level of current deep renovation is far from the nZEB levels both in terms of design specifications and performance of works (limited insulation, attention to thermal bridges, no mandatory airtightness levels or mechanical ventilation with heat recovery, etc.). Nevertheless, minimum requirements in terms of maximum primary energy use for space heating are in force for major renovation of existing buildings since 2017. One could envisage that this is a first step towards building renovation at nZEB levels in Romania, still regulation has to be improved, nZEB technology market growth has to be stimulated and private investments have to be attracted by innovative and sustained communication campaign along the public funding energy renovation programs applied for demonstration buildings.

4.3. Common Practice and Current Projects of Energy Renovation in Italy

The requalification of the multi-storey RC buildings is one of the hardest achievement [99]. Recently, a specific research study has verified the possibility to transform this kind of buildings into nZEB, with special attention to the Southern regions of the country [100]. The target of this study was also to contain the Pay Back Time (PBT). To get these aims, the authors have defined the most economical way to insulate the whole building envelope and to integrate PV panels in the façades. The simulations were carried on two multi-storey building of Librino, a popular neighbourhood of Catania, designed in the Seventies by Japanese architect Kenzo Tange [101].

In the first case study (Figure 26), the design actions have been limited, in order to contain the PBT in around 10 years (taking advantage of the current fiscal incentives). The U-value of the envelope has been reduced by applying an external insulation (Table 7). The installation of a new electrically powered air-water reversible heat pump has been considered for heating and cooling purposes. The calculation of the primary energy balance before and after renovation has shown a reduction of 37.1% (Table 8). Copper Indium Gallium Selenide (CIGS) PV panels integrated in the façades will be responsible for the electricity production onsite (Figure 26). In particular, in spring and fall the electricity production exceeds the electricity demand (Figure 27); in winter, external electricity contributions are limited, while in summer the electricity demand turns out to be higher than the electricity production.

Figure 26. Energy renovation of an apartment block in Librino—Catania [100].

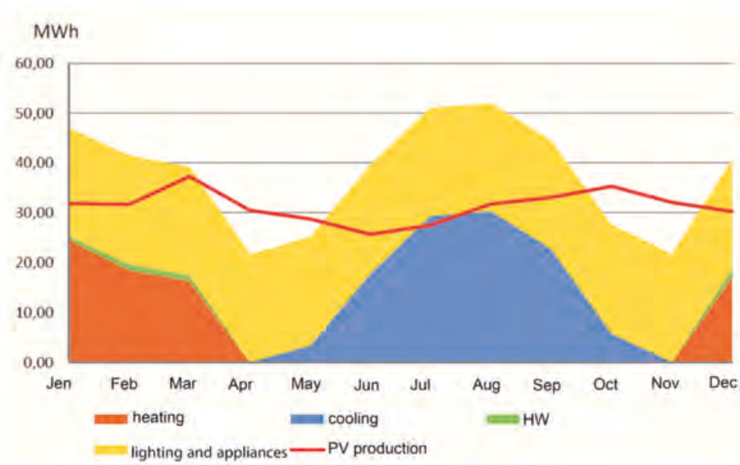

Figure 27. Comparison between electricity production from photovoltaic (PV) and electricity consumption [100].

Table 7. U-value of the building envelope before and after renovation.

Building Component	**Before**	**After**
	[W/m²K]	
External walls (RC)	1.71	0.35
External walls (clay bricks)	0.51	0.23
Roof	0.44	0.44
Slab over the porch	0.90	0.46
Ground slab	2.09	0.37

Table 8. Primary energy balance before and after renovation (without renewables) (H=heating, C = cooling, W = DHW, L = lighting.

[kWh/m^{2}a]	PE_H	PE_C	PE_W	PE_L	PE
Before	61.99	15.43	20.27	75.36	173.05
After	38.31	10.27	0.00	60.29	108.87
Reduction	38.2%	33.4%	100.0%	20.0%	37.1%

In the second case study, Cadmium Telluride (CdTe) PV panels were specifically dimensioned to get the nZEB standard, covering large part of the façade (more than 60%, excluding the northern side). In this case the energy renovation becomes also an opportunity to redesign the façades (Figure 28), changing the building architectural image. The energy demand has been reduced by insulating the whole envelope from the outside and by providing an air-water reversible heat pump. Table 9 shows the improvement of the thermal insulation of the building envelope after the proposed intervention. According to the calculation of the primary energy balance before and after renovation (Table 10), the primary energy needs decrease by 62%. The PBT turned out to be 9 years (with fiscal incentives).

Figure 28. Comparison between the PV energy production and energy consumptions [100].

Table 9. U-value of the building envelope before and after renovation.

Building Component	Before	After
	[W/m^{2}K]	
External walls (RC)	4.10	0.40
External walls (lightweight concrete)	1.96	0,39
Windows	5.80	1.60
Roof	3.85	0.30
Slab over the porch	3.14	0.38

Table 10. Primary energy balance before and after renovation without renewables) (H = heating, C = cooling, W = DHW, L = lighting).

[kWh/m^{2}a]	PE_H	PE_C	PE_W	PE_L	PE
Before	153.42	15.13	19.26	66.85	256.46
After	20.79	21.78	0.00	54.92	97.49
Reduction	86.4%	−43.9%	100.0%	20.0%	62.0%

The exploitation of the façades for PV installation turned out to be essential, since the roof surface of apartment blocks with more than 4 stories is generally insufficient to host all the panels required to reach the nZEB standard.

5. Seismic versus Energy Renovation: Technical Solutions, between Opportunities and Constraints

In Italy and Romania, a large number of RC structures need seismic strengthening. While for some recent generations the base isolation and bracing is possible and feasible, for most of cases a considerable amount of new structural members is required. Many traditional techniques are available and provisions that regulate their use are given in the relevant parts of the Italian [12–14], Romanian [35] and European [15] codes. Some examples of possible solutions are presented below, along with comments on their implications on the energy renovation solutions.

Figure 29 shows the strengthening of columns by concrete jackets. The concrete cover added to most of columns involves also the cutting and/or removal of some envelope material. The final design must take into account the adequate detailing and calculation in order to ensure a continuous thermal insulation for control of thermal bridges impact on performances.

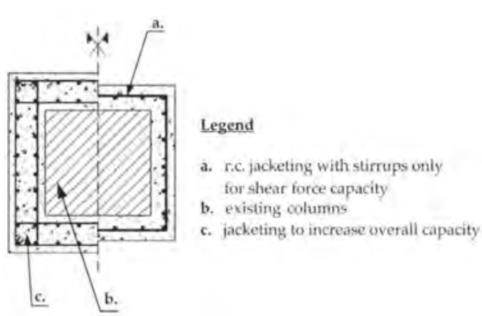

Figure 29. Strengthening solution for existing columns, using concrete jacketing (adapted after [34]).

In Figure 30 the new shear wall, when and if it is added at exterior, will change completely the envelope thermal parameters therefore the energy renovation design shall take into account the new details and thermal transmittance values. In Figures 31 and 32 the jacketing of shear walls is necessary on the edges. In case of external walls, the need of special care for energy renovation detailing may be limited to those areas.

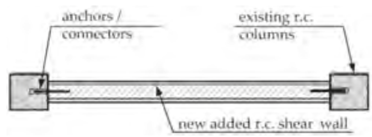

Figure 30. Strengthening solution using new structural walls, as shear walls (adapted after [34]).

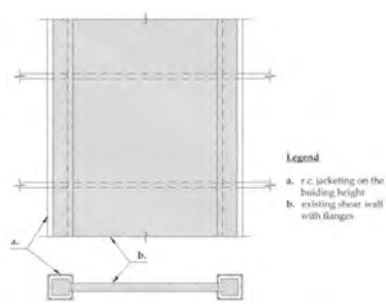

Figure 31. Strengthening solution for structural walls, with RC jacketing interventions on the edges (adapted after [34]).

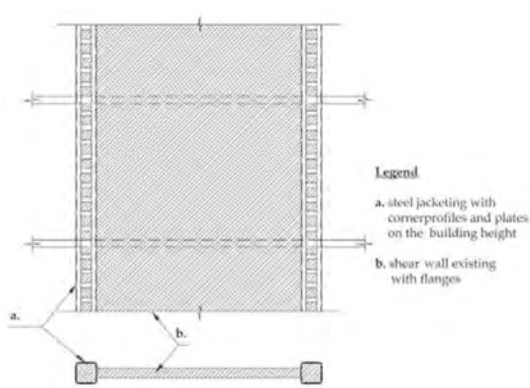

Figure 32. Strengthening solution for structural walls, with steel jacketing interventions on the edges (adapted after [34]).

However, when looking in details of such solutions, as in Figure 33, the building of a new and greater flange-column of a shear wall also changes the envelope situation, with the need of careful thermal bridges analysis. In Figure 34, the renovation with steel elements is much easier to apply but steel has a greater heat transfer capacity and also changes the envelope situation, with the need of careful thermal bridges analysis.

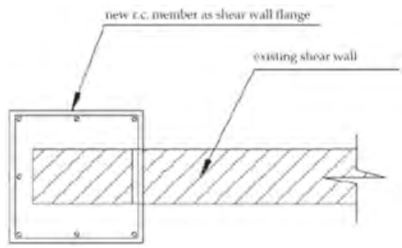

Figure 33. Detail of strengthening solution for structural walls, with RC jacketing interventions on the edges (adapted after [34]).

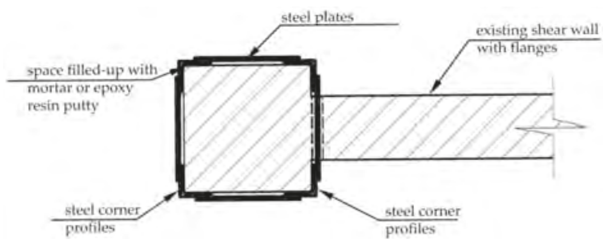

Figure 34. Detail of strengthening solution for structural walls, with steel jacketing interventions on the edges (adapted after [34]).

The examples herein presented point out that many solutions are available in literature to upgrade existing structures by enhancing its stiffness, strength and ductility capacity. However, these interventions may have a negative impact on the thermal performance of the building, thus requiring additional measures. On the other hand, any intervention devoted only to the energy requalification of RC buildings could be nullified by the effect of the earthquake if the building is not seismic-resistant. The interventions depicted in the previous figures (Figures 29–34) are intended to add lacking properties, in terms of resistance and ductility, to structural members in existing buildings. The cases referred to shall ensure such qualities by adding stronger or more ductile flanges to shear-walls, of inserting a web between columns, as to become structural ones. They shall be associated with other reinforcement measures. Based on this consideration, existing buildings should always be assessed in terms of both seismic and energy deficiencies and the new challenge will be to ideate, design and realize interventions that integrate seismic upgrading and energy renovation. An example that fits well this philosophy is the intervention by Takeuchi et al. [102,103] on the Midorigaoka-1st building of Tokyo Institute of Technology, a 6-story RC building designed in 1966 before the revision of Building Code of Japan in 1971. The main deficiency of the structure was the low ductility capacity of the columns. Furthermore, the thermal performance of the building envelope did not satisfy the current standard in Japan. The solution proposed by Takeuchi et al. is an integrated facade that includes glasses, louvers and a steel BRB frame (Figure 35). This multi-skin exoskeleton improves both the seismic and the thermal performance of the building. In particular, the steel frame equipped with BRBs is firmly attached to the ground and to the building façade. In occurrence of ground motions, the BRBs act as hysteretic dampers, yield and absorb input seismic energy before that the RC structure is damaged, thus reducing the drifts and protecting the structure. The system of glasses and louvers properly oriented can mitigate the inner temperature both in summer and winter and reduce the consumption of energy needed for heating and refreshing, respectively.

Figure 35. Midorigaoka-1st building after retrofit [103] (photographs by Mamoru Ishiguro).

There are also some recent and interesting research works that propose and/or assess combined seismic ad energy renovation scenarios for recent buildings. For instance, Leone and Zuccaro [104] have developed, within the EU-FP7 CRISMA project, a multi-criteria decision support system to select the optimal integrated retrofitting scenario, taking into account technical, financial and economic aspects. The proposed tool aims at enabling decision makers and local authorities to implement policies and large-scale programs devoted to the sustainable improvement of the existing residential stock. Calvi et al. [105] have proposed a "green and resilient indicator" to evaluate the earthquake resilience and energy efficiency of the exiting building stock. Manfredi and Masi [106] have proposed an integrated retrofitting intervention that consists in replacing the existing masonry infill walls with hollow clay blocks that are able to increase both seismic and thermal performance. For mid-low hazard areas, this technique could determine a full rehabilitation with regards to both seismic and thermal requirements, in compliance with the corresponding codes. La Greca and Margani [19] have highlighted the advantages of combined renovation actions, indicating the barriers that currently limit such actions and suggesting possible countermeasures. Moreover, the H2020 ProGETone project [107] is currently developing retrofitting solutions based on the implementation of multi-skin exoskeletons to enhance the seismic resilience and the energy performance.

6. Discussion

The seismic and energy renovation combined approach has strong and weak points, both in Italy and in Romania.

The recent Italian legislative has introduced different incentives, in form of tax credit (so-called 'SismaBonus'), which, especially from 2017, considerably reduce the economic investment for the renovation of earthquake-prone buildings. In particular, the building owners in seismic areas may receive a tax credit distributed over 5 years that covers up to 85% of the cost of the retrofit intervention, with a cost limit of €96,000 per apartment. Simple guidelines are provided to assess the seismic risk class of buildings in compliance with the current seismic technical code for constructions. Hence, the amount of the tax deduction is related to the class increase due to the strengthening intervention.

In addition, in Italy also the energy efficient renovation benefits from different fiscal incentives, which since 1998 have considerably encouraged this kind of intervention. Nowadays, energy retrofitting investments take advantage of VAT reductions (10% instead of 22%) and tax credits that range from 36% to 75% of the renovation cost, with a limit of €40,000 per apartment (so-called 'EcoBonus'). In particular, interventions on single family houses benefit from fiscal incentives that allow to write off 36% of costs on taxes, with deductions equally distributed over 10 years. This share increases from 70% up to 75% for apartments buildings, according to the reached energy performance. If required, the tax credit can be assigned to third parties, such as construction companies. Alternatively, it is possible to benefit from incentives governed by the Ministerial Decree of 16 February 2016 (also known as 'Conto Termico 2.0') that provides subsidies for the production of thermal energy from RES and the increase in energy efficiency. These subsidies cover 40% of the eligible expenditure, with specific limits for the unit and total costs of each type of interventions. They will be refunded either in five annual rates or in a single solution in the case of public administrations or Energy Service Companies (ESCOs).

From January 2018 [108], it is also possible to benefit from tax credits that cover up to 85% of the cost for combined seismic and energy renovation actions of apartment blocks, with a limit of €136,000 per apartment and deductions distributed over 10 years (so-called 'SuperBonus').

The Italian residential real estate has a very high level of fragmentation. It is usually quite difficult to reach a consensus among the building owners for the implementation of renovation works.

In Romania, since 69% of residential buildings existing in 2011 have been erected before 1977, many dwellings may have insufficient earthquake protection. The technical aspects of assessment, design and solutions for seismic strengthening are solved in relevant codes and laws starting during the1990s, while the energy rehabilitation has also a pertinent evolution, fully correlated with the EU Directives.

The problem of funding seismic strengthening is legally and financially solved since 1994 but the key issue is that of relationship between the funding provided by MDRAPFE and actual management of seismic strengthening projects which is done by local authorities. In Bucharest, there is a large list of pre-1940 buildings ranked at seismic risk but the number of buildings that were strengthened is relatively low.

Presently in Romania, is in force a yearly National Program for seismic risk reduction (based on Ordinance n. 20/1994) [81] correlated with Code P100-3/2008 [35] and EC8 provisions. For the time being, the National Program for thermal and energy rehabilitation [80] is a more successful social project, because it was applied on buildings with low or any seismic risk. The cost of energy rehabilitation was born in most cases by local authorities, from own budgets or European Programs.

In both countries, the main reason that makes the energy rehabilitation to be one step in front of structural interventions is that seismic strengthening involves the structure and is operated mainly from the inside of the building, while the energy renovation involves, above all, the envelope and is operated mostly from the outside. The energy renovation works are speedy, while for seismic strengthening owners are often afraid of high costs and related mortgaging; many of them are rather old and low-income, absentees or just do not want to de disturbed by evacuation and long-term noisy works. On the other hand, the funding is from separate sources and under separate legal framework, thus the full renovation approach is difficult.

From the energy renovation perspective, the level of ambition in terms of performance follows the nZEB target. Even if these performances are made mandatory only for new buildings authorized in very short time from now, the EU policies are rapidly advancing towards the renovation of existing building stock at nearly zero energy levels. This implicates a very high insulation level, high performance (and usually heavy) windows (installed in line with the applied insulation, that is, outside the mechanical resistance layer) and with minimized thermal bridges. This could be a very difficult task for the design of energy renovation technical solutions, especially in respect to the highly enforced design provisions due to the high seismic risk. In current practice, most of the building envelope renovation details (e.g., joining different building components) are designed with greater focus on mechanical resistance issues than heat transfer concept (e.g., avoiding thermal bridges), the result being usually an interrupted insulating envelope. In all cases, mechanical resistance has to be ensured but if penetration of the insulating layer is unavoidable, then the thermal conductivity of the penetrating material should be as low as possible and insulation layers at building component connections should merge into each other over the entire surface without interruption.

In this respect, best-practice guidelines and detailed specification for the building envelope have to be developed in order to support suitable solutions for nZEBs, tested in order to comply with the rigorous seismic design provisions. The aim is to inform and to shape the internal market in order to increase the current level of technical knowledge and technologies before the legal requirements under Directive 2010/31/EU cause a blockage of the local construction industry due to the inability to fulfil the Directive.

7. Conclusions

The European and National Standards and Directives have been promoting, from different sustainability reasons, seismic and energy renovation actions to mitigate disasters and climate changes impact. In Italy, over 60% of the current building stock was built between the 1950s and the 1980s, when seismic safety and energy efficiency regulations were absent or mandatory only in few regions. As a consequence, most of the real estate is earthquake-prone and highly energy-consuming [19]. The combined seismic and energy renovation of Italian buildings is of paramount importance for the safety of the population against earthquakes and other natural hazards related to climate change.

In Romania, there is a comprehensive framework of laws and technical regulations, both for earthquakes and energy, implemented over the last five decades for new and existing buildings. In this country, the wide impact of the 1940 and 1977 earthquake is a landmark, while the probability of a large earthquake in the near future is increasing, thus the seismic risk reduction is a national priority. The National Program for thermal and energy rehabilitation of buildings is a separate endeavour, also a priority, pushed by the impact of climate changes and the related European Union Directives. In order to achieve the ambitious and very demanding objectives of Eurocodes and European Energy Performance Directives, under Romanian laws, it is necessary to mobilize all the involved stakeholders, to identify and face the positive and negative aspects and barriers, as well as the deficiencies that exist or may occur in the future.

In both countries, the policy of renovation of the real estate is hindered especially by high costs and disruptions for users. The integration of structural, architectural and urban planning approaches may improve the effectiveness and diffusion of these actions. However, steps like structural analysis, energy audits, public tender procedures, quality of projects and execution, regulatory framework, financial and fiscal incentives, quality control, training of designers and builders and workers' qualification still represent critical issues.

A variety of techniques for seismic upgrading and energy renovation of buildings are already available. Some of these techniques are known to structural designers and construction companies for a long time now and provisions for their application are provided in the current technical regulations. Other techniques, which are classified as innovative, are also applicable because studies that demonstrate their effectiveness and the relevant design guidelines are available in the technical literature. However, each of these techniques aims at improving only one aspect of the building performance: reduction of the risk of damage/failure caused by earthquakes or reduction of the energy consumption during the building operation. Based on the framework depicted above, it emerges that often seismic upgrading interventions can have no effect or may be even detrimental on the energy performance of the building and vice versa. Hence, the main challenge of the next years is to develop approaches that integrate together techniques for energy and seismic renovation. Important aspect to be deepened are the study of the compatibility of the integrated techniques and the definition of interventions that improve both seismic energy performance. The target of these approach should be the transformation of the existing energy-consuming and seismic-prone buildings in nZEB seismic-resistant ones. The availability of such integrated approaches for seismic-energy upgrading can promote the renovation of existing buildings by pursuing multiple targets: (i) to benefit from fiscal and financial incentives for both seismic and energy renovation, (ii) to maximize the positive effect gained by the intervention on the building (two performance objectives are reached with a single intervention) and (iii) to preserve in time the value of the investment (the investment for energy renovation could be nullified by earthquakes if seismic upgrading has not been pursued too). To this purpose, the exchange of experience among countries with similar issues, such as Italy and Romania, plays a crucial role to share best practices and to define correct skill and adequate competences.

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Acronyms

BEMS	Building Energy Management Systems
BIPV	Building Integrated Photovoltaics
BRB	Buckling Restrained Braces
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
DHW	Domestic Hot Water
DL	Damage Limitation
EN 1988	Eurocode 8
ESCO	Energy Service Company
ETICS	External Thermal Insulation Composite System
FRP	Fibre Reinforced Polymer
HDD	Heating Degree Days
H'T	transmission heat loss coefficient
HVAC	Heating, Ventilating and Air Conditioning
NC	Near Collapse
NTC08	"Norme Tecniche per le Costruzioni" enforced in 2008
KL	Knowledge Levels
NSC	Non-Structural Components
nZEB	nearly Zero Energy Building
PBT	Pay Back Time
PCM	Phase Change Materials
PV	PhotoVoltaic
PV/T	PhotoVoltaic and Thermal
PGA	Peak Ground Acceleration
R	Thermal Resistance
RC	Reinforced Concrete
RES	Renewable Energy Sources
SD	Significant Damage
ST	Solar Thermal
TIM	Transparent Insulation Materials
U	Thermal Trasmittance
VIP	Vacuum Insulating Panels

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From the Efficiency of Nature to Parametric Design. A Holistic Approach for Sustainable Building Renovation in Seismic Regions

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Abstract: Cities are growing dramatically. At the same time, we are witnessing the obsolescence of the existing building stock due to its low performance in terms of structural stability, energy efficiency and, last but not least, beauty. Especially in Italy, a highly seismic country, most of the buildings erected between the 1950s and the 1980s are not only earthquake-prone but also aesthetically unpleasant. In this perspective, the urgency of improving the existing building stock in terms of seismic vulnerability opens up the opportunity to also work on its architectural image. This article draws from the assumption that the search for beauty represents an important and often neglected dimension of the search for sustainability. In particular, the presented study suggests and combines the use of parametric design and the structural shape of steel exoskeletons to renovate a typical earthquake-prone apartment block from the 1960s in Italy. The results show that the proposed parametric approach can provide and select different effective renovation solutions.

Keywords: sustainability and aesthetics; architectural image; parametric design; exoskeleton; seismic renovation; apartment blocks

1. Introduction

Despite the unprecedented post-second world war growth of cities [1], little attention has been paid to the issue of sustainability. In Italy, in particular, real-estate developments between the 1950s and the 1980s [2] were characterized by some local conditions that favored the spread of buildings that are far from being earthquake-resistant, as they usually failed to take into account the geographical, geological and topological features of the territory. Italy is a highly seismic territory. Politicians however, have, for many years, ignored this hazard. The first map that classifies, using a scientific approach, the Italian territory into seismic areas was in fact only produced between 1981 and 1984 (Ministerial Decree March 7, 1981), after the 1976 earthquake in the region of Friuli. Until then, most buildings located in highly seismic areas had been built without taking into account horizontal seismic actions [3]. Moreover, according to the Italian National Institute of Statistics (ISTAT) 2011 census [2,4] more than 60% of the existing buildings predate 1974, which is the year the first specific and extensive Italian code for earthquake-resistant buildings was issued (law 64/1974) [3]. This means that a large part of the current building stock was realized without anti-seismic restrictions and norms: about 10 million homes are located in the areas most at risk of which 1.4 million homes are located in zone 1 (high seismicity: Peak Ground Acceleration PGA > 0.25) and about 9 million homes in zone 2 (middle seismicity: $0.15 < PGA \leq 0.25$); while 8.5 million homes are in zone 3 (low seismicity: $0.05 < PGA \leq 0.15$) and 9.4 million ones in zone 4 (very low seismicity: $ag \leq PGA$) [5].

Lack of careful planning and the urban speculation allowed Italian real estate developers after the second world war to build poor quality structures in terms of materials, construction details and in terms of architectural image as well [6–8]. It is also worth noting that most Italian buildings erected in compliance with the seismic regulations implemented between the 1950s and the 1990s are incompatible with current regulations, which feature much higher standards of anti-seismic efficiency. Hence, as stated by La Greca and Margani, over 50% of the Italian residential constructions are earthquake-prone but we have to highlight that they are also undeniably inadequate in terms of architectural aesthetics and design if compared to the beautiful Italian historic districts (Figure 1).

Figure 1. An example of a reinforced concrete building that does not take into account the aesthetic value of its urban landscape nor the seismic risk of the area in the Baroque city of Noto, Italy.

Therefore, a policy of renovation is urgent not only to meet the demands for higher standards of anti-seismic and energy efficiency, but globally. Nevertheless, there are a number of limits to a global renovation of the existing building stock: (i) technical limits due to the difficulties and often ineffectiveness of conventional solutions when it comes to renovating existing buildings; (ii) organizational limits related to providing accommodation to the building's residents during renovation: in fact, the current seismic and energy interventions generally mean relocating people and furniture to temporary accommodation throughout the duration of the work, which may last up to a year or more; (iii) economic limits due to the high costs of renovation. In addition to these limits, one must also take into account the current economic crisis [2].

Research should, therefore, explore both different solutions to the problems described above and the tools to be used to overcome such limits. Parametric design, the tool proposed and used for this work, makes it possible to overcome various building renovation limits. Indeed, this type of design tool can control many variables at once to obtain a set of solutions among which it is possible to choose the most effective and appropriate ones. This paper also aims to underline that the buildings' aesthetics and design are critical elements that should be linked to the concept of sustainability, as they affect all aspects of human life and experience. Nature has thus become our criterion in this study because it works taking into consideration all variables at play in the realm of sustainability, and parametric design is a tool that works in ways comparable to natural processes. It is the first time that parametric design has been used to retrofit buildings to better withstand seismic events while to date, literature shows only cases in which parametric design has been adopted for energy efficiency or architectural solutions. However, the main purpose of this paper is to show how this method works considering different variables, such as geometry, weight, materials, energy efficiency and structures. The relationship between sustainability, nature and the pursuit of beauty will be discussed in Section 2.

Section 3 introduces steel exoskeletons as an optimal combination of shape and structure in nature as well as in architecture.

Section 4 presents our approach to the use of exoskeletons, and, in particular, introduces our prototyping algorithm.

Section 5 shows the creation of exoskeletons.

Section 6 illustrates the application of our methodology, tools and software (Figure 2) to a case study. We chose a typical case study representative of the Italian residential stock. The same case study was analyzed in a previous research project and this work is a development of that research. Unlike the latter, here we focused on architectural shape, both in terms of seismic performance and the relationship with the urban context. Finally, Section 7 presents our analysis and results.

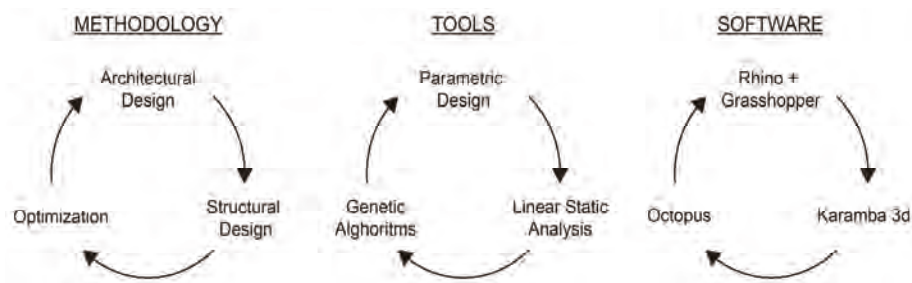

Figure 2. Scheme of the proposed methodology, tools and software.

2. Aesthetics and Nature as a Reference for Parametric Design

To highlight the unsustainability of unaesthetic architecture and its consequences on society, we should be aware of the beneficial effects that beauty can have on human beings, as proposed by Wohlwill [9]. To do so we draw on the theories of James Hillman, who believes that the quest for beauty and aesthetics may give an answer to many of the problems of contemporary civilization [10]. The search for sustainability should also be the pursuit of beauty. Sustainability, when working in a holistic way with a building, aims at recreating as much of a harmonious relationship as possible with the environment. Good architecture is always a complex activity that establishes a relationship with the environment. In fact, the more relationships with the environment architecture is capable of establishing, the more sustainable it is. Lack of aesthetics and unsustainability, on the other hand, derive from overlooking the critical relationship with the environment. Moreover, not considering environmental issues means neglecting the local seismicity and climate, ignoring the integration of cultural traditions, overlooking the local economy and its anthropological specifications as well as the sense of the living experience in one's own context. Sustainability, like beauty [11–13], depends on the level of complexity that can be achieved through design and it can be seen as the result of a truly holistic approach. Using the concept of sustainability as a measure of beauty does not presuppose a change of paradigm of aesthetics [14,15] but it is an important element of good design. Since design is an intrinsically complex and multidimensional activity, the designer normally tends to reduce complexity in smaller chunks that can be more easily managed. Through parametric design, that tends to imitate the generative algorithms of nature, it is possible to consider the multiple dimensions of design. The goal is to enhance the designing process and optimize results, aware that variables such as aesthetic value, given their intrinsic nature, lend themselves to subjective interpretations. However, through the concept of aesthetics as a value of sustainability, even when the results are not optimal because there is no formula that guarantees optimization, we can address the dilemma between performance and shape and between genotype and phenotype in architecture. The parametric architecture thus conceived is of great help in terms of optimization in relation to the technical parameters pertaining to the sustainability of structural stability [16], energy efficiency, thermal and visual comfort, cost-effectiveness and architectural image.

In our case study and more generally in the context of structural optimization of buildings, we can proceed with three basic types of parametric designs that mimic the modus operandi of nature: the first intervenes on the dimensions of the structural elements, having fixed the shape of the building a priori; the second researches the formal configuration that best resists according to their relative shape; the third intervenes on the arrangement of the structural elements and on the connections between them.

The procedures nature implements, depending on each and every particular situation, develop one or more optimization solutions starting from their genotype. The genotypes nature offers as a reference are manifold. In our case study, exoskeletons seem to be the ones that promise more possibilities for effective solutions.

3. The Exoskeleton: Shape and Structure

The steel exoskeleton, when the characteristics of the building make it possible, is installed outside the building. This is the ideal choice in term of mechanical strength and quantity of materials, which are key features for the construction of new buildings and to retrofit existing ones to improve their anti-seismic performance.

As already stated, among the many limitations highlighted by conventional systems of anti-seismic solutions, emerges the difficulty of enhancing buildings also from an architectural point of view, reducing at the same time the inconveniences residents experience during renovation. For these reasons, the model of the exoskeleton, besides offering a more effective anti-seismic solution is also a support for energy-efficient devices and, we would emphasize, a way redesign the architectural image of the building [17]. Furthermore, the external installation of an exoskeleton does not imply an interruption of the building's operation during the construction works, avoiding temporary relocating costs [18] and other inconveniences caused by large demolition activities, thus contributing to stimulating building owners to retrofit their buildings. As exoskeletons require less major structural intervention and reconstruction activities this is also in accordance with the principles of environmental sustainability and eco-efficiency. In fact, the use of new construction materials and the production of waste are minimized. However, some preliminary requirements are necessary to apply an exoskeleton to an existing building: the presence of free external spaces in front of the buildings' façades is a mandatory requirement for the installation of exoskeletons and their foundations; moreover, the installation of the exoskeleton must be often preceded by local interventions to reinforce the existing beam-column joints, to which the new steel structure will be connected.

Nevertheless, even by using exoskeletons, if we do not proceed by considering the problem of renovation in a global way and we consider only one aspect, we could only produce structural prostheses that do not regard aesthetics in terms of sustainability (Figure 3).

Figure 3. Examples of seismic retrofitting with steel exoskeletons.

Even the example of the exoskeleton used for the seismic retrofit of the Magneti Marelli headquarters in Crevalcore is typical of a non-holistic approach [19] (Figure 4).

Figure 4. Steps of the seismic retrofit of the Magneti Marelli headquarters in Crevalcore, Italy.

Here the adopted exoskeleton converts an office construction built in the 1970s into an earthquake-proof edifice, but this new structure does not integrate with the architecture it intends to strengthen and presents itself as a prosthesis that meets only its structural needs [8]. Moreover, much of the building was demolished and then rebuilt. In fact, engineers spared only the existing reinforced concrete structure and repaired and adapted it to accommodate an external dissipative-type steel frame.

An interesting example in holistic terms is the one by European research project Pro-GET-onE (acronym of *Proactive Sinergy of integrate Efficient Technologies on Buildings' Envelopes*) [8] (Figure 5). The set of solutions tested in this case is part of a holistic view of the problem. The holistic vision promoted by Pro-GET-onE is based on the integration of different technologies with the aim of increasing building performance in terms of energy efficiency, seismic safety and social and economic sustainability. In this case too, the objective is to rely on such external envelopes, which not only make the building earthquake-proof, but also support technologies for renewable energy supplies, especially solar and wind energy. As a result, the architectural transformation, delivers, among the others, a renewed and harmonious image of the case study selected for the verification of the theoretical approach discussed here. In this case, the original reinforced concrete structure was not affected by repairs and betterments.

Figure 5. Case study of the Pro-GET-onE research project.

Among the most used exoskeletons, the diagrid system stands out: a two-dimensional structural system, made up of triangular modules capable of resisting both horizontal and vertical loads without the need for additional elements [20].

From an architectural point of view, the ability of this system to adapt to any three-dimensional shape, even if not straight, offers the possibility to try an infinite number of configurations. On the external structure it is possible to obtain multiple solutions for the façade, from the simplest to the complex technological options available. Moreover, the geometry of the exoskeleton allows for a better management of the relationship between the full and empty spaces of the façade. The choice of materials plays a critical role in the diagrid solution. This choice often falls on steel because of the advantages it offers, but reinforced concrete diagrids are available too. In fact, steel exoskeletons provide the following advantages: high levels of prefabrication and dry assembly standards, which involve shorter construction times and, therefore, less disruption in urban areas; use of recyclable materials; and easy maintenance and replacement in case of seismic damage or breakage. Finally, a diagrid-type structure requires the use of a smaller amount of material, with significant economic advantages despite the initial higher financial costs. The advantages of using an exoskeleton system are relevant in the case of reinforced concrete constructions built after World War II, which have no historical and artistic constraints thus representing a viable solution, as it allows them to operate, as much as possible from the outside, through the application of a three-dimensional external structure that envelops the existing building, structurally linking itself to it as an exoskeleton. On the other hand, the application of exoskeletons on existing structures may have other disadvantages, for example the exoskeleton rods, if not properly designed, could become an obstacle to natural lighting and ventilation.

Among the advantages, using a diagrid system, or an exoskeleton in general, the only elements subject to demolition and reconstruction are the balconies. This could be, however, the input for the implementation of energy retrofit interventions [8] with the consequent reduction of the thermal bridges, which would be limited only to the structural connections between the building and the exoskeleton. The exoskeleton could be the support for a second envelope which, if properly distanced from the façades of the existing building, can work as ventilated shading walls. The exoskeleton could also provide support for renewable energy production devices, increasingly used as elements for façade composition, as well as vertical gardens that contribute to passive cooling, and solar shadings of any kind for direct radiation control and natural lighting.

Finally, structural advantages are primarily linked to the ability to adapt to the shape of existing structures. The exoskeletons could also be combined with other structural seismic retrofit solutions, but even on their own they can solve the renovation issue. Furthermore, this type of structure ensures a better distribution of loads, thanks to the redundant character provided by the mesh, whose basic modules' geometry is of fundamental importance.

The size of the modules making up the diagrid is usually calculated by dividing in equal parts the height of the building on which it is applied. The number of modules, and consequently the angle in relation to the horizontal plane of the diagonal elements, has a great influence on the general response of the system, and often represents one of the parameters of structural optimization. The basic form of a diagrid usually has a rhomboidal shape. However, in the composition of exoskeletons with diagrid geometry, triangular meshes are preferred for the various advantages they offer both in terms of design and construction phases. The triangle is in fact a non-deformable figure and this gives the structure an intrinsic stability. The designer can also think of the nodes as hinges, which result in less stress on the rods due to the absence of bending moments. A division into triangles, moreover, returns only flat faces, which are more compatible with a possible coating of the structure.

The theme of the renovation of apartment blocks has been addressed taking into account all of the above with an integrated parametric design approach, which is illustrated below. While some studies on parametric design aimed at energy rehabilitation are present in the scientific literature [21], the use of this discipline in the field of seismic retrofit has remained unexplored until now.

4. The Prototyping Algorithm

The increasing diffusion of algorithms in design practice has led to the creation of user-friendly tools that can be exploited by all the professional figures involved in this field, regardless of the knowledge of complex programming languages. These tools are, in practice, software designed as graphic editors of algorithms.

The most widespread among the professionals in the field of architecture is Grasshopper [22], capable of interfacing with the three-dimensional modeling software Rhinoceros, and equipped with a vast community that has led to the development of countless faces to increase power and versatility.

Within this software it is possible to build your own script simply by connecting graphic elements (components), which represent the nodes of the parametric diagram and which are characterized by certain inputs and outputs, depending on the function that they perform [23]. The connections are made through wires, graphically characterized according to the structure of the data transported.

In the present work, the Grasshopper software was used to create a procedural algorithm aimed at computation generation and optimization through genetic algorithms of structural steel exoskeletons. Applied externally to reinforced concrete buildings designed to withstand vertical actions alone, they aim to improve the seismic response of the latter, while at the same time characterizing them from an architectural point of view.

The structural treatment within Grasshopper was carried out thanks to the Karamba3d plug-in [24], which uses finite element modeling to perform interactive static analyses on two-dimensional or three-dimensional systems, composed of both rods and shells. This plug-in does not present itself as a "full optional" structural calculation program for carrying out detailed engineering analyses but aims to be a support tool for architects and engineers, guiding the design choices from the initial stages of the process.

The procedural algorithm developed is presented as in Figure 6. This was divided into modules, marked with different colors, each containing the components that perform a specific function. These modules are related to: the geometry of the existing structures (1), the geometry of the exoskeleton (2), the variables of the optimization, i.e., the variations of the exoskeleton geometry, obtained through the optimization process (3), the creation of the finite element model (FEM) (4), structural analysis (5), study of the results and definition of the fitness function for optimization (6), export to SAP2000 (7). The modules concerning the geometry of the exoskeleton and the variables of the optimization represent the "variable" part of the script and therefore are closely linked to the project idea. Their treatment is then referred to in paragraph 6. The remaining modules remain constant and compose the algorithm to develop the shapes of the exoskeleton that have not yet been optimized. Most relevant modules (4, 5, 6) are described in detail in Figure 7.

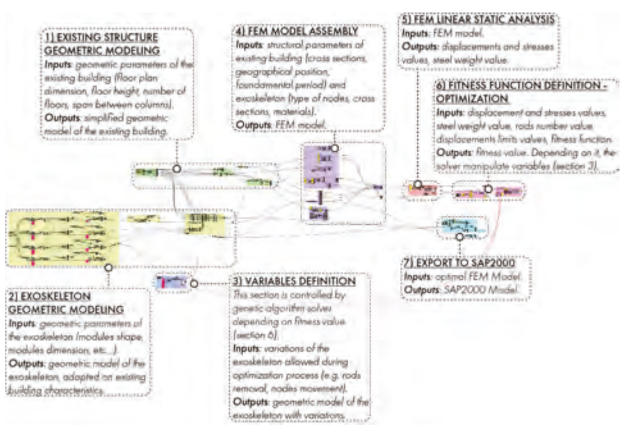

Figure 6. The prototyping algorithm within Grasshopper.

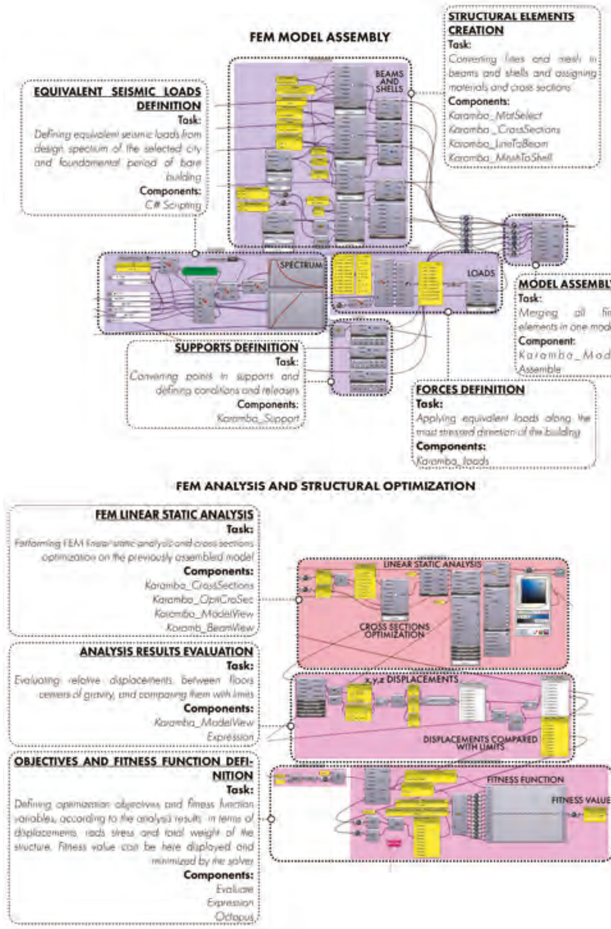

Figure 7. Description of the main modules of the algorithm: finite element model assembly, linear structural analysis and optimization.

First of all, the geometries of the structure are modeled. The inputs to be specified at this stage are the planimetric dimensions, the number of floors, the floor height and the span between columns in both directions. The definition of these parameters allows extending the use of the proposed algorithm to most buildings with reinforced concrete structure. The structure of the existing building (Figure 8a) is not entirely modeled, but is approximated to a series of vertical lines, placed one on top of the other, in a number equal to that of the levels. Each of these lines represents the axis of a column with equivalent stiffness to that calculated on each storey. At the top of each of these lines lies a surface that represents the floor slab, surrounded by a system of linear elements, later made non-deformable, useful to avoid inconvenient deformation and torsional phenomena. Within this module it is also necessary to obtain the geometries related to the beam-pillar nodes of the existing structure, which represent the points of connection with the new steel exoskeleton.

The outputs of the geometric modeling flow into the module for the creation of the finite element model, visible in relation to the existing structure in Figure 8b. This section is divided into three groups. The first has the task of converting the geometries into structural elements. In particular, we need linear elements as starting geometries for the creation of beams, of two-dimensional mesh elements for the creation of shells. In this phase, information relating to the materials is included: concrete is assigned to the existing structure, while steel is assigned to the exoskeleton. Here, also the cross sections assigned to the pillars of the existing structure are defined, which are useful to simulate the equivalent stiffness rate provided by the reinforced concrete building and drawn backwards from an FEM built in the SAP2000 environment.

The other two groups of the module in question are aimed at defining the supports, for creating the joints at the base and the carriages (useful to simulate a deformed beam attributable to a "shear-type" frame (Figure 8c) placed at the top of the pillars with equivalent stiffness, and loads.

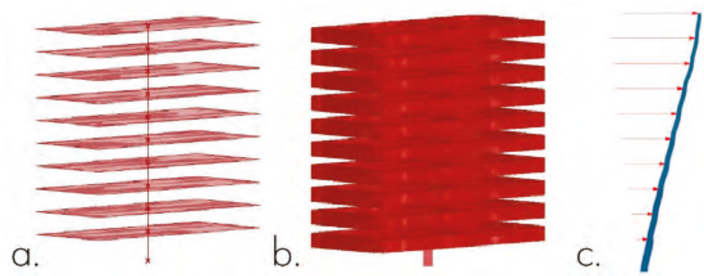

Figure 8. Simplified modeling of the existing reinforced concrete structure. (**a**) geometries, (**b**) finite element model, (**c**) deformed beam attributable to a "shear type" frame.

Although related to a seismic problem, the evaluations related to the stresses, in this phase, have been dealt with by adopting static simplifications. Despite this, the algorithm was not created to optimize an eternally static condition: the results of this process, in fact, will then be used in a dynamic treatment. The loads involved are, therefore, represented by equivalent seismic actions acting on each individual floor of the structure, obtained through a script created ad hoc, according to the project spectrum and to the fundamental period of the structure. These last two parameters must be inserted as inputs and vary according to the geographical location of the existing building and its structural characteristics.

Once the finite element model is assembled, it is subject to a linear static structural analysis, carried out within Grasshopper thanks to the Karamba3d plug-in. In this step, simultaneously with the structural analysis, a first process of optimization of the cross sections of the structural elements is carried out: on each beam of the exoskeleton, to which the minimum section, chosen in a range of user-defined profiles, is assigned according to a verification of resistance in the elastic field, combined, in the case of elements subjected to compression, on an instability test. Here, the solver is required to draw from a range of commercial tubular profiles with a diameter of approximately 30 cm. If none of the profiles contained in the chosen range are verified, the algorithm returns an error message.

The results of the linear static structural analysis, expressed in terms of nodal displacements and stresses on the rods, flow into the optimization module. The optimization process is carried out using genetic algorithms, that represent a tool that use Darwinian theories of evolution to solve problems related to parametric design [25]. The optimization is based on a fitness function, built by the user, which returns a numerical value that defines the objectives of the process. In this case, the solver, the Octopus plug-in, starts a solution generation routine obtained by varying the intrinsic parameters of the model, located in the module related to variables definition. Among these solutions, only those that return a better fitness value than the previous ones survive.

The considered algorithm is aimed at minimizing the weight of steel used, keeping the totality of the structural elements of the exoskeleton under verification conditions and maintaining the relative drifts between the levels of the existing reinforced concrete building, below the limits, reduced to take into account the life safeguard limit [26]. In order to pursue these objectives, the fitness function is obtained by increasing to the actual weight of the exoskeleton steel, of suitably calibrated coefficients, which are different from zero only in cases where there are drift values beyond the limits, or unverified beams. In this way, the configurations in which these conditions occur, tend to be discarded by the solver (the Octopus plug-in in this case), due to the higher fitness value that characterizes them.

The last of the modules that make up the algorithm is related to the export of the FEM model from Grasshopper to SAP2000, for the development of detailed dynamic analyses. For this operation to be possible, the GeometryGym plug-in [27] is used. The dialogue between the software handled in this work, exploits the API interface integrated in SAP2000 [28], able to provide complete and efficient access to all the tools of the structural software, allowing a bidirectional transfer of the models and control on the execution of the analysis and on the management of the data. A dialogue of this type between the software allows one to bypass the conventional user interface once again, and to speed up the export and import phases, especially in case of repeated modifications to the model.

5. The Creation of Structural Exoskeletons

Summing up, once you have modeled the geometry related to the structure equivalent to the existing building, you can move on to create the elements related to the exoskeleton and to the definition of the optimization variables. These are nothing but the possible morphological transformations that the model can undergo during the search for the solution capable of using the lowest amount of steel. It should, therefore, be noted that the geometry of the exoskeleton modeled in this phase does not yet represent the final shape of the latter, but a starting configuration that will be manipulated automatically during the optimization phase.

Together with the vectors inherent to the equivalent seismic actions, the totality of the geometries represents one of the inputs for the assembly of the finite element model, on which a linear static analysis is then carried out. The results of this become the parameters that make up the fitness function, built by the user to define the objectives of the process. In order to achieve a fitness value congruent with the objective, the solver will make changes to the geometry of the exoskeleton (allowed by the user via the upstream imposition of the variables), and then re-analyze the variant created. In this way a routine is generated will end only when the numerical value of the fitness function is suitable to the objectives of the optimization. The process of generating structural exoskeletons is summarized in Figure 9.

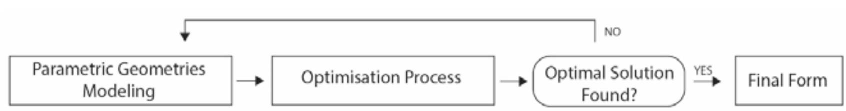

Figure 9. Flowchart that summarizes the process of generating structural exoskeletons.

It should be noted that the algorithm developed during the present work is not aimed at the seismic improvement of a specific building but, due to the parametric character that distinguishes it, its use can be extended to any existing multi-storey building with a framed structure in reinforced concrete. By varying the size of the sections assigned to the pillars that simulate the existing structure, it is possible to manage the stiffness equivalent to the real one, while the number and shape of the slabs, and the positioning of the beam-pillar nodes, can be adapted to the building by modifying the geometric values that represent the input for their creation. Likewise, the forces applied in assembling the FEM vary depending on the geographic location of the building and its natural oscillation period.

6. Application to a Case Study

As a case study, we adopted a prototype building consisting in an apartment block, already analyzed in a previous research project (Figure 10) [26,29].

Figure 10. Three-dimensional model of the simulated building.

The structure of this prototype building has no real evidence but is obtained from a process called "simulated design", based on the regulations in force before the introduction of the seismic and energy-efficiency legislation, on the construction uses of the time, and on the architectural peculiarities that distinguished the building boom between 1950 and 1980. This prototype is representative of a large share (almost 20%) [6] of the existing residential stock in the city of Catania, located in the eastern coast of Sicily and classified as seismic-prone in 1981. From a morphological point of view this building type is characterized by medium height, between 5 and 12 floors, elongated rectangular plant, central stairs and strong regularity both in plan and in elevation. The structure, characterized by resistant elements placed in only one direction and frames symmetrically arranged, is able to withstand only vertical loads. To aggravate its behavior under horizontal loads there is the lack of masonry infill on the ground floor, which may cause a soft story collapse [26,29].

More in detail the considered case study is characterized by a reinforced concrete frame. It has 10 residential floors, and a commercial ground floor. The building is 35 m high and has a rectangular plan (31.80 × 13.80 m), symmetrical along the transversal axis. On each floor there are three apartments, each of which has an area of approximately 140 m^2. The two external apartments are perfectly mirrored, with the central one interposed between them. Most windows are on the long sides and only two small windows per floor are on the short fronts.

The elevations reflect the symmetry of the plan, and are characterized by a strong repetitiveness in height, due to the identical configuration of the spaces between the various levels.

On each floor there are balconies, placed symmetrically along the two axes. Each apartment therefore has a portion of its balcony and can enjoy an outdoor space.

Using a prototype building as case study is beneficial to perform structural analysis. Results, considerations and possible retrofit solutions may be replicated, in fact, on most apartment blocks having the same structural and constructive characteristics. However, to set up relations with the specific urban landscape and seismic area, it was decided to place the case study inside the so-called "sea zone" of Catania, a prestigious neighborhood built between the 1960s and the 1970s, during the economic and construction boom. The building stock of this area was largely realized before the enforcement of regulations for energy-efficient and seismic-resistant buildings, and the construction practice strongly clashes with the "rules of art", which up to some decades before, even in the absence of a theoretical awareness, allowed buildings to be respectful of the environment and often resistant to the earthquakes [30].

The selection of the site took place considering the characteristics of the lot in which it is placed as the primary criterion. In particular, in view of the construction of an external structure, we need a free space, on all fronts, to be used for laying foundation works. The choice fell on a large green area near the urban waterfront (Figure 11).

Figure 11. Rendering of the simulated building located in the selected site.

The advantages of the parametric approach to design include the possibility of easily creating multiple versions of the same project. Borrowing the term *versioning* from the jargon of software development, this indicates the opportunity offered by the management of files that are no longer static, but capable of evolving and generating variations when new forces and conditions come into play.

Two project ideas are proposed, each of which, due to the intrinsic nature of the parametric approach of generating multiple versions of the same concept, will return more than one final form in varying the parameters within the model and the definition of structural optimization. In a design of this type the design idea does not translate directly into the final shape of the exoskeleton, but in a starting geometric shape and in a series of variables that represent "what will happen to the model" during the optimization process.

The first project idea stems from the desire to clash, in order to cancel them, with the symmetry and regularity that characterize the considered building. Therefore, this leads to the creation of a strongly irregular structure-envelope, which, like a beneficial parasite, enters into symbiosis with the original structure, attacking it only where necessary and allowing the emergence of glimpses, through which to continue observing the existing building.

The first step is the one related to the creation of the starting form of the exoskeleton, which, once subjected to an optimization process according to rules imposed upstream, will return the final geometry of the structure. The starting structure is represented by a diagrid, of regular shape, that wraps the building parallel to its façades. The basic module of this structure, quadrangular with height equal to the floor (3.3m), is divided into four triangles deriving from the connection of the opposite nodes. The division into triangular modules enables the creation of a structure whose nodes are of the hinge type. Although more difficult to achieve in practice, these allow us to reduce the stresses on the rods to only axial stress, eliminating the bending momentum rates. In order to obtain a perfect closure of the mesh, at the corners of the building, the reticular system has been moved away from the façades of a distance equal to half the light of the span (2.25m). This is also convenient to avoid a "cage" effect, which risks generating feelings of oppression in the inhabitants of the building itself.

The starting diagrid system is modeled from four surfaces, each of which is parallel to a façade and divided into rectangular sub-areas measuring 3.3 × 2.25 m. Each of these has been divided into the four triangular surfaces whose sides represent the linear elements to be converted into rods (Figure 12).

Figure 12. Geometries of the starting diagrid related to the first design idea.

As for the optimization variables, the model just described is allowed to "curl up" thanks to the movement, with respect to the initial position, in the range from one meter to the outside, one meter inwards, orthogonally at the respective façade, of the diagrid nodes. This transformation granted to the model is aimed at finding a configuration that returns the best resistance, exploiting the shape, to seismic actions. The movement of the nodes is accompanied by a process of removing the rods that do not contribute to the response to horizontal loads, in order to pursue the objective of minimizing the steel used. The strategy adopted for the removal of the rods is as follows: thinking of the building as a box inside which they have freedom to move points, in a number chosen by the user. Each of these represents the center of a sphere (Figure 13) capable of removing the triangular modules of which it incorporates the barycenters. The position of the spheres and their radius, as well as the value relative to the displacement of the nodes, fall within the optimization variables, and are therefore parameters that are automatically controlled by the solver of genetic algorithms, and in any case set manually by the 'user. The module for the geometric modeling of the exoskeleton also generates, automatically, and depending on the portions of the exoskeleton that are not removed, the connecting elements between the nodes of the new structure and those of the existing one. It was decided to operate with 20 spheres, each with a variable radius of 1 to 5 m.

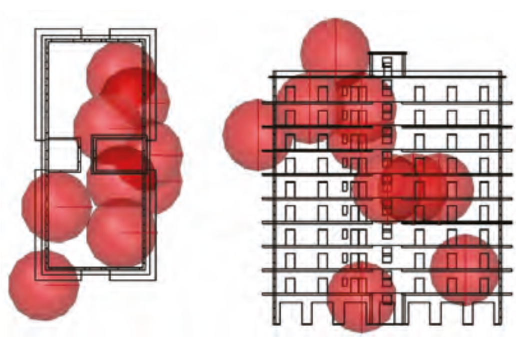

Figure 13. Spheres, controlled by the solver of genetic algorithms, responsible for removing the modules during the optimization process.

The second project idea involves the creation of an exoskeleton which, while remaining regular in shape, aims at eliminating the symmetry that characterizes the existing building. While in the previously described solution, the solver of genetic algorithms is called to carry out a rod removal process, this time it aims to implement an additive strategy. The optimization, in fact, involves the insertion of structural elements in the areas of the exoskeleton that require greater rigidity.

Even in the case of the second design idea, the starting structure is a diagrid system, this time with quadrangular base module (Figure 14) and therefore formed by rods stuck to the ends. Also in this case, the structure is moved, on each front, at a distance equal to half of the light of the span (2.25 m) to allow for an optimal closure of the angular modules. Similarly to the first design idea, the geometric modeling involves the creation of four surfaces parallel to the façades, each of which is divided into rhomboid portions of height equal to the storey height (3.3 m) and width equal to the light of the span (4.5 m). The sides of these diamonds represent the linear elements to be converted into rods in the phase of creating the finite element model.

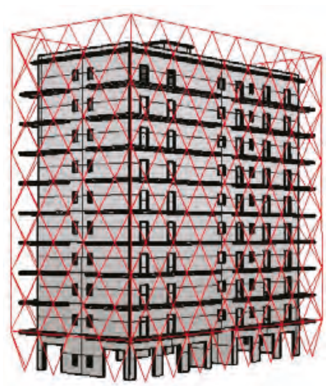

Figure 14. Geometries of the starting diagrid related to the first design idea.

The only transformation granted to the shape of this model consists in the possibility of each single rhomboidal module, to subdivide, in the optimization phase, into an additional four or 16 sub-modules, in order to obtain an increase in stiffness in the exoskeleton areas, under more stress caused by horizontal actions. Also in this case, the number of subdivisions represents one of the parameters of the optimization, and is automatically modified by the solver of genetic algorithms. As in the development of the first design idea, the portion of the algorithm relating to the modeling allows for the automatic generation of the connecting elements between the exoskeleton and the existing structure in reinforced concrete.

7. Analysis and Results

The results are now illustrated and compared, in numerical and geometrical terms, returned by the optimization processes carried out. As already mentioned above, the configuration of the exoskeleton obtained is not unique. The approach used, in fact, provides the possibility to choose among several variants, deriving from the modification of the model parameters and the objectives defined in the fitness function.

In the present work, the first distinction is feasible since two different design ideas are taken into consideration. For both, an optimization process was carried out aimed at minimizing the weight of steel used and maintaining relative drift below the limits reported in Table 1. These are calculated by considering two thirds of the last minimum rotation of each storey of the concrete structure to obtain the value at the life-saving limit state.

Table 1. Displacement limits.

Storey	h	Dlim	Dmax	2/3 Dmax
	[m]	–	[m]	[m]
1	4.3	0.003	0.0129	0.0086
2	3.3	0.003	0.0099	0.0066
3	3.3	0.003	0.0099	0.0066
4	3.3	0.003	0.0099	0.0066
5	3.3	0.003	0.0099	0.0066
6	3.3	0.003	0.0099	0.0066
7	3.3	0.003	0.0099	0.0066
8	3.3	0.003	0.0099	0.0066
9	3.3	0.003	0.0099	0.0066
10	3.3	0.003	0.0099	0.0066

It was also required to verify all the rods by following the assignment of a cross-section included in a pre-established range. The solution obtained by imposing these conditions on the first design idea (variant 1), shown in Figure 15a, is not satisfactory since the removal of the rods is minimal. This is maybe caused by an incorrect interpretation of the problem by the genetic algorithm solver, and returns a design variant that is capable of maintaining the relative displacements below the limits. The result is a naked structural cage without any relationship with the context. In fact, the cage is neutral with respect to the surrounding environment: an indifferent isotropic metal structure that does not favor any relation. The minimization of steel weight resulting from this optimization process is also minimal, and for this reason this solution cannot be considered optimal. For this reason, this solution was compared with an equivalent that provided for a modification of the fitness function. Therefore, it is necessary for the optimization to point to the minimization, not more than the weight, but of the number of rods used. The exoskeleton obtained (variant 2), visible in Figure 15b, despite keeping the displacements below the imposed limits, most likely presents problems related to the earthquake response and it is therefore not adequate from a structural point of view. The elimination of rods in the angular zones of the building induces, in fact, an accentuation of the torsional response of the building-exoskeleton complex subjected to the earthquake. In order to avoid excessive irregular configurations, the movement of the 20 spheres capable of removing the diagrid modules has been limited. First extended to the whole building, it now takes place exclusively in the central area, ensuring the integrity of the angular zones of the exoskeleton. This solution (variant 3) is illustrated in Figure 15c. This optimization process led, in this case, to a considerable reduction of the weight of steel compared to the initial configuration, while maintaining relative displacements below the limits and a regular configuration in the corner areas of the building. Variant 3 is therefore characterized by a good balance between structural behavior and use of materials. It is interesting to analyze the solution (variant 4) obtained without imposing symmetry (Figure 15d), considering limit displacement values, greater than previous solutions. Given the fewer restrictions, the solver is given more freedom in removing the rods. This variant is purely aimed at experimentation and, given the exceeding of the values allowed in terms of displacements, certainly does not return an adequate structural behavior.

Numerical data about each variant, in terms of steel weight, rods number and relative displacements, are compared in Table 2.

Two distinct optimizations were carried out also for the option with embedded quadrangular modules, with the objective of minimizing the weight (variant 5) and the number of rods (variant 6). Because of the initial configuration, the resulting geometries, shown in Figure 15e,f, do not present substantial differences in terms of the overall image of the system, and they both harmoniously relate to the existing building. In contrast to the previous design idea, in this case the definition of the fitness function that aims at minimizing the weight, shows better results.

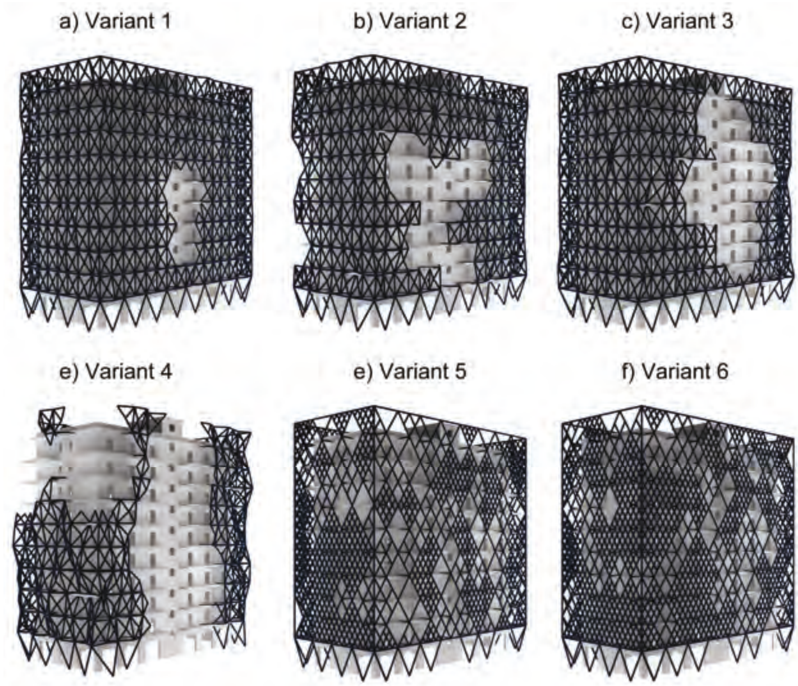

Figure 15. Variants obtained by modifying the parameters of the geometric models and the definition of the fitness function.

Table 2. Comparison between the versions in terms of steel weight, rods number and floors displacements.

		DESIGN IDEA 1					DESIGN IDEA 2		
		Pre-Optimisation	Version 1	Version 2	Version 3	Version 4	Pre-Optimisation	Version 5	Version 6
Weight	kg	336,134	319,900	284,133	269,704	206,155	103,512	225,200	229,124
Rods Number	-	3376	3201	2818	2673	2005	616	4456	4536
u1	m	0.0076	0.0074	0.0071	0.0076	0.0060	0.0100	0.0082	0.0083
u2	m	0.0048	0.0050	0.0058	0.0060	0.0086	0.0185	0.0066	0.0066
u3	m	0.0042	0.0047	0.0061	0.0054	0.0068	0.0266	0.0059	0.0060
u4	m	0.0044	0.0049	0.0063	0.0059	0.0071	0.0355	0.0063	0.0064
u5	m	0.0044	0.0053	0.0064	0.0053	0.0075	0.0457	0.0065	0.0066
u6	m	0.0042	0.0049	0.0065	0.0060	0.0078	0.0541	0.0065	0.0066
u7	m	0.0040	0.0045	0.0064	0.0056	0.0096	0.0661	0.0064	0.0064
u8	m	0.0037	0.0043	0.0058	0.0058	0.0099	0.0701	0.0054	0.0053
u9	m	0.0032	0.0037	0.0051	0.0052	0.0096	0.0848	0.0048	0.0048
u10	m	0.0026	0.0030	0.0048	0.0062	0.0070	0.0797	0.0040	0.0040

Among all the obtained variants, numbers 3 and 5 are considered the best because of their structural responses in terms of displacements, obtained using a limited number of structural elements and a lower weight of steel compared to the other solutions.

The models of these variants were then exported within the SAP2000 finite element software to perform dynamic structural analyses of the existing building-exoskeleton assembly, confronting them with the bare building model. It should be noted that all data relating to materials, cross-sections of structural elements, nodal constraints and degrees of freedom of the rods are transferred automatically using the GeometryGym plug-in. In the SAP2000 environment we proceed exclusively to the introduction of the inputs for modal analysis and linear dynamic analysis.

The two variants, topologically different, but deriving from the same optimization process, respond in a similar way to the dynamic loads. From the modal analysis, a substantial increase in stiffness is denoted, as expected, which causes a reduction of the fundamental periods of oscillation (Figure 16). At the same time, from the examination of the results of the linear dynamic analyses, what emerged was that neither of the two geometric solutions obtained from the exoskeleton is able to maintain the displacements of the existing building within the fixed limits, even if, analyzing the overlap of the displacements over time, of the same point, for all the seven accelerograms chosen [26], a notable reduction of the maximum mean value can be seen. From the 400mm of the actual state, it goes to about 160mm in the project states (Figure 17). Although these are to be considered rough results, as deduced from a linear analysis applied to a problem that, with reference to the existing structure, is markedly non-linear, the results obtained glimpses of a positive response of the generated system.

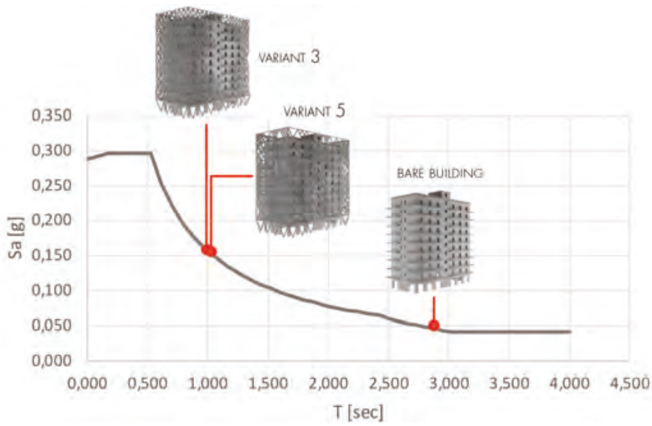

Figure 16. Comparison, using design spectrum, between fundamental periods of the bare building and proposed solutions.

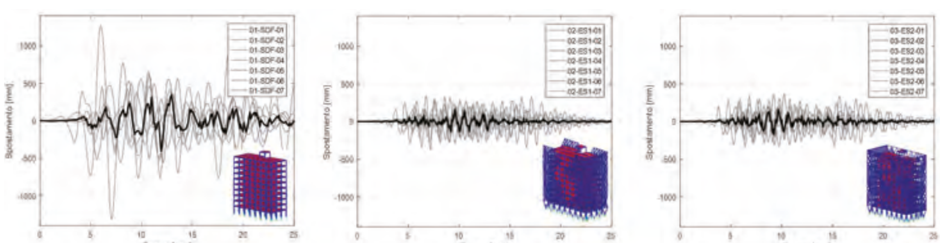

Figure 17. Comparison between the bare building and the two proposed solutions. Displacement diagrams in the most stressed direction. According to NTC18, the response in average terms is considered.

Among these are renderings (Figure 18) that show how further variations can be obtained by completing the exoskeleton with non-structural elements, such as shielding and panels of all kinds, vegetation and solar modules.

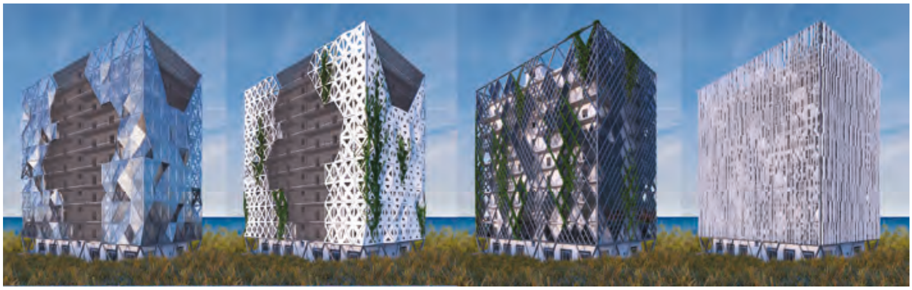

Figure 18. Renderings of the selected variants completed with non-structural elements.

8. Conclusions

The urgency of improving the existing building stock in terms of seismic vulnerability offered us the opportunity to reflect both on the structural aspects and on the architectural image. Thus, the present work has tried to highlight the need to consider aesthetic issue as an important—albeit often neglected—dimension of the search for sustainability. Even if the concept of beauty is hard to tackle, almost impossible to objectify and impossible to be fully reached, it can be considered as a research horizon. And the issue of sustainability offers the opportunity to approach aesthetic research: an opportunity that should be seized since beauty affects all aspects of human life and experience.

The proposed solutions are just proof of the concept of a holistic renovation strategy. In fact, these do not represent the best solutions from an aesthetic point of view. They just demonstrate how, with parametric design, it is possible to produce many complex solutions easily and to choose that which better interprets the aesthetic canons selected by the designer.

In more detail, we have proposed the use of exoskeletons for the seismic retrofit of apartment blocks with reinforced concrete frames. Since the exoskeleton is applied from the outside, it has the advantage of not interfering with the regular operation of the building during the renovation works.

The adopted parametric approach allowed us to consider many variables (geometry and shape, weight, materials, structural elements, forces), leading to a set of solutions that contemplate a multiplicity of aspects of sustainable renovation. In fact, since the early architectural design stages, the creative process has integrated both form and structural functions, as well as information relating on materials and stress response.

This approach is a single tool that offers the possibility to generate multiple retrofitting alternatives based on variables drawn from multiple disciplines, opening the door to a great variety of integrated solutions. In the case presented, we verified the adaptability potential of different types of exoskeleton, which change their shape according to the variability of the external conditions: as occurs in the evolutionary process, reproduction and mutation operate on the genotype, while competition and selection occur at the level of the phenotype. In fact, the use of exoskeleton genotype in this work starts from the simple structural cage to achieve an elaborate structural texture on the façade: an exoskeleton with asymmetrical balance between empty and full spaces. Furthermore, the structure opens (with empty spaces) towards the most interesting landscape points of view and closes (with full ones) to protect itself from unfavorable climatic conditions. In this way we try to establish further relations with the environment.

Such a tool has taken the form of a genetic algorithm, within the Grasshopper graphic editor, aimed at generating and optimizing the form of the steel frames, based on their structural response to equivalent static seismic stresses. The generated geometries are optimized to keep the relative drifts below the limits, to verify all rods, and to minimize the steel weight and the number of rods. Both these parameters were decisive for choosing the best options among the multiple solutions obtained according to different design concepts, geometric inputs and variables of the objective function. These variables have been subjected to linear dynamic analysis that has shown a considerable reduction of the structure displacements in comparison to the actual state. Due to the non-linear nature of the problem, the presented linear, static and dynamic analyses are to be considered preliminary. More detailed results could be expected from a non-linear analysis, thanks to the resistance contribution of steel in the plastic field.

Finally, the proposed solution, although limited to buildings whose footprint can be slightly enlarged, overcomes many of the limitations usually associated with seismic renovation actions including: (i) technical limits, because exoskeletons effectively minimize the renovation activities on the existing building and allow combining multiple interventions in a single stage (structural, energy efficiency, and architectural retrofitting); (ii) organizational limits, since occupants do not need to leave their apartments during renovation works, avoiding transfer disruption and costs, and facilitating condominium consensus; (iii) economic limits, since exoskeletons may reduce time and cost for renovation in comparison with other combined interventions.

The next development of this study will pursue the extension of the algorithm functionalities, introducing parameters related to thermal comfort and energy efficiency among the factors that influence the selection of the optimal exoskeleton shape. The introduction of new variables may further improve the holistic dimension of the proposed methodology, as well as its complexity and completeness.

Author Contributions: Conceptualization, aestethic issue and supervision, S.D.; introduction and state-of-the-art, S.D.; aesthetics and nature as a reference for parametric design, S.D.; the exoskeleton: shape and structure, S.D.; the prototyping algorithm, B.C.; the creation of structural exoskeletons, B.C.; case study, S.D. and B.C.; application to a case study, B.C.; analysis and results, S.D. and B.C.; conclusions, S.D.

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Article

Reducing Seismic Vulnerability and Energy Demand of Cities through Green Infrastructure

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Abstract: Historically, urbanization processes in Italy resulted in built environments with high levels of seismic vulnerability, low energy efficiency and a lack of green spaces. The latter represent the main providers of ecosystem services in cities and play a relevant role in reducing the effects of climate change by the regulation of microclimate and urban heat islands that are responsible for building energy consumption. Despite their importance in providing ecosystem services, the implementation of green infrastructure challenges limited financial resources for the public acquisition of private plots. This paper proposes a strategy to implement an urban green infrastructure aimed at generating a double positive effect on cities by triggering seismic retrofitting and the reduction of cooling energy demand of the existing urban fabric. This is proposed through a transfer of development rights program where landowners gain economic incentives to adopt seismic retrofitting interventions and, at the same time, public administrations implement the green infrastructure in the portion of areas transferred to the municipality. The energy efficiency of buildings closer to the green infrastructure, therefore, benefits from the cooling effects of this new greenery. The strategy is tested under different scenarios of acquisition of private land by public administrations in the metropolitan area of Catania (Italy).

Keywords: green infrastructure; seismic retrofitting; energy retrofitting; ecosystem services; urban planning

1. Introduction

In urban contexts, there is a growing interest in using and deploying natural ecosystems to provide solutions to several urban issues and improve the overall sustainability of urban environments [1]. These nature-based solutions provide sustainable, cost-effective, multi-purpose, and flexible alternatives for various planning objectives and can significantly enhance the resilience of cities [2]. Furthermore, by reshaping the built environment, nature-based solutions can enhance the inclusivity, equitability, and livability of cities, regenerate deprived districts through urban regeneration programs, improve mental and physical health and quality of life for citizens, reduce urban violence, and decrease social tensions through better social cohesion (particularly for some vulnerable social groups, such as children, the elderly, and people of low socio-economic status) [3].

Among nature-based solutions, green infrastructure is a natural, semi-natural and artificial network of multifunctional ecological systems within, around and between urban areas, at all spatial scales [4]. This definition emphasizes the holistic ecosystem vision of urban environments (including the abiotic, biotic and cultural functions) and claims for multi-scale approaches able to take into account the scale-dependent relationships of ecological processes occurring in cities, with particular reference to human health and the well-being of citizens and residents.

Green infrastructure can comprise several urban ecosystems including parks and woodland, blue areas (lakes and streams), greenery, semi-natural areas and other urban features such as green roofs and street trees. In particular, for high-density urban contexts, green infrastructure aims at the following actions: (i) environmental protection and integration of agriculture into urban context, providing specific new agricultural land-use types such as agricultural parks, community supported agriculture, and allotment gardens; (ii) development of suburban green areas in order to provide a more equal distribution of public parks and gardens; and (iii) enhancement of current urban green spaces by improving quality, usability, and accessibility [5]. Ecosystems included in the green infrastructure provide important functions and relative services, such as CO_2 sequestration, production of O_2, reduction of air pollutants and noise, regulation of microclimate and heat island effect, flood damage reduction, filtering water, pollination and supply of recreational value, and play a fundamental role in health, well-being, and social safety [6–8].

This paper focuses on the services of regulation of a microclimate, mainly provided by urban vegetation [9]. Urban vegetation can bring beneficial microclimatic effects, including air temperature reduction, which eases the urban heat island effect. The microclimatic benefits of trees are obtained through several physical processes [10,11]: (1) solar heat gains on windows, walls, roofs, and urban surfaces, including human bodies, are lowered through shading; (2) the buildings' long-wave exchanges are reduced at lower surface temperatures through shading; (3) the dry-bulb temperatures are lowered through evapotranspiration processes; and (4) latent cooling is increased due to the addition of moisture to the air through evapotranspiration. Estimating the cooling effect that can be obtained with different configurations of new greenery is, therefore, a crucial step in enhancing the regulating capacity of urban environments and therefore planning cities more resilient to climate change.

2. Implementation of a Green Infrastructure for Reducing Seismic Vulnerability and Enhancing Energy Efficiency

2.1. Challenges for Planning a Green Infrastructure

Despite its importance in providing the aforementioned ecosystem services, green infrastructure faces several difficulties and limitations for its real development and management, especially in dense urban contexts. The most relevant of these challenges is the public acquisition of the land where green infrastructure will be designed and implemented. This is mainly due to the lack of available areas belonging to municipalities or other public bodies that could be used to develop the green infrastructure. This may dramatically hamper the economic feasibility of implementation, as the direct public acquisitions of land may be economically unsustainable for local administration and often face resistance from private landowners [12].

The issue of economic feasibility for managing public intervention and providing accessible public green spaces could be addressed through incentive-based approaches, including the transfer of development rights (TDR) [13,14]. TDR allows the sale and transfer of development rights from a specific parcel of land to other properties. Future use of the original parcel is then protected from development by a permanent conservation easement or deed restriction prohibiting development. A TDR programme defines an area to be protected from development (sending area) and one where development will be allowed to occur (receiving area) [15,16]. Landowners can transfer the rights to develop one parcel of land to another. As a consequence, the parcel from which the development rights are being transferred can no longer be developed, or developed only in a limited way [15]. Private landowners will get economic incentives from selling developing rights and the opportunity to adopt retrofitting measures aimed at the reduction of seismic vulnerability. This issue can be convenient for districts characterized by multi-storey apartment buildings and shared open setback yards.

2.2. Seismic Vulnerability and Energy Efficiency of Existing Urban Fabric

The assessment of seismic risk of buildings is a complex task requiring the contributions of different scientific fields (from social science to engineering and economic sciences) to evaluate the three main parameters of exposure, vulnerability and seismic hazard [17,18].

Many urban contexts in Europe and especially in Italy face a strong seismic risk. The Italian Institute for Statistics indicates that more than 60% of Italian buildings were built without seismic provisions [19] and 50% of the residential stock is earthquake-prone [20]. Actions, norms and policies aimed at reducing seismic risk to target not only single buildings but, more significantly, be tailored for different portions of urban contexts, at different scales, from single buildings, to blocks, neighborhoods and entire urban areas [21].

To this end, urban policies and actions must be designed to minimise damage caused by earthquakes through reducing vulnerability and specifically, exposure to heritage buildings. In particular, the reduction of vulnerability is a key issue in the debate related to seismic risk reduction [18,22].

Different approaches are available to face seismic vulnerability, such the adoption of specific seismic binding norms, urban planning, and enhancing construction practices. However, in Italy building replacement is still limited [20] and, therefore, seismic retrofitting of existing vulnerable buildings is an essential way to reduce earthquake damage [23]. Retrofitting of historical and modern residential fabric can be an economically efficient approach if compared to post-earthquake re-construction or recovery [24].

An analog situation can be found when looking at the current energy efficiency of Italy's building stock, where more than 1/3 of the overall demand for energy can be attributed to the household and tertiary sector [20]. This high energy demand urges the adoption of energy retrofitting measures and policies at different political and administrative levels.

Many retrofitting technologies and approaches are available, and they can be categorised into three main categories: supply side management, demand side management, and change of energy consumption patterns due to human habits [25]. The choice of which technology, policy or measure should be used is a multi-objective problem with many variables, constraints and limitations. The optimal solution can be considered as a trade-off among a number of factors, such as energy, economics, technical, environmental, regulations, social, etc. [25].

However, seismic and energy retrofitting policies have to face a number of complex issues related to the required economic efforts, technical feasibility, number of actors involved, the political coordination among different administrative levels, the need of involving many disciplines and local requirements [20,23]. At the national level fiscal incentives are currently proposed, especially in the form of a tax credit (up to 65% in 10 years) to those willing to implement retrofitting actions. However, the required costs for the investment are still far from the possibilities of the majority of people, so alternative mechanisms to support seismic and energy retrofitting are still needed [26]. Urban planning strategies should, therefore, foster and support retrofitting measures for low-income people and to facilitate the engagement of building owners in retrofitting activities [20].

2.3. A Green Infrastructure Strategy for Reducing Seismic Vulnerability and Increasing Energy Efficiency

We propose in this paper a strategy for implementing the components of a green infrastructure aimed at triggering seismic retrofitting and energy demand reduction of urban fabrics through a TDR programme. Typically, in a TDR programme, development rights are assigned to strips of private land parcels that are designated for accommodating the green infrastructure. Development rights can be then transferred from these portions of parcels to other urban zones and used for new developments. As a result of the sale of the development rights, the involved parcels of urban fabric can be seismic-retrofitted, the strips transferred to public property for placing new components of a green infrastructure, and the new greenery provide cooling effects and generate a considerable decrease of energy demand in adjacent buildings.

The amount of development rights to be assigned to strips of land parcels is identified according to an economic feasibility assessment tool (see Section 3.2.3). To ensure the economic feasibility of the seismic retrofitting, this tool enables the quantification of equitable development rights to be assigned to each private parcel taking into account the amount of current developed volume of buildings, size of open spaces to be potentially left, seismic retrofitting costs, and economic rate of development rights to be sold.

3. Materials and Methods

3.1. A Case Study in the Catania Metropolitan Area (Italy)

The case study investigated in this work is located in the metropolitan area of Catania, the largest in Sicily. Catania has experienced dramatic urban growth in recent decades, and is characterized by a high urban density and severe lack of public green spaces. In 40 years (1961–2001), the total population of 27 municipalities included in the metropolitan area grew more than 27% in terms of built-up areas. In 2017, approximately 60% of its total population lived outside the main city, indicating progressive population expansion beyond the city center. We chose the municipality of Tremestieri Etneo (Figure 1), as a representative area where urbanization processes have been characterized by multi-storey builidings urban development [27]. Furthermore, the entire metro area is one of the areas most exposed to seismic risk in Italy.

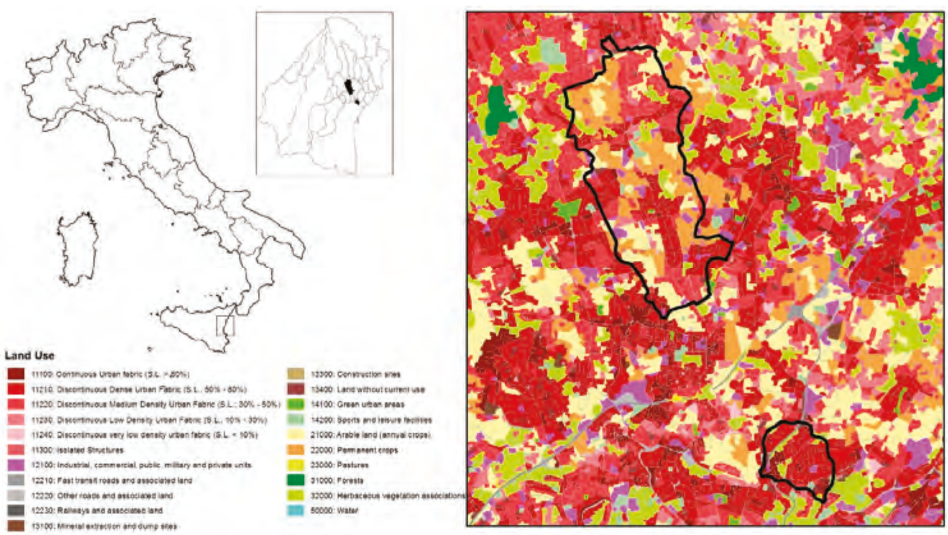


Figure 1. Localization and land-use the municipality of Tremesteri Etneo within the Metropolitan area of Catania (Italy) (source: Urban Atlas 2012).

3.2. Method

The method is composed of four different phases: (1) urban growth and urban morphology analyses to identify building age classes and categorization of urban morphology types in order to select the most suitable type of urban fabric to apply the proposed strategy of green infrastructure; (2) a land-use/land-ownership analysis to identify the land-use and landownership asset of each compound; (3) An economic feasibility assessment tool to quantify the equitable development rights to be assigned to private land parcels and the size of open spaces to be transferred to public property, taking into account different economic costs of seismic retrofitting and urban development parameters;

(4) a microclimate model to evaluate the potential cooling effect of new vegetation in the green infrastructure, estimating the reduction of energy demand for typical multi-storey buildings.

3.2.1. Urban Growth and Urban Morphology Analyses (First Phase)

The analyses of urban growth and urban morphology are a key phase because seismic vulnerability and energy demand options depend on the age and form of the urban fabric [28].

Urban growth analysis was developed at block and sub-block level through the examination of the mean building age of urban fabrics and identifying six age classes: buildings and fabric built until 1928, 1964, 1985, 2000, 2007 and 2015. These years represent the available topographic sources used to map urban growth. Buildings belonging to different age classes were characterised by different materials and construction technologies (stonemasonry, mix of stonemasonry and steel structures, reinforced concrete structures) that show different levels of resistance to seismic activity [29]. In particular, buildings built-up to 1928 were mainly stonemasonry buildings while reinforced concrete buildings appeared in the period 1928–1964. In Italy, the first regulation requiring the evaluation of the seismic actions on reinforced concrete buildings was introduced in 1975. The DM 3/3/1975 Act represented a fundamental innovation in the analytical procedures by taking into account the dynamic properties of the structures [30]. However, the very first set of technical indications for designing reinforced concrete buildings in seismic zones was introduced in 1986 by the DM 24/1/1986. This act provided the first requirements concerning structural maximum allowable deformation under seismic actions. Nevertheless, more comprehensive and reliable seismic design concepts only appeared in Italy in 1996 through the DM 16/1/1996 Code that introduced the capacity design concept, even based on non-structural damage limitation [30].

Thus, norms and regulations have significantly shaped the seismic features of reinforced concrete buildings over the past decades. Buildings built-up to 1985 (before the DM 24/1/1986 Act) can be considered as more vulnerable to seismic events compared to buildings constructed from 1986 and even more after the implementation of DM 16/1/1996 Code. In this study, according to the available six interval classes of building age, reinforced concrete buildings belonging to the age classes of 1964 and 1985 have been considered more vulnerable than buildings belonging to the age classes of 2000, 2007 and 2015 and, consequently, can be prior targets of seismic retrofitting policies.

Urban morphology analysis identified those buildings where the green infrastructure strategy could be implemented. This was developed at block and sub-block level taking into account results from the previous urban growth analysis and considered two additional features: type of buildings, such as detached or semi-detached houses, terraced houses, multi-storey apartments, towers; and the relationship among buildings, streets and public and private open spaces, that can be characterized by interior courtyards or front/rear/side setback yards, sidewalks, parking lots, or small urban gardens. Different combinations of these features produced varied morphological layouts and built-up density. Building coverage ratio and percentage of open spaces were measured to identify urban morphology types. The urban morphology analysis was based on a regional topographic map (1:10,000) and a more detailed municipal topographic map (1:2000). Here the green infrastructure strategy was implemented for regular and irregular blocks with multi-storey buildings of reinforced concrete frame structures. Regular and irregular blocks are composed of different compounds, defined as gated residential units of buildings and related open spaces. These compounds are characterized by very large residential population, multiple private properties (apartments, garages), spaces with shared assets such as lobbies, staircases, lifts and adjacent open setback yards (walkways, green spaces, and park plots) (Figure 2).

Figure 2. Landownership Analysis. Visual interpretation of high-resolution orthophoto (25 cm, 1:10,000) on a sample Compound (B = building, P = private open space, S = shared open space).

3.2.2. Land-Use/Land-Ownership Analysis (Second Phase)

Since regular and irregular blocks with multi-storey buildings morphology type can be composed by a mix of both private and shared land uses, the land-use and the land-ownership asset of each compound were analyzed to verify the presence of open spaces that can be transferred to public property in the TDR programme. This was performed by visual interpretation of available high resolution orthophotos on sample areas for each of the selected three morphology types. Three land-use types were chosen and identified in each morphology type: buildings, private adjacent setback yards, and shared open spaces (walkways, green spaces, and park plots) (Figure 2). Among these land-use types, the shared open spaces represent those portions that could be left to public property against corresponding economic benefits in the TDR programme.

3.2.3. Economic Feasibility Assessment Tool (Third Phase)

The implementation of a suitable and realistic TDR programme represents a crucial phase in the proposed strategy. This is based on the assignment of development rights to the shared open spaces within the compounds that could be designated for the green infrastructure. Development rights could be transferred from these private parcels to other urban zones and used for new development. Landowners of the compounds could also sell development rights to other private developers obtaining economic earnings for covering the costs of the seismic-retrofitting. Finally, the shared open spaces could be transferred to the municipality which will plant the new greenery, thus generating a cooling effect through the shading effect of trees on adjacent buildings and a consequent decrease in their energy demand.

In the third phase, the economic viability of the TDR programme was evaluated. This was accomplished through a tool that was developed to quantify the equitable development rights to be assigned to each compound for leaving to become public property a percentage of the shared open spaces, transferring to other privates and developers the virtual amount of development while gaining economic revenues for future seismic retrofitting (Table 1).

To evaluate the economic feasibility, the tool sets the values of three main input parameters. First, a virtual floor area ratio (VFA) of 4.50 m^3/m^2 was identified over the land parcel of shared open spaces to be transferred (TFA) in terms of amount of development to be transferred (VT). This value of VFA represents the mean value in existing buildings calculated as the ratio between the developed volume (V) and the land parcel unit area (LPA). Second, a seismic retrofitting rate (SRR) was defined as 70 €/m^3, in accordance to the value indicated by the Italian Urban Developers National Association [31]. This allows evaluation of the total retrofitting costs of buildings within the compound taking into account the number of storeys (S) and the total amount of developed volume

(V). Finally, the provided economic rate of development rights ERT = 150 €/m^3 allows the evaluation of potential economic revenues (ERV) to be gained after selling. ERT was been calculated according to the economic feasibility of new development that will occur in other parts of the urban settlement where the virtual development rights will be allocated. Indeed, developers buying these rights have to deal with further costs while striving for a final economic profit ≥25% that is considered by Italian Urban Developers National Association as a reasonable percentage value of investment profit [31]. According to the tool, the overall seismic retrofitting costs can be achieved when the final balance (B) between economic earnings from development rights (ERV) and the total retrofitting costs (SRC) is ≥0.

Table 1. Economic feasibility assessment tool for seismic retrofitting intervention.

Economic Feasibility Assessment Tool—Seismic Retrofitting		
Compound Morphology Parameters	Buildings Area	BA
	Land Parcel unit Area	LPA
	Buildings Coverage Ratio	BCR = BA/LPA
	gross height of single storey	h
	number of Storeys	S
	total building Height	H = h × S
	amount of developed Volume	V = BA × H
	Floor Area Ratio	FAR
	Open spaces floor area	OFA = LPA − BFA
	% of open spaces to be transferred	% OFA
	Floor Area to be transferred	TFA = OFA × % OFA
Input Parameters	Seismic retrofitting rate	SRR
	Seismic retrofitting cost	SRC = SRR × V
	Virtual Floor Area Ratio	VFA
	amount of development to be tranferred	VT = VFA × TFA
	% increasing of new development	% V = VT/V
	economic rate of development rights	ERT
Costs Coverage Parameters	economic revenues from development rights	ERV = ERT × VT
	percentage of costs Coverage	% C = ERV/SRC
	final Balance	B = ERV − SRC

3.2.4. Potential Local Cooling Effect of Trees and Relative Building Energy Demand Reduction (Fourth Phase)

The interactions among urban vegetation, urban structures, and urban climate generate different microclimate conditions that also need to be evaluated for each urban context studied. Typically, vegetation can lower both the air temperature and wind speed of the surrounding microclimate, reducing the cooling load, but current research agrees that the cooling effect in small areas is obtained mainly through shading [10]. Other factors that inhibit the penetration of solar radiation, besides shading, may also play a role in determining the cooling effect of an urban green space. The geometric configuration may also affect temperature variations, as happens for non-wooded building structures [32]. Although a cooling effect has been reported even for small green areas [33], the extent of this effect on neighbouring buildings is less evident and subject to limited research [34].

We postulated that the implementation of green infrastructure in portions of private shared open spaces as a result of the TDR programme could result in a relevant energy saving through the shading effect of the new trees that are planted. To quantify the possible energy savings, we considered the model by [10], who analysed the dynamic interaction between microclimate and buildings. These authors simulated the optimal position of trees around a building through parametric design in order to estimate the energy saving that could be achieved through the shading effect of trees on the buildings. Results of the simulations resulted in an energy saving ranging from a minimum of 11% when locating only 1 tree to a maximum of 48.5% when locating 5 trees around buildings, therefore highlighting that a limited amount of greenery is able to achieve a relevant energy saving.

Figure 3 reports the possible configurations of the position of trees with respect to the buildings studied in this paper. Table 2 shows the relative energy savings (in %) according to those configurations as modelled by [35], for the configurations 1, 4, 6 and 7. Configurations 2, 3 and 5 were not taken into account as they were not assessed by [35].

Table 2. Energy reduction for configuration of trees (Calcerano and Martinelli, 2016).

#Configuration of Shading Trees	Range of Energy Demand Reduction (%)
1 (W + E + S)	44.4–48.5
4 (W + E)	37.3–41.8
6 (E)	19.2–21.2
7 (S)	11.1–12.8

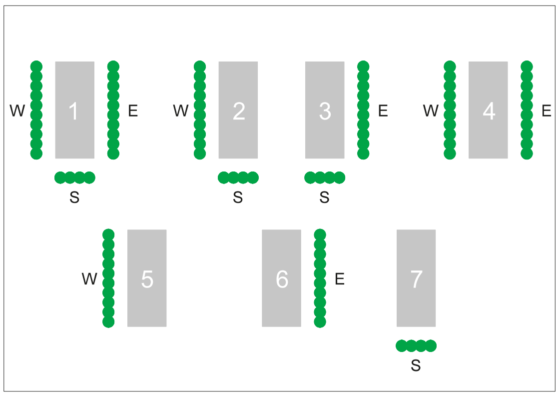


Figure 3. Possible configurations (W = West, E = East, S = South) of shading trees (in green) around buildings (in grey).

4. Results

Urban growth analysis showed that in the tested municipality the majority of the urban fabric was developed after 1964 (56% in terms of building area, BA), with a first impressive boost in the period 1964–1985 and a second in the period 1985–2000 [32] (Figure 4, Table 3).

Table 3. Size and proportion of buildings and urban fabric alongside in the period 1928–2015.

Buildings and Urban Fabric to	Area (m^2)	Area (%)
1928	257,761	9.47
1964	213,667	7.85
1985	1,337,113	49.10
2000	774,885	28.46
2007	121,269	4.45
2015	18,294	0.67
Total	2,722,989	100.00

Urban morphology analysis identified eight urban morphology types within the study area, sub-divided into two sub-classes: historical and modern urban fabrics. Modern urban fabric includes more categories, since a great variety of buildings typologies have been used since the 1960s. These are often characterised by urban patterns with multi-storey apartment buildings set back from streets and including private or semi-private open spaces. Urban morphology analysis was mapped in Figure 5 and summarised in Table 4 [36]. The category of Regular and Irregular blocks with multi-storey buildings represents almost 30% of the urban fabric, with a total of 132 compounds.

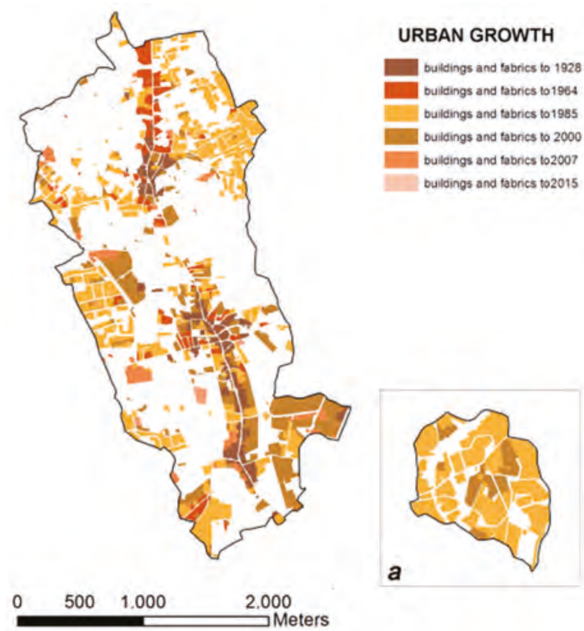


Figure 4. Urban growth map of the municipality of Tremestieri Etneo, Catania (Italy); (a) enclave of the municipality located at the south-east end of the territory.

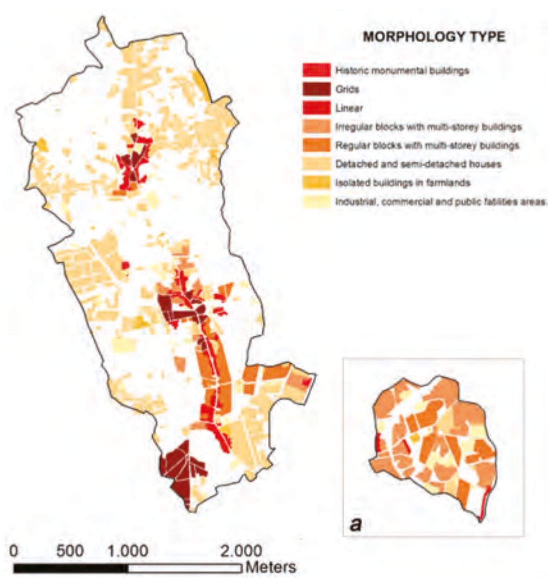


Figure 5. Urban morphology map of the municipality of Tremestieri Etneo, Catania (Italy); (a) enclave of the municipality located at the south-east end of the territory.

Table 4. Size and proportion of each urban morphology type within the urban fabric.

Urban Morphology Types	Area (m^2)	Area (%)
Historic monumental buildings	10,263.30	0.37
Grids	183,251.90	6.60
Linear	176,763.30	6.36
Irregular blocks with multi-storey buildings	440,140.00	15.85
Regular blocks with multi-storey buildings	345,091.70	12.42
Detached and semi-detached houses	1,324,738.70	47.69
Isolated buildings in farmlands	73,722.90	2.65
Industrial, commercial and public utilities areas	223,569.20	8.05
Total	2,777,541.00	100.00

15 patches were further detected and then excluded from the evaluation because they belonged to other morphological types and were mixed-up with the Regular and Irregular ones. The amount of shared open spaces (walkways, green spaces, and park plots) was also evaluated to understand the suitability of compounds for the proposed strategy. As a result, 49 compounds out of the remaining 117 were evaluated as not suitable because they lacked or showed an insufficient quantity of shared open spaces to be left as public property against the assignment of development rights as quantified by the strategy. Another 35 compounds belonged to the age classes 2000, 2007 and 2015 (see Figure 5) and, therefore, were considered as not a priority for seismic retrofitting actions compared to the reinforced concrete buildings belonging to the age classes of 1928, 1964 and 1985. As a final result, 33 compounds out of the initial 132 were evaluated as being seismically vulnerable and thus suitable for urban transformation and eligible for the proposed strategy (Figure 6).

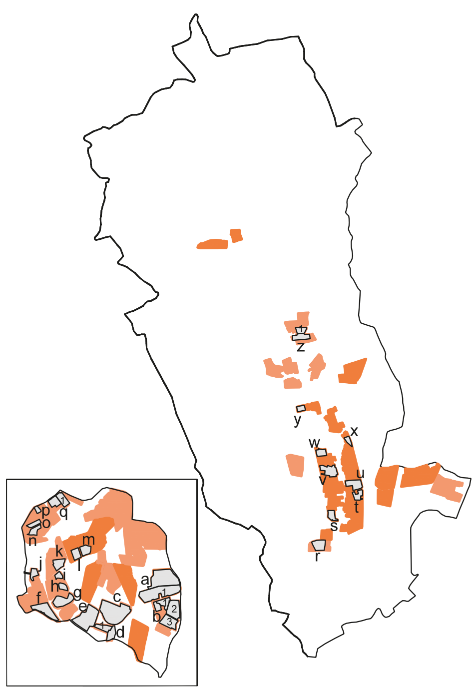


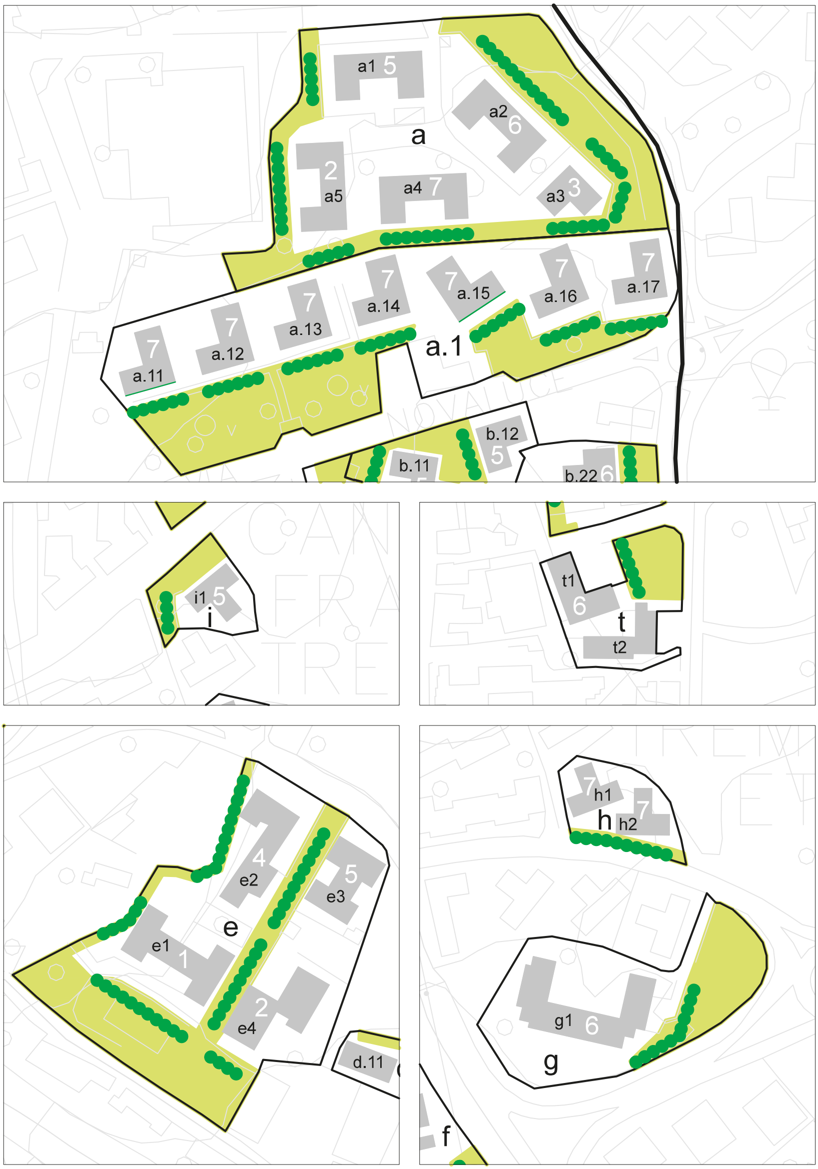
Figure 6. Thirty-three selected compounds (from a to z.1, in grey) out of the initial 132 belonging to the morphology category of Regular (dark orange) and Irregular (light orange) Blocks with multi-storey buildings.

These compounds show different features in terms of land parcel unit area, building coverage ratio, amount of developed building volume, and open spaces floor area. The economic feasibility assessment tool presented in Section 3.2.3 assigned a virtual floor area ratio (VFA) = 4.50 m^3/m^2 to the shared open spaces designated for being left to public property, and estimated an economic rate of development rights (ERT) = 150 €/m^3, and a seismic retrofitting rate SRR= 70 €/m^3. As an example, Table 5 reports the results of the application of the tool for the compound a.1.

Table 5. Economic feasibility assessment. Results from the compound a.1.

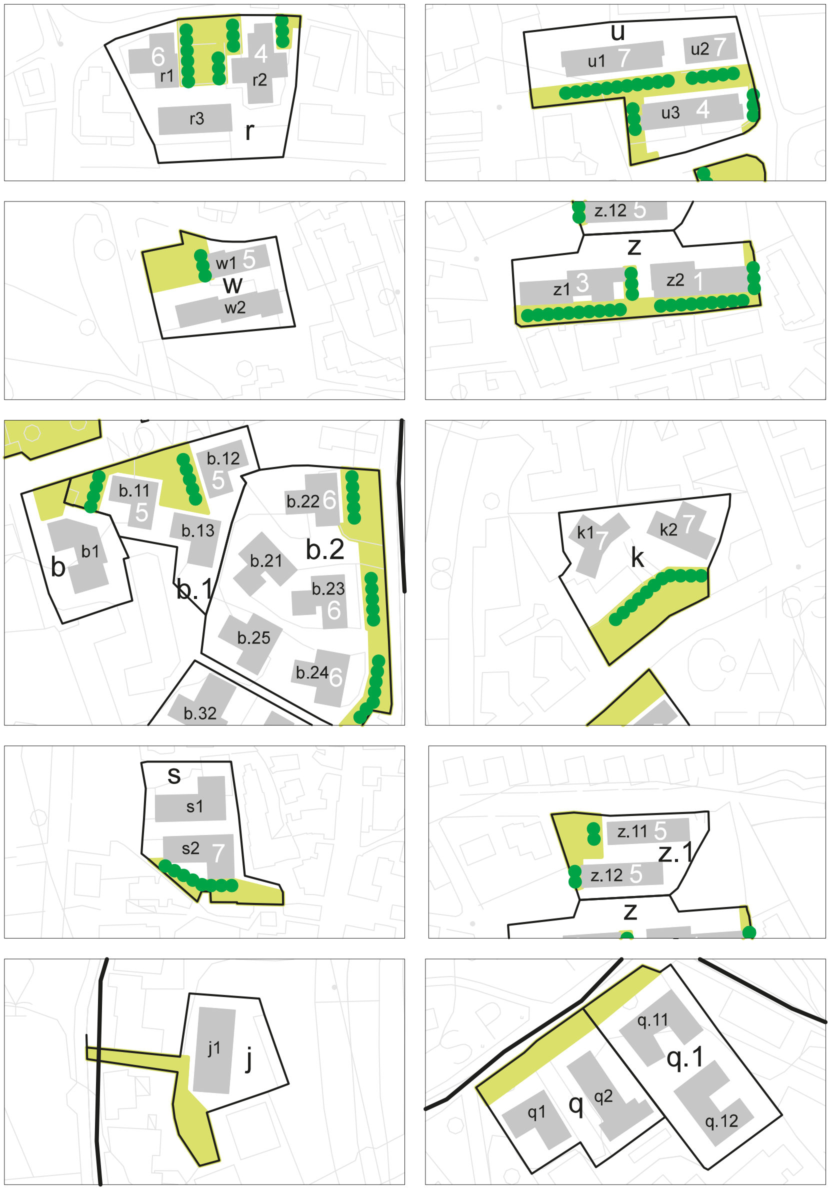
Economic Feasibility Assessment—#Compound a.1			
Buildings area	BA	3867.00	m^2
Land parcel unit area	LPA	18,858.00	m^2
Buildings coverage ratio	BCR = BA/LPA	20.51	%
Gross height of single storey	h	3.00	m
Number of storeys	S	5.00	
Total building height	H = h × S	15.00	m
Amount of developed volume	V = BFA × H	58,005.00	m^3
Floor area ratio	FAR	3.08	m^3/m^2
Open spaces floor area	OFA = LPA − BFA	14,991.00	m^2
% of open spaces to be transferred	% OFA	40.42	%
Floor area to be transferred	TFA = OFA × % OFA	6060.00	m^2
Seismic retrofitting rate	SRR	70.00	€/m^3
Seismic retrofitting cost	SRC = SRR × V	4,060,350.00	€
Virtual floor area ratio	VFA	4.50	m^3/m^2
Amount of development to be tranferred	VT = VFA × TFA	27,270.00	m^3
% increasing of new development	% V = VT/V	47.01	%
Economic rate of development rights	ERT	150.00	€/m^3
Economic revenues from development rights	ERV = ERT × VT	4,090,500.00	€
Percentage of costs coverage	% C = ERV/SRC	100.74	%
Final balance	B = ERV − SRC	30,150.00	€

The tool showed that the overall seismic retrofitting costs can be covered at 95–100% (final balance B $\geq$ 0) when floor area ratio (FAR) $\leq$ 3.3 m^3/m^2 and % open spaces floor area (% OFA) $\geq$ 40% (compounds a, a1, i, t) (Figure 7a). Values of % OFA $\geq$ 24% and FAR $\leq$ 4.5 m^3/m^2 determine at least 2/3 of costs coverage (66%) and can cover up to a maximum of 94% that means a final balance < 0; this is the case of the compounds e, g (Figure 7b), d.1, j, n, r, u, v, w, z (Figure 7b). When FAR $\leq$ 5.3 m^3/m^2 and % OFA $\leq$ 26% costs coverage are covered at least 50% and up to 65%: this is the case of the compound b.1, d, k, s, z.1 (Figure 7b). In all other remaining compounds (b, b.2, b.3, c, f, h, l, m, o, p, q, q.1, x, y), values of FAR and % OFA imply that potential economic earnings from development rights can no longer balance the total retrofitting costs with a percentage of cost coverage % C decreasing from 49% to about 8%. As a final result, in the 12% of the total amount of compounds (4 out of 33) seismic retrofitting is economically viable and can be fully funded (Table 6). For most of the compounds (30%, 10 compounds) retrofitting can be undertaken through covering 66% up to 94% of the total costs; 15% of the compounds (5) can get economic restoration and covering from 50% to 65% of the retrofitting costs. The remaining 47% of the compounds can be considered disadvantaged and the seismic retrofitting resulted to be not economically viable (Table 7). Plotting the values of the four seismic retrofitting costs coverage (% C) classes (>50%, 50–64%, 65–94%, >95%), Figure 8 shows that corresponding values of FAR and % OFA identify four clusters and that the economic feasibility of the compounds transformation increases according to the increasing values of FAR and the decreasing values of % OFA.



(a)

Figure 7. *Cont.*



(**b**)

Figure 7. (**a**) Compounds a, a.1, i, t (seismic retrofitting costs coverage = 95–100%); compounds e, g, h (seismic retrofitting costs coverage = 66–94%). Buildings in dark grey, shared open spaces in light green, private adjacent setback yards in white, trees line in dark green. (**b**) Compounds r, u, w, z (seismic retrofitting costs coverage = 66–94%); compounds b.1, k, s, z.1 (seismic retrofitting costs coverage = 50–65%); compounds j, q, q1 (seismic retrofitting costs coverage = 8–49%). Buildings in dark grey, shared open spaces in light green, private adjacent setback yards in white, treelines in dark green.

Table 6. Morphology parameters and percentage of costs coverage for the 33 selected compounds.

#Compound	Floor Area Ratio (FAR) m^3/m^2	% Open Spaces to Be Transferred (% OFA)	% of Costs Coverage (% C)
a	3.29	42.91	102.68
a.1	3.08	42.91	100.74
b	3.18	12.41	27.68
b.1	4.46	35.60	54.16
b.2	3.87	24.00	44.44
b.3	4.88	24.60	32.80
c	2.94	15.88	39.23
d	5.29	43.30	55.76
d.1	4.49	42.21	68.10
e	3.74	37.97	77.69
f	4.42	28.84	47.51
g	3.21	32.37	79.80
h	6.08	20.24	21.25
i	3.13	48.05	117.15
j	3.44	36.24	78.30
k	4.22	33.72	61.54
l	9.74	30.13	16.00
m	8.44	12.16	8.30
n	4.20	41.16	68.02
o	7.12	31.58	25.88
p	6.04	26.68	28.33
q	3,38	22,78	46,63
q.1	3.53	13.63	26.24
r	2.44	24.25	69.91
s	3.13	25.96	52.21
t	3.12	47.43	95.93
u	2.39	31.18	92.62
v	2.46	29.86	85.17
w	2.61	30.61	80.45
x	2.65	19.22	49.42
y	3.99	35.02	47.04
z	3.51	38.53	75.03
z.1	2.98	30.15	65.31

Table 7. Viability of seismic retrofitting (% of costs coverage) for each selected compound.

#Compound	Number of Compounds	% Compounds	% of Costs Coverage (% C)
a, a.1, i, t	4	12.12	95–100%
d.1, e, g, j, n, r, u, v, w, z	10	30.30	66–94%
b.1, d, k, s, z.1	5	15.15	50–65%
b, b.2, b.3, c, f, h, l, m, o, p, q, q.1, x, y	14	42.42	8–49%

Following the model reported in Section 3.2.4, the 33 selected compounds were analysed to evaluate the potential local cooling effect of the new trees in reducing the buildings' energy demand. Alongside the shared open spaces of each compound, seven configurations of shading trees were identified (Figure 3). The possible layouts of new trees to be planted around each building depend on the spatial relationship between buildings and the available shared open spaces. Among the 93 buildings in the 33 compounds, configuration #7 (S, South) resulted in being the most suitable for 27 buildings, configuration #6 (E, East) for 13 buildings, configuration #5 (W, West) for 14 buildings, and configuration #4 (E + W), configuration #3 (S + E), configuration #2 (S + W) and configuration #1 (S + E + W) were suitable for 3 buildings each. For the remaining 27 buildings, no configuration of shading trees can be proposed because of the lack of surrounding shared open spaces (Table 8).

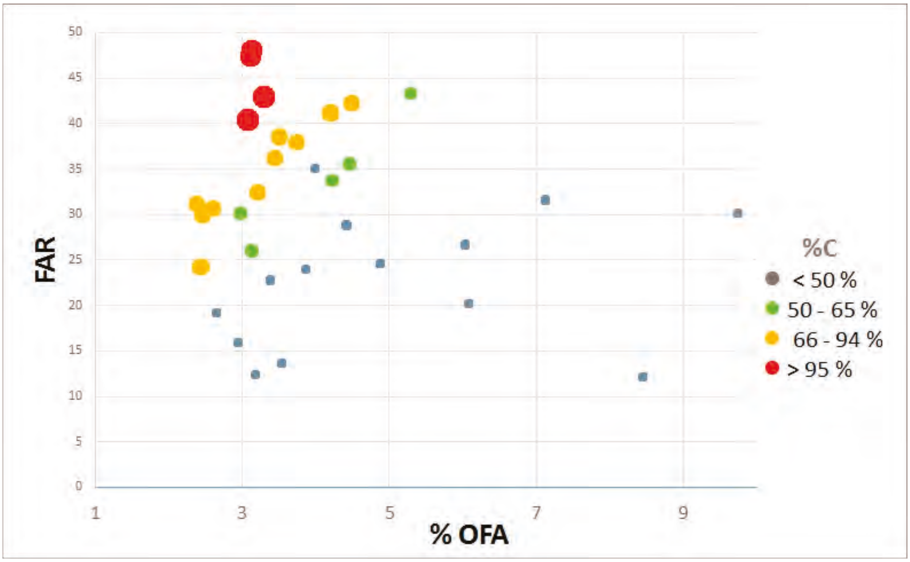


Figure 8. Distribution of seismic retrofitting costs coverage (% C) according to the values of FAR (m^3/m^2) and % OFA (%).

Table 8. Number and percentage of buildings per each configuration of shading trees.

#Configuration of Shading Trees	Number of Buildings	% of Buildings
1	3	3.23
2	3	3.23
3	3	3.23
4	3	3.23
5	14	15.05
6	13	13.98
7	27	29.03
/	27	29.03
Total	93	100

The highest values of energy demand reduction (varying from 37.3–41.8% up to 44.4–48.5%) involve a total 6% of the buildings (respectively, configurations #4 and #1) and producing significant results in terms of cooling by shading and, therefore, decreasing the relative energy demands.

For most of the buildings (more than 29%), the range of energy demand reduction is 11.1–12.8% (configuration #7) while for almost 14% of the buildings the percentage of energy reduction varies from 19.2% to 21.2% (Table 9).

Table 9. Percentage of energy demand reduction per each building within the configuration of shading trees #1, 4, 6, 7.

Range of Energy Demand Reduction (%)	#Configuration of Shading Trees	Number of Buildings	% of Buildings
44.4–48.5	1	3	3.23
37.3–41.8	4	3	3.23
19.2–21.2	6	13	13.98
11.1–12.8	7	27	29.03

Within each compound, the number of buildings benefitting from the shading effect of the trees, varies according to the amount of surrounding shared open spaces (Table 10). It can be seen that for 15 compounds (45.45%), the total amount of existing buildings (100%) can benefit from reduced energy demand while the percentage of beneficiary buildings decreased from 83.33% up to 60% in another 5 compounds. Moreover, in 8 compounds (24.24% of the total), only 50% of the buildings can be surrounded by shading trees. While in the remaining 5 compounds (15.15%) the lack of surrounding shared open space does not allow any plantation of shading trees.

Table 10. Proportion of buildings benefiting from the shading effect of the trees within each compound.

% of Buildings Benefitting from Shading Trees	Number of Compounds	% of Compounds
100	15	45.45
83.33–60	5	15.15
50	8	24.24
/	5	15.15

5. Discussions

5.1. A Multi-Benefits Strategy Depending on Economic Viability

Overall, the benefits could be considered as the result of many intertwined attributes of the built environment, such as built-up density, building coverage ratio and percentage of open spaces within the blocks. Regular and Irregular blocks with multi-storey buildings include compounds that present different proportions and spatial arrangements of built-up areas and shared open spaces. Especially for dense urban contexts lacking green spaces, the peculiarities of these compounds may represent an opportunity for implementing a green infrastructure: they include open spaces with shared property assets that can be transferred to public property against the provision of development rights and can be used as areas in which to implement the green infrastructure.

The urban transformations of the future imply the potential achievement of new open spaces without financial efforts for local administrations. This could represent the basis for designing and implementing a new public green network of walking and cycling routes crossing-over the urban fabric. On the other hand, the landowners of the compounds, who have left their own shared open spaces to public property, could obtain as compensation a suitable amount of development rights to be sold to other private landowners and/or developers. The latter would be then able to transfer and use the development rights in other urban areas to increase the square footage and the height of existing buildings or developing new residential units.

The application of the strategy also returned a scenario of hundreds of small private open spaces scattered within the city that could be potentially transferred to public property and linked to existing roads, parking areas, playgrounds and existing small gardens. Even though the positive effects of just a few trees around each building was recognised, a green infrastructure strategy incorporating plantations of longer treelines could provide urban greenery and deliver a wider set of ecosystem services [37].

The multi-scale impact (from municipal level to building level) was the most significant feature of the proposed strategy. The possibility to improve the seismic safety and the energy efficiency of the built-up environment from neighbourhood level to the smallest scale of the single building, while enhancing the ecosystem performance of the overall urban fabric, represents a relevant opportunity for any planning strategy and transformation action. The urgent issue of making cities more sustainable, efficient, healthy and safer places [7] can only be addressed through a strategy which is grounded on an economic feasibility assessment of urban transformation and ensures the viability of the fragmented property assets balancing public/private costs and benefits [15].

Indeed, the economic feasibility of the proposed green infrastructure strategy might be affected by different market factors such as land and property prices that often depend strictly on local real estate dynamics [38]. Investigation of the economic land value of existing shared open spaces and the final market value of the potential up-zoning or new developments is crucial for better identifying the appropriate amount of development rights to be assigned to the compounds. Thus, the correct identification of the economic rate of development rights (ERT), through a specific local market prices survey, is required to trigger the transfer of development rights from compounds to other urban areas to be developed. Landowners of compounds would be willing to sell their own development rights whether the economic earnings will be enough to cover the seismic retrofitting costs. On the other hand, developers could buy the available development rights whether their cost will allow an adequate economic profit compared to the final market value of the new developments.

5.2. Achieving Seismic Retrofitting and Reduction of Cooling Energy Demand

Concerning seismic retrofitting, the results highlight that half of the total compounds would need some seismic retrofitting but only 25% were suitable according to the availability of shared open spaces. More specifically, seismic retrofitting was found to be economically viable in more than 40% of these selected compounds, allowing landowners to be funded for more than 2/3 of the total costs. The availability of such funds to be shared among the landowners is a key issue for the viability of a seismic retrofitting due to the multi-fragmented ownership of each compound. The large amount of single private properties in the compound such as apartments and garages, mixed up with shared assets such as lobbies, staircases and lifts but also walkways, green spaces and park plots, represents a real obstacle for implementing any kind of intervention. A property asset with a high number of private landowners implies a challenging decision that needs to address the willingness and the financial means of all owners in the compound [39]. However, these results appear promising because efforts to reduce the seismic vulnerability of the existing real estate are limited and urban policies for seismic risk mitigation are still at an early stage of development [20].

At the building scale, results show that more than 50% could benefit from the cooling effect of the trees if planted alongside the public acquired open spaces. According to the results, planting a treeline simultaneously alongside east, west and south sides (or just east and west sides) of the buildings could lead to a reduction of energy demand of up to 48.5%: locating trees alongside these orientations represents the best option to obstruct solar radiation in summertime, provide a shading effect on buildings, while reducing the local temperature around.

The reduction of buildings' energy demand has been evaluated according to the study conducted by [35] that clearly showed the potential cooling effect of different tree layouts around buildings. Investigation in other similar research has detected different approaches and models for evaluating the trees' shade effect on cooling energy reduction. These studies confirmed and validated the trees shading effect on the reduction of building cooling energy demand with different results that depend on the different urban environments, land-use configurations, and micro-climate conditions. For example, [40] highlighted that shaded building by greenery have a greater inertia in warming up and demonstrated how shading can result in an important saving of money for cooling (up to 218 € in the case study of Akure, Nigeria). Reference [41] valuated that the savings associated with urban shade trees can be up to $200 per tree (including the carbon sequestration effect). Reference [42] compared two identical buildings in Alabama (USA) and calculated that the unshaded building under full sunlight during the summer period required more than 2.6 times the amount of cooling energy than a shaded one. Moreover, a further but limited cooling effect could be provided by the evapotranspiration process of greenery, that could decrease local temperature in the surrounding of the buildings proportionally to the amount of tree canopy. Reference [43] quantified an energy saving of 15% when a scenario of shading and transpiration was considered.

Finally, tree species should be chosen and placed in order to properly shade the entire facades of the buildings and, therefore, maximise the reduction of energy demand: to this end, deciduous trees allowing for solar gain during the wintertime could be preferred, yet differences in cooling effects can be observed among different species [44,45].

5.3. Limitations

Beside the positive relevance of the results, the proposed strategy also shows some limitations. Implementing a green infrastructure is not always viable and may be strongly affected by the quality and amount of the open spaces to be acquired. The size, shape and location of the shared open spaces within the compounds were not always considered suitable for conversion into components of a green network. Their reduced size and narrow shape could negatively affect the design of the green intervention while their location, remoteness and interrelationship with the private residential buildings could affect the real possibility to connect open spaces to existing public gardens and roads. Moreover, the amount and the geographical distribution of these open spaces (which could be concentrated in specific areas) could generate some inequality in the provision of new urban green spaces at municipal level [46].

Although not all the possible configurations of greenery around the buildings were assessed (Figure 3), we choose those configurations that limited the number of trees to be located and that, therefore, represented more economical solutions in terms of financial resources needed for their deployment.

The implementation of retrofitting actions would generate new development of more than +50% of the total current development volume of the compounds. This is dependent on the amount of development rights to be granted to private compounds as a compensation for leaving their shared open spaces. The total amount of development depends on the number of compounds which could be retrofitted. In this case study, seismic retrofitting is viable for a very small proportion of compounds (6% of the selected ones, more than 1% of the total compounds) and this means that a limited amount of new developments could be transferred to other areas to be developed. When the number of compounds to be retrofitted would be higher, this amount of development could exceed the real need of the municipality and generate unsustainable scenarios of excessive soil sealing. In these cases, to limit the new development, a priority plan should be used to reduce the number of compounds to be retrofitted by selecting those most vulnerable and exposed in terms of the number of residents.

We also have to underline that cost of retrofitting interventions could be dependent on the level of seismic risk and, therefore, not be constant when changing the geographical contexts or city. This is especially true for stonemasonry buildings that require higher retrofitting cost [18]. In this method we have used a value (the seismic retrofitting rate) derived by the Italian Urban Developers National Association [31] that is suitable for a high-risk seismic context, but this value could be different in other cities.

However, the use of a constant cost for a city represents a reasonable choice, as the green infrastructure strategy is supposed to be implemented in a single municipality. Within a single city, only the availability of high-resolution information on soils and other geological features (i.e., obtained by a detailed seismic zonation) or spatial survey of building types (which is not the objectives of our paper) would allow differentiated costs of retrofitting to be obtained.

The reduction of energy demand is limited to the summertime period and for a proportion of buildings within each compound. Results of the proposed method show that shading effects provided by tree plantation could not be extended to all buildings in the same compound. This would imply unbalanced benefits for only a few landowners—those benefiting from the energy demand reduction of their buildings—against the transfer of shared open spaces property belonging to all landowners in the compound.

Also, the method presents some specific limitations. The land-ownership analysis (second phase), based on the visual interpretation of available high-resolution orthophotos on sample areas for each of the selected three morphology types, could be more time-consuming at a wider scale than the municipal level, due the large amount of compounds to be analysed. Thus, the method, as proposed, is particularly effective only at a municipal scale. Moreover, the economic feasibility assessment tool (third phase) is based on the assumption of three basic input parameters. Different values of these parameters could affect the results and the final findings of the research. To overcome this issue, a next step of the proposed study could include a sensitivity analysis of these input parameters for improving the quality and the reliability of the economic evaluation.

6. Conclusions

Seismic vulnerability and energy inefficiency in existing urban fabric represent challenging issues for local spatial planning targeting more livable, healthy and safer cities. When urban fabric lacks public green space and is characterized by compounds with multi-storey buildings and several individual landowners sharing the same property, the real opportunities to undertake any sustainable urban transformation could be nearly null. The double nature of the compound property asset, characterised by single private properties mixed up to shared ownership properties, implies complex decision processes when planning an intervention at compound level. In these respects, the willingness and availability of financial means to contribute to any intervention could be different and conflicting among landowners concerned and could affect and even prevent the implementation of the compound transformation.

Such complexity calls planners and policy makers to have a better understanding of the morphological features and property assets of urban contexts while claiming new approaches and policies for managing urban transformation. In this perspective, the proposed study represents an innovative urban strategy able to combine the needs of implementing public green infrastructure for cities lacking green spaces with the need for seismic retrofitting and the reduction of cooling energy demand of private existing buildings. The strategy is based on an economic feasibility assessment of the urban transformation which ensures viability in fragmented property assets while balancing public and private costs and benefits.

The proposed strategy presents a scenario in which landowners of the compound leave portions of shared open spaces to public property and obtain, as a compensation, an equitable amount of development rights to be sold to other private landowners and/or developers. Economic earnings deriving from selling development rights constitute a shared budget for funding a seismic retrofitting intervention of the buildings belonging to the compound. The developers transfer the purchased development rights in other urban areas for increasing the square footage and the height of existing buildings or developing new residential units. Local administrators acquire new open spaces without financial efforts and implement a new green infrastructure.

Finally, new greenery to be located alongside these new public areas provides further benefits to private buildings in terms of a significant reduction of cooling energy demand through the shading effect. Such a multi-scale strategy, acting from municipal level to building level, would allow the regeneration of vulnerable, inefficient and seismically unsafe portions of the city and increase the number and quality of ecosystem services provided by the new green infrastructure.

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A European Project for Safer and Energy Efficient Buildings: Pro-GET-onE (Proactive Synergy of inteGrated Efficient Technologies on Buildings' Envelopes)

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Abstract: The paper describes the progress of the four-year European project Pro-GET-onE currently under implementation. This research and innovation project is based on the assumption that greater efficiency, attractiveness, and marketable renovation can only be achieved through an integrated set of technologies where all the different requirements (energy, structural, functional) are optimally managed. Thus, the project focuses on the unprecedented integration of different technologies to achieve a multi-benefit approach that is provided by a closer integration between energy and non-energy related benefits. The project aims to combine different pre-fabricated elements in a unified and integrated system resulting in a higher performance in terms of energy requirements, structural safety, and social sustainability. The project attempts to achieve this goal through the introduction of innovative solutions for building envelopes to optimally combine the climatic, structural, and functional aspects through a significant architectural transformation and a substantial increase of the real estate value of the buildings. This augmented value obtained through the application of the inteGrated Efficient Technologies (GETs) is extremely important when considering the necessity of creating an innovative and attractive market in the energy renovation of existing buildings towards the target of nearly zero energy buildings (nZEBs).

Keywords: building envelope; energy efficiency; seismic improvement; sustainability

1. Introduction and State of the Art

The research project Pro-GET-onE is based on the integration of different technologies to achieve a multi-benefit approach through the closer integration between energy and non-energy related benefits, promoting a holistic vision based on the integration of different technologies where numerous requirements (energy, structural, functional) are managed as a whole. Thus, by implementing a same holistic and integrated system based on pre-assembled components, the research project aimed to achieve the highest performances in terms of:

1. energy requirements—by adding (or substituting the existing with) new prefab and plug and play high energy performing envelopes and HVAC (Heating, Ventilation, Air Conditioning) systems;
2. safety—using appropriate external structures to increase the overall structural capacity of the building while supporting the new envelope consisting of timber based components for opaque parts/surfaces, and aluminum, glass, PV photovoltaic, solar panels;

3. social and economic sustainability—increasing the real estate value of the buildings and the desirability of retrofit options by providing tailored and customized solutions for users, owners and house managers, increasing safeness and minimizing disturbance to inhabitants.

The goal of this research project was to provide the market with an innovative, yet readily implementable system for the building envelope to be applied to an energy, structural, and user-oriented retrofit that would significantly increase the commercial value and the life cycle of buildings, involve the users in attractive and visible solutions and, ultimately, reduce the costs of energy retrofit options in the whole building life cycle. This goal will be attained through the application of solutions for the building envelopes, as well as through optimum climatic-structural-functional management, grounded on the substantial increase of the real estate value of the buildings through significant energy and architectural transformation. This incremented value will be obtained through the development and application of inteGrated Efficient Technologies (GETs) with the strategic aim of creating a new and attractive market in the deep renovation of existing buildings towards the target of nearly zero energy buildings nZEBs [1].

By coupling and combining these technologies, Pro-GET-onE aims to provide existing buildings with poor structural performance with improved, safer seismic performance to get as close as possible to the levels of the European standard EN 1998, Eurocode 8 [2].

Housing in the European Union (EU) represents a huge part of the building stock. EU dwelling stocks account for about 200 million units, representing around 27% of energy consumption in the EU: the potential reduction in CO_2 emissions that energy efficient housing would provide cannot be underestimated. Three quarters of the buildings standing today including the residential stock are expected to remain in use in 2050. So far, only 1.2% of the EU's existing buildings are renovated every year [3,4]. The EU's energy efficiency challenge in buildings mainly concerns the energy efficient refurbishment and investments in its existing building stock. However, there is a clear investment gap in this sector with regards to the private housing market.

The cost-benefit assessments of retrofit actions in this sector have shown excessive payback times (payback times are up to 35–45 years). Furthermore, high investments are required up-front and are generally characterized by a high degree of risk with a potential limited return on investments.

In the Mediterranean and seismic areas of the EU, this gap is even exacerbated, being associated with a strong and generalized lack of confidence by the final users and owners and by weaker market conditions. In fact, the harder economic crisis that these areas are experiencing and the lack of confidence in the perceived sense of safeness in the majority of existing buildings are both major barriers when approaching the subject on building retrofit.

Information from the SHARE Project [5] indicates that Italy, Greece, Romania, and the Mediterranean countries of the European Union as the areas with the highest probability of an earthquake. In these areas, recent seismic events have shown how relevant the issue of seismic vulnerability for existing buildings of reinforced concrete is, given that many of these were designed without any reference to anti-seismic criteria. The evaluation of the vulnerability of the existing buildings and the subsequent assessment of the potential benefit provided by solutions and actions for seismic improvement is a much more complex topic than the design of new earthquake-resistant buildings.

Seismic improvement solutions for existing reinforced concrete buildings can be distinguished according to the number of resistant elements involved and the strategy of the intervention adopted. Local interventions that strengthen the structural elements (beams, columns), reinforce the seismic joints, and secure the vulnerable elements are commonly used. These interventions can increase stiffness, resistance, and eventually ductility at the expense of a significant invasiveness for the users of the building.

Pro-GET-onE proposes a technique that until now has not been commonly used and can be configured as an exoskeleton connected to the reinforced concrete frame of the existing buildings. This new structure can collaborate in order to resist the horizontal seismic actions. Outstanding projects that have adopted this idea are, for example, the Magneti Marelli factory offices and warehouse buildings in Crevalcore (Italy) by Teleios Srl [6,7]. In the office building, the external structure was composed of steel frames connected to the existing reinforced concrete building where the vertical elements had been released from horizontal loads, being completely assigned to the new structure. In the warehouse of the same factory complex, the steel frames were instead inserted inside the building, directly connected to the reinforced concrete portals. Both the interventions ensured full resistance to a designed earthquake according to the current Italian regulation. However, in the described cases, the exoskeleton does not provide integrated solutions for energy improvement and possible volumetric expansion, as in the case of this research project. Another case with a similar approach, and similarly limited to the structural aspect, was the seismic reinforcement of the rural and surveying engineering department of A.U.TH., Thessaloniki, Greece [8]. This project regarded the construction of a steel exoskeleton on the entire perimeter of the existing building, thus providing structural strengthening.

Regarding energy retrofit, several studies have been already carried out to overcome the barriers of high costs and time through technological solutions using prefab systems like TES FAÇADE [9], More Connect [10], and EU Prefabricated Systems for Low Energy Renovation. Most of these solutions are generally founded on the load bearing capacity of the existing buildings, conditions that are rarely applicable in the highly seismic areas of the Mediterranean countries. Thus, in the Mediterranean and seismic areas of the EU, it has become imperative to couple energy retrofits with the development of tools to increase confidence in safeness, and to make it clear that higher initial investments of retrofit are more interesting in the long-term than lower investments with higher paybacks.

2. Multi-Benefit Solutions

As briefly discussed, renovation in buildings implies the solution of issues beyond the energetic sphere (namely structural and seismic safety, fire safety and functional, new technological networks as well as spatial and aesthetical amenities). Undeniable costs and long payback time of renovations led us to consider that an acceptable payback time for energy retrofitting was very difficult to achieve without considering the multiple benefits in economic, social, and environmental terms. In this frame, Pro-GET-onE focuses on the willingness to pay rather than the mere cost reduction. In fact, the core element of every redevelopment is the increase in value for the client (investor, building owner, and tenant), since focusing solely on the optimization of energy efficiency may result in failing to meet the overall requirements.

2.1. Structural Requirements

Regarding the structural response under seismic loading, simulations using FEM software (EN 1998) performed for different residential buildings have shown an overall reduction of horizontal displacements and internal forces of the retrofitted structures. From the perspective of maximum compatibility and a minimum invasiveness, the overarching goal of the strategy adopted was to provide an intervention that increased the capacity of the building as a whole and only secondarily acted locally on existing vulnerabilities, minimizing and/or avoiding interventions that are not cost-effective and very invasive when applied extensively. External metal bracings like exoskeletons are a suitable solution to increase the capacity of existing structures when subjected to horizontal actions by increasing the rigidity, and consequently reducing the displacements (Figure 1).

More in-depth analyses were carried out. One of the virtual cases is reported in this paragraph. Following the Italian code and guidelines NTC 2008 (which refers to the Eurocode 8), modal analysis with response spectrum (or linear dynamic) was performed. In this case, the equilibrium was treated dynamically, and the seismic action modeled directly through the acceleration project spectra obtained from the seismic parameters related to a seismic zone selected by the authors (Table 1). The results shown below correspond to a seismic action determined with the following data:

Table 1. Seismic parameters of Bologna.

Bologna, Emilia Romagna—Seismic Zone III (NTC 2008)
SLV (SD)—P_{VR} = 10%; T_R = 475 years; V_R = 50 years
• a_g/g = 0.166 • F_0 = 2.398 • T_C = 0.310

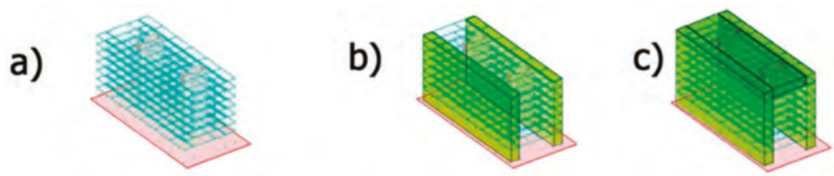


Figure 1. Model of the existing (**a**) and the new structures (**b**)—GET structure; (**c**)—GET structures connected on top—portal. This figure shows, as an example, the contribution of GETs on an existing reinforced concrete structure with columns and shear walls. The new structure (**b**)—in this example, steel columns and beams, steel stiffeners and XLAM plates when connected to the nodes of the existing building resulted in a reduction of displacements and internal forces in the existing structure (**a**). Further improvements resulted when the additional structures on each façade were connected on the top of the building (**c**).

The selected parameters allowed the evaluation of the seismic structural efficiency of the different design solutions of the GET system. As a direct consequence of earthquakes, the absolute displacements of the structure were used. As established by the code, the structure was analyzed with combined actions (SLV and SLD as indicated by the NTC 2008), with the displacements reported in both cases. Only the results of the SLV combination (coincident with the significant damage limit state for Eurocode 8) are shown since they were more severe. As part of the procedures for the analysis of structures, the fundamental period of vibration is an important feature in the evaluation of the stresses caused by the seismic action. The variations of the period depend on the mass and stiffness of the structures. The application of the steel external structure connected to the existing reinforced concrete building increases the rigidity of the structure k with a minimum mass increase, resulting in a decrease in the structure's period. In linear analysis methods, the identification of the period leads the estimation of the horizontal forces of the project. In general, it connects the capacity to seismic requirement, in order to determine the expected performance and therefore the safety design. Most common types of reinforced concrete construction were conceived and built largely between the 60s and the 90s when no clear characterization of the seismic territory had yet to be defined and horizontal earthquake actions were not considered. They were designed for only static loads or according to obsolete/poor seismic design criteria; thus, they resulted in small elemental sections and irregular rigidity distribution. To highlight the effectiveness of Pro-GET-onE, reinforced concrete buildings that had a geometric irregularity in the plan, with predominantly longitudinal development, were considered (Figure 2). Smaller section dimensions and different mechanical properties of the materials result in less resistance, leading to longer periods and displacements with a wide margin of improvement (Table 2).

The additional structure provided by the project consists of steel frame (two columns and a beam) for each floor, with bracings in the transversal direction, connected to the existing reinforced concrete frame at the column-beam joints. These frames are also connected in the longitudinal direction to create a space frame together with the existing one.

The first design solution provides a continuous addition on both longitudinal facades (Figure 3a) and therefore increases the depth of the building on the smaller side to give it a more regular geometry in plan and an increase in stiffness to cause a decrease in displacements and profile stresses.

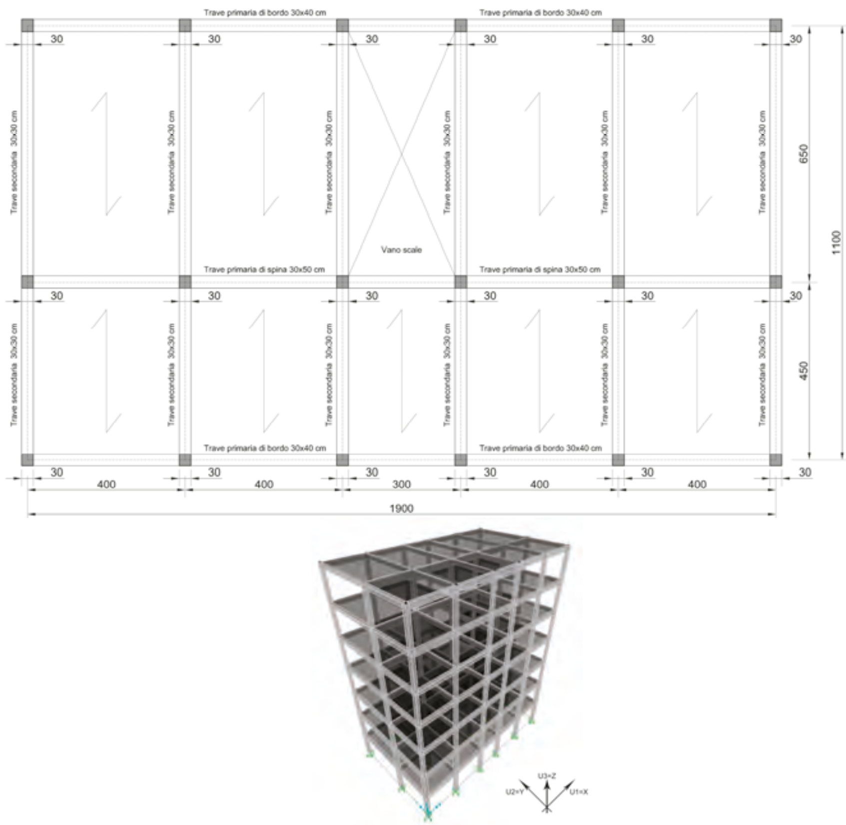
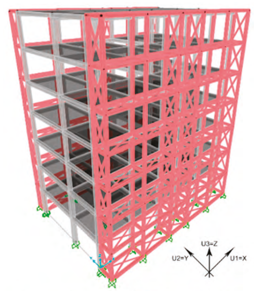


Figure 2. Plan and finite element model of the virtual case study, below there are also the main analysis results.

Table 2. Maximum displacements and periods of the initial state structure.

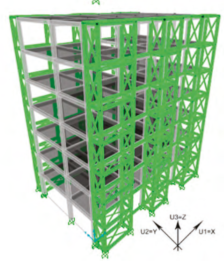
Maximum Displacements			Structural Periods	
Node	**U1 (m)**	**U2 (m)**	**Vibration Mode**	**T—Period**
127	0.1148	0.1618	1	2.761
139	0.1108	0.1617	**2**	2.197
			3	1.818
			4	0.896

The second solution is instead an alternate addition on the same facades (Figure 3b). This attempt provides a reduction in the amount of steel used and therefore of material costs. The alternation of exploitable spaces allows an increase in the presence of bracing frames, resulting in a substantial transversal displacement reduction. The third design solution provides an improved connection between the two lateral frames made by trusses (Figure 3c).



SLV (SD)	U2 (m)	-Δ- U2 (%)	U1 (m)	-Δ- U1 (%)
I.S.	0.162	-	0.115	-
-Δ- min.	0.099	38.75	0.080	30.75
...	...	...	...	...
-Δ- MAX.	0.052	68.05	0.056	51.22

(a)	T—Period	-Δ- T (%)
I.S.	2.761	-
-Δ- min.	1.499	45.71
...	...	...
-Δ- MAX	1.144	58.57



SLV (SD)	U2 (m)	-Δ- U2 (%)	U1 (m)	-Δ- U1 (%)
I.S.	0.162	-	0.115	-
-Δ- min.	0.096	40.67	0.082	28.57
...	...	...	...	...
-Δ- MAX.	0.056	65.64	0.062	45.82

(b)	T—Period	-Δ- T (%)
I.S.	2.761	-
-Δ- min.	1.440	47.85
...	...	...
-Δ- MAX	1.182	57.19

SLV (SD)	U2 (m)	-Δ- U2 (%)	U1 (m)	-Δ- U1 (%)
I.S.	0.162	-	0.115	-
-Δ- min.	0.099	38.75	0.080	30.75
...	...	...	...	...
-Δ- MAX.	0.052	68.05	0.056	51.22

(c)	T—Period	-Δ- T (%)
I.S.	2.761	-
-Δ- min.	1.486	46.18
...	...	...
-Δ- MAX	1.149	58.39

Figure 3. Finite element models of the three design solutions (**a**–**c**) and the related analysis results. SLV, load combination of "*stato limite di salvaguardia della vita*" (NTC 2008) equivalent to *significant damage* (SD, Eurocode 8); I.S., initial state; -Δ-, difference; T, period of vibration.

The range of results is determined by changes in the new structure as shown in Table 3 below.

Table 3. Variation and consequences obtained from FEM models.

Profiles used in the new structure	HEA 240 HEA 300	↓	↓	δ max	↓	T_1
Depth of the addition	1.5 m 2.5 m	↓	↓	δ max	↑	T_1
Connection constraint between the two structures	Hinge joints Rigid joints	↓	↓	δ max	=	T_1

In each of the designed solutions, these variations have the same effects. The increase in the size of the profile used clearly results in an improvement as it increases the overall structure's rigidity. The depth of the exoskeleton brings out conflicting effects: on the one hand, wider depths produce minor displacements as the resulting building (given by the existing and the added volumes) is more rigid; on the other hand, the same increase in depth comes across with a slightly worse period of the structure due to an increase in floor masses despite minor stiffness improvements.

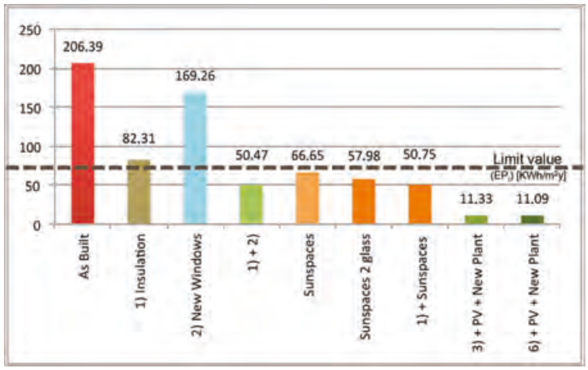
The GET system introduces a metal structure with efficient stiffness; furthermore, the GET is applied externally to the existing building with a beneficial effect in terms of construction site management given that it does not require the performance of special operations inside the existing building. The installation is less complicated with respect to the usual insertion of new reinforced concrete structures within the existing building. Moreover, with respect to this insertion, the GET structure implies a significant reduction in terms of cost for the new foundations.

Regarding the connections, the use of rigid joints results in a reduction in both displacement and period. However, it should be highlighted that this connection is not easily implemented in the construction practice. This is especially true in the case of a connection between an existing reinforced concrete structure and a new steel frame. The element of great importance for the system is the connection linking the existing structure in reinforced concrete and the new metal structure "GET". To create an effective collaboration for horizontal actions while avoiding burdening the existing structure with vertical loads, this joint is assumed as a vertically sliding joint that allows only vertical movements.

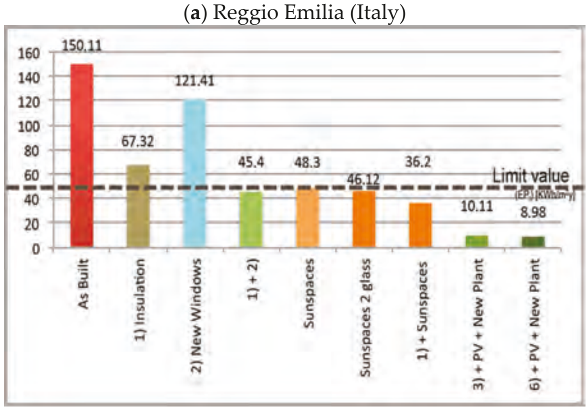
2.2. Energy Requirements

The GET structure will be combined with energy and space requirements. To this aim, energy simulations performed have demonstrated that enclosing the structure with solar spaces that can be opened in summer may provide an energy reduction of up to the 75% in the cold winter season while reducing solar gains and increasing natural ventilation rates, thus achieving about 35% energy consumption. Simulations have been performed from northern climates to the Mediterranean area reaching nZEB performances with traditional thermal insulation coating combined with controlled mechanical ventilation (VMC). Many references in the literature have also confirmed this potential energy reduction [11]. Specific calculations have been performed for the three cases of the research project by using a monthly-based method according to the EN 13,790 standards (Figure 4).

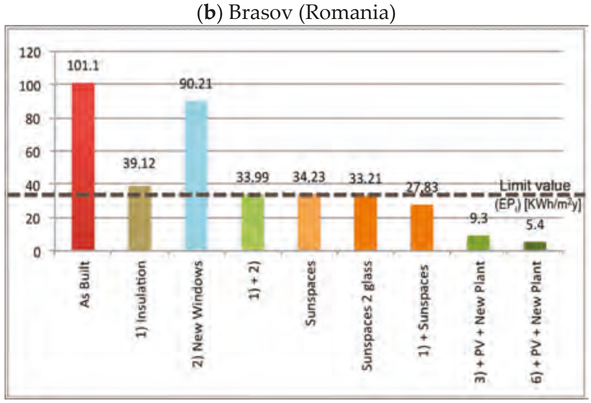
Concerning technical HVAC plants, the GET system can be coupled with new network lines (thermal fluids, electricity, etc.) with the predisposition for future systems (i.e., water drainage pipes, telecommunication lines) to be integrated in the external structure for a "plug-and-play" connection with internal devices. External allocation of all main plant system (EHP, PV system, hydraulic pipes, electric lines) will allow for simple plant maintenance and/or substitution. As a whole, GET can be equipped with several installation plants. The structure may also be used as support for the telecoms infrastructure such as to ensure easy access to superfast broadband services as required by new EU directives for new and renovated buildings [12]. Thus, Pro-GET-onE proposes the highest transformation of an existing building shell with external strengthening structures that generate energy efficient buffer zones (by reducing radiation in summer, providing solar heating in winter, and hosting flexible/adaptable plug-and-play installations), and increase the flat volume (with balconies, loggias, sunspaces, and extra rooms, according to the users' needs or expectations). See section of the GET system in Figure 5. These solutions have been designed and analyzed in a large set of existing buildings [11].



(**a**) Reggio Emilia (Italy)



(**b**) Brasov (Romania)



(**c**) Peristeri (Greece)

Figure 4. Simulations in three of the case studies show how combining the enclosure of volumes with insulation of existing envelopes will save up to 75% of the energy consumption.

Figure 5. Exoskeleton providing existing building (5) with: strengthening by GET structure (2), energy saving and plant distribution (1, 4, 6) increased comfort and living areas for residents, and additional new units (3).

Fotopoulou et al. [13] investigated an individual residential unit in a set of various hypotheses for targeted energy retrofitting interventions with different options both individually and in combination. The study was executed for three different climatic zones (Athens, Riga, Bologna) and showed that energy savings were larger during the winter period in southern climatic conditions while northern countries showed a larger energy saving during summer. Undoubtedly, in all three different climatic conditions, a zero energy building with the extension on the façade and with a standard retrofit seems to be an achievable goal.

Simulations of different scenarios of the additions on the existing building resulted in corresponding diverse energy performances, from the very low grade of performance in the "as built" scenario of the existing building, and up to nearly zero energy demand for selected technological solutions applied in specific climatic contexts. In different ways, the results proved that façade additions were very effective; therefore, the additional building envelope is a powerful technological solution combining the improved energy performance of the buildings with a new aesthetic/formal quality.

2.3. User Oriented Requirements

Last, but not least, the increased value of the buildings and the users that can benefit from the extended space, is quite clear. The resulting building may finally provide:

- comfort for users (combined with a proper ventilation system); and
- increased attractiveness even from social sectors that are usually more reluctant to change like elderly inhabitants, providing them with balconies and loggias for small individual gardens.

Potential problems that can be expected in terms of daylight reduction can be tackled by evaluating the appropriate depth of GET structure, the use of highly reflective surfaces for the internal coatings, the potential application of solar pipes to achieve visual comfort, and energy requirements while maintaining the seismic improvement. Thermal bridges are also foreseen. Thus, effort will be concentrated in searching for adequate materials and/or geometrical features for the structural joints to minimize thermal bridges while preserving the necessary structural cohesion. Depending on the original structural performance of the building, the structural frame can be designed according to different geometrical solutions and materials (aluminum, steel and wood). Figure 6 outlines different possible solutions of additional structures on the existing building's envelope.

(**a**) (**b**) (**c**)

Figure 6. Interactions between the existing façade and the steel aluminum structure (**a**); the possible positioning of ducts/pipes/storage (**b**); and the same external structure in timber or X-Lam structure (**c**). Different options for enclosures on the steel/aluminum.

To sum up, rather than the innovation in products, the Pro-GET-onE innovative aspect relies on the approach of the user and the building at the center of the energy retrofit to successfully implement energy strategies and solutions for deep renovation.

2.4. Economic Viability of the GET System

Undoubtedly, the GET systems will be characterized by higher up-front costs with respect to a deep energy renovation. Nonetheless, if we consider the associated costs for seismic retrofitting in the case of a standard seismic renovation, the GET system can produce a significant cost saving. In fact, in the proposed strategy, the avoided disturbance for residents and the moving costs for an average cost reduction of the GET system must be considered and compared to the case of the standard seismic and energy retrofit.

The comparison between the estimated unit costs/time (indicative costs) of a typical deep renovation and the GET system is presented in the following table (Figure 7). The various interventions were divided into the three main requirements of the project: the energy renovation, structural safety, and limited disturbance to the users.

Pro-GET-onE meets the target of 15% of cost reduction when compared to a typical renovation (i.e., renovation that meets the minimum energy and seismic safety requirement). In particular, this is achieved by summing up the construction costs of:

1. Energy renovation: the standard renovation costs are estimated at around 360 euro/m^2 when compared to Pro-GET-onE where the renovation costs are 380 euro/m^2
2. Structural safety: the standard renovation costs are estimated around 390 euro/m^2 when compared to Pro-GET-onE where the renovation costs are 330 euro/m^2
3. Inhabitants' relocation: the standard renovation costs include a quota of 100 euro/m^2; this cost is avoided through Pro-GET-onE, which allows the inhabitants to stay in the building during renovation. The actual cost reduction is therefore about 16.5%. Moreover, it is also significant to consider the added value in economic terms consisting of the extra surface generated by the Pro-GET-onE system. The real estate increased unit value has been evaluated to be around 130–180 euro/m^2 depending on the different regional markets. This consideration reduces

the payback time and increases the impact of the project on the economical side. It can be stated that Pro-GET-onE achieves a unit cost reduction of up to 32–38% when compared to a typical renovation.

	TYPICAL DEEP RENOVATION			PRO-GET-ONE SYSTEM RENOVATION		
MEET ENERGY REQUIREMENTS	INTERVENTIONS	Cost €/m²	Days	INTERVENTIONS	Cost €/m²	Days
	External thermal insulation + finishing systems	60	90	PRO-GET-ONE standard system (structural not included)	90	60
	Windows replacement	70	30	Windows replacement	80	30
	HVAC and water heating system improvements/replacements	80	90	HVAC and water heating system improvements/replacements, plug and play	80	60
	Related demolitions and reconstructions	30	30	Related demolitions and reconstructions	0	0
	Scaffoldings and safety installations	30	240	Scaffoldings and safety installations	10	0
	New renewable energy systems	100	30	PRO-GET-ONE standard renewable energy systems	100	30
	TOTAL CONSTRUCTION COSTS AND DURATION	360	240	TOTAL COSTRUCTION COSTS AND DURATION	380	60
	Maintenance and replacements (25 years cycle, heating/cooling running costs not included)	135	---	Maintenance and replacements (25 years cycle, heating/cooling running costs not included)	115	---
MEET SAFETY REQUIREMENTS	INTERVENTIONS	Unit Cost €/m²	Days	INTERVENTIONS	Unit Cost €/m²	Days
	New reinforced concrete structures (e.g., shear walls) + foundations	350	180	PRO-GET-ONE steel and wood structure + foundations	320	60
	Demolitions and reconstructions related to new structures (e.g., floor replacement)	40	60	Demolitions and reconstructions related to new structures	10	10
	TOTAL CONSTRUCTION COSTS AND DURATION	390	240	TOTAL CONSTRUCTION COSTS AND DURATION	330	70
	Maintenance and replacements (25 years cycle)	5	---	Maintenance and replacements (25 years cycle)	25	---
MEET USER REQUIREMENTS	INTERVENTIONS	Unit Cost €/m2	Days	INTERVENTIONS	Unit Cost €/m²	Days
	Inhabitants relocation (no tailored design)	100	360	Inhabitants relocation (user-oriented design)	0	0
ALL REQUIREMENTS	TOTAL CONSTRUCTION COSTS	850		TOTAL CONSTRUCTION COSTS Per m² of existing UFA	710	
				TOTAL CONSTRUCTION COSTS Per m² of existing UFA plus extra surface (+20% of UFA)	560	
	LIFE CYCLE COSTS (after 25 years, excluding energy running costs)	990		LIFE CYCLE COSTS (after 25 years, excluding energy running costs)	850	
	EXPECTED REAL ESTATE VALUE AFTER INTERVENTION	+15%		EXPECTED REAL ESTATE VALUE AFTER INTERVENTION	+50%	

Figure 7. Comparison of construction unit costs between a typical and GETs deep renovation.

3. Results of a Case Study

One of Pro-GET-onE feasibility studies was located in Greece, more precisely in Peristeri, a suburban municipality of Athens in the Attica region. It has a population of 146,000 inhabitants and is located at a distance of 5 km in the western part of Athens and is the biggest and the second densest suburb of the Attica region. The pilot case of the Peristeri compound (Athens, Greece) is a typical social housing development from the late 1960s.

The main structure of the buildings is reinforced concrete (pillars and beams), concrete slabs, and hollow brick external walls. This is a typical construction typology and is globally presented in all Attican suburbs and the city center. It also has a common structure with similar building blocks all over Europe.

Each building block has a centralized heating system plant. Existing windows are made of an aluminum or wooden frame with single glass although part of the external windows has already been replaced. The energy performance of the buildings is very low and in need of energy retrofit (160 Kwh/m^2 × y (winter)/110 Kwh/m^2 × y (summer)).

The majority of these buildings are residential use with the only exception being the building block (B6) where small businesses shops, offices, and retail are located at the ground floor level. Ownership is 100% by private owners. In total, there are 550 apartments while the average heated residential area per unit is 85 m^2 (Figure 8).

Figure 8. Peristeri urban compound where is located the feasibility study.

A retrofitting project that can guarantee a high level of energy performance can be a source of savings for the inhabitants and municipalities. High-energy costs have led the majority of the residents to choose alternative and less efficient heating solutions such as kerosene, electricity, coal or wood, increasing environmental pollution. The large number of standardized multi-apartment residential blocks leads to the possibility of adopting similar solutions to improve energy efficiency, thus ensuring an economy of scale.

The building identified in compound (A7) is the one outlined in red in Figure 8.

The application of the project could guarantee a substantial energy improvement and would not be limited to this aspect. As we have already seen, the benefits of the "GET" structure would span the improvement of earthquake performance, which is a fundamental aspect to increase the value of the intervention.

Regarding the seismic classification of Greece, as for the Italian case, the territory is divided into zones. The four zones that were created are characterized by a probability of excess of 10% in a reference period of 50 years and a return period of 475 years (PGA values assigned to areas with soil type A). Figure 9 and Table 4 show the seismic subdivision of the territory as reported in the Greek standards, EAK 2000 [14].

Figure 9. Seismic areas of Greece, as reported in EAK 2000 [14].

Table 4. Subdivision of the seismic areas of Greece.

Seismic Zone	Anchor Acceleration Values
I	0.12 g
II	0.16 g
III	0.24 g
IV	0.36 g

Following this classification, Athens is located in Zone II with an anchor acceleration value of 0.16 g to be applied in the definition of the response spectrum to carry out the checks. In the analysis phase, the structure was subjected to a greater acceleration to highlight the results of the system.

3.1. Seismic Analysis

The building is from the 60s and has a longitudinal shape with a reinforced concrete structure. It was built in the period after World War II when there was a "boom" in construction of this type in the suburbs of all European cities. Unlike the Italian case, despite the construction period, this building testifies to the already present conception of seismic design, as demonstrated by the dimensions of the structural elements.

It has a reinforced concrete structure with a mainly longitudinal development. It is composed by frames arranged in the direction of the shorter side. The concrete slabs lie on these frames. There are also two secondary frames on the edges and one in the middle characterized by the presence of flat beams. A twenty-centimeter reinforced concrete wall can be identified near the stairwells and the elevators.

The original geometrical and architectural data of the initial state were provided to the authors by the municipality of Peristeri. The dimensions and the structural schemes of the beams were obtained by photographic survey, while those of the columns and of the concrete walls were taken from the original architectural plans.

The structure is composed of six units with an average span 6.60 m in the longitudinal development, (the two external ones are of about 6.55 m while the four internal ones have a distance of 6.8 m).Transversely, the space is divided into two zones of a spacing of 3.25 m and 6.05 m. On the ground floor is the *pilotis* while the six upper floors are dedicated to residential units (Figure 10).

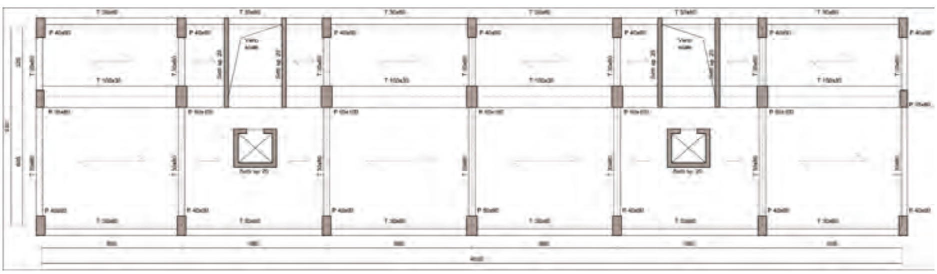


Figure 10. Structural plan—Type plan.

The simulations carried out were done with finite elements software SAP2000 [15]. Linear dynamics (modal analysis with response spectrum) was chosen for the seismic analyses. Table 5 shows data regarding the modeling phase, while Table 6 indicates the seismic parameter for the response spectrum definition for the analyses and for the verifications.

Table 5. Modeling data.

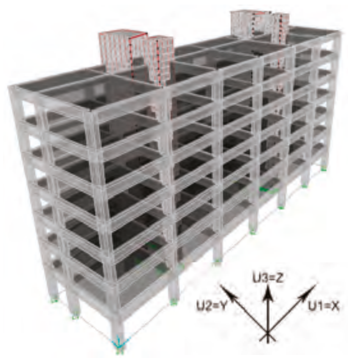
Analysis	Linear Dynamics
Modal combination	CQC (§ 4.3.3.3.2 Eurocode 8)
Eccentricity value	5%
Directional combination	$1.00 \cdot E_x + 0.30 \cdot E_y + 0.30 \cdot E_z$
Limit state	Significant Damage—SD
Behavior factor	$q = 2.00$
Reference parameters in assessments	Maximum absolute displacements—δmax Structural period—T1

Table 6. Seismic parameters for the definition of the elastic response spectrum.

Analysis
SLV (SD)—$P_{VR} = 10\%$; $T_R = 475$ years; $V_R = 50$ years • $a_g/g = 0.259$ • $F_0 = 2.363$ • $T_C = 0.342$
Verification—Seismic Zone II (EAK 2000)
SLV (SD)—$P_{VR} = 10\%$; $T_R = 475$ years; $V_R = 50$ years • $a_g/g = 0.16$

In this section, we refer to two parameters regarding the results of the proposed structure: the absolute displacements at the top of the existing building, and the period of the structure.

The assumed structure composed briefly as shown above in the structural plan was modeled in SAP2000 [15] through the use of linear elements (for beams and columns) and bilinear elements, shells (for concrete walls). Figure 11 reports the main results of the linear dynamics analysis of the initial state.



	U1 (m)	U2 (m)
δmax	0.0874	0.0763

	T—Period
1° MV	1.004

Figure 11. Displacements and structural period of the linear dynamics analysis of the initial state.

Regarding the building's seismic response, it is evident that it was designed to withstand seismic actions. In fact, despite the high level of the applied seismic action, there are limited displacements considering the height of the building. From the analyses carried out after the application of the "GET" system, it was therefore predictable to obtain very limited improvements when compared to the virtual cases previously described.

The additional structure provided for the project consists of steel frames (columns and beams) for each floor, braced in the transversal direction due to the architectural requirements, and linked to the joints of the existing reinforced concrete frame (created from the intersection of beams and pillars). These frames are also connected in the longitudinal direction to create a spatial frame interconnected with the existing structure.

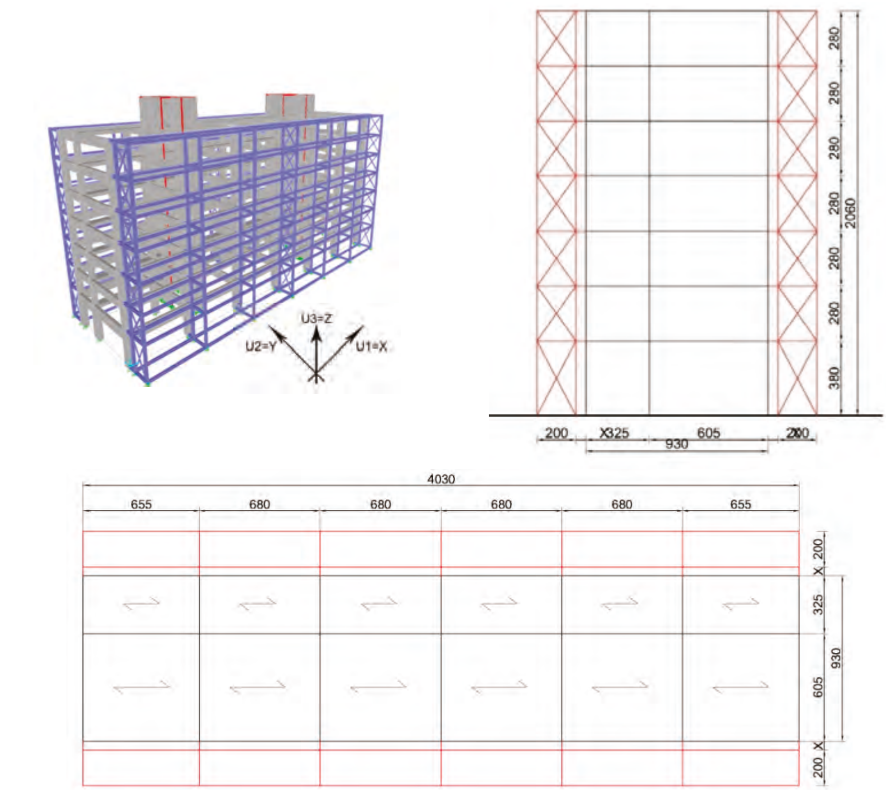
The depth increase of the smaller side of the building allows it to obtain more regularity in plan and to increase the stiffness, causing a reduction of displacements and internal forces in the elements.

The first steel structure solution (solution A, shown in Figure 12) is continuous on the whole façade and presents transversal bracing at the middle and at the ends of the new structure.

Here we show the results due to the variation of the profiles that compose the structure (columns and beams). The improvement is calculated on the comparison before and after the application of the steel structure.

In this phase, several profiles were examined initially by varying the type at the same weight and subsequently by varying the type with the same height in order to obtain a general scheme. Based on these analyses, the incidence of the profiles has been verified.

It has been verified that the choice of the columns is decisive in the improvement and that the types of profiles that have a different inertia module in the two directions (e.g., IPE type) are inconvenient. In fact, in some cases, these profiles aggravate the displacements in the longitudinal direction. The other way around, profiles with equivalent stiffness or almost in the two directions are ideal for the intervention (HE and pipes). Clearly, HE profiles are preferable during the assembly procedure.



SD	U2 (m)	-Δ- U2 (%)	U1 (m)	-Δ- U1 (%)
I.S.	0.076	-	0.087	-
-Δ- min.	0.071	**7.60**	0.090	**−2.56**
...	...	**...**	...	**...**
-Δ- MAX.	0.059	**21.49**	0.079	**8.58**

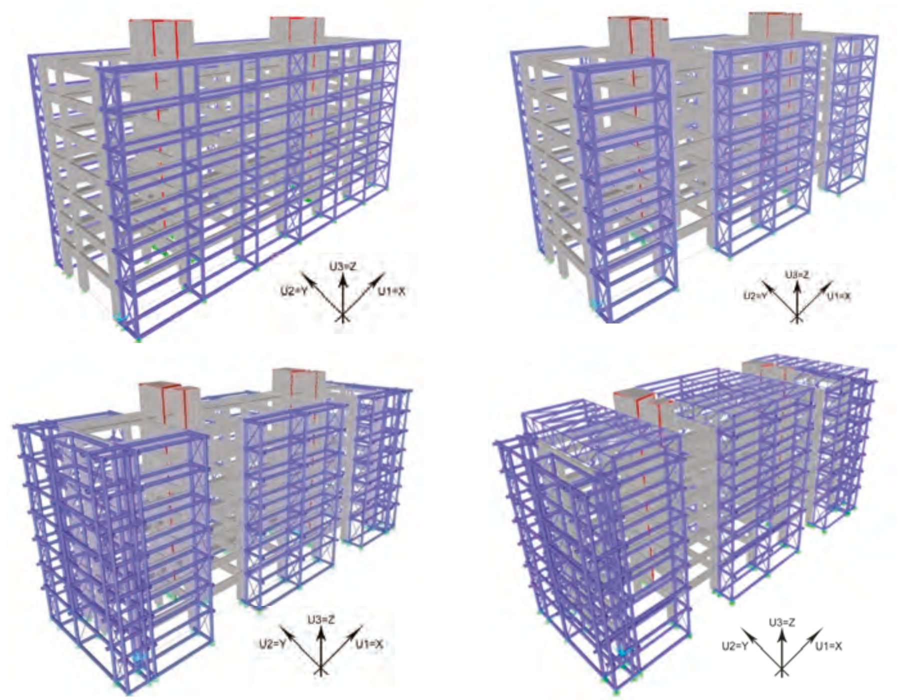
	T—Period	-Δ- T (%)
I.S.	1.004	-
-Δ- min.	1.097	−8.48
...	...	...
-Δ- MAX.	0.955	4.88

Figure 12. Finite element model of solution A, structural schemes of the new external structure and results in displacements and periods.

The following analyses were carried out with the use of HEB 240 and Φ323.9/12 profiles. The results obtained using the last indicated profile are shown below, but follow different structural configurations as described in Section 2.1:

- A—Continuous addition to the longitudinal façades. It presents transversal bracing at the middle and at the ends of the new structure.
- B—Alternate addition to the longitudinal façades. It presents transversal bracing at each span.
- C—Alternate addition to the longitudinal façades combined with continuous addition on the transversals.
- D—Alternate addition to the longitudinal façades, continuous addition on the transversals plus top connection with reticular beams.

Looking at the results obtained from the analyses (Figure 13), design solution B had more diagonal bracing on the transversal planes and smaller displacements in the Y (U2) direction. Moreover, this solution turned out to be the least expensive by using lower quantities of steel in the project.



SD	U2 (m)	-Δ- U2 (%)	U1 (m)	-Δ- U1 (%)
I.S.	0.076	**-**	0.087	**-**
Sol. A	0.062	**19.14**	0.081	**6.98**
Sol. B	0.059	**22.81**	0.082	**6.64**
Sol. C	0.057	**24.77**	0.077	**12.6**
Sol. D	0.057	**26.0**	0.077	**12.6**

	T—Period	-Δ- T (%)
I.S.	1.004	**-**
Sol. A	0.977	**2.69**
Sol. B	0.974	**2.99**
Sol. C	0.926	**7.8**
Sol. D	0.933	**7.1**

Figure 13. Finite element model of solution A, structural schemes of the new external structure, and results in displacements and periods.

Solution C had an alternate addition to the longitudinal facades and a continuous addition on the transversals. The addition on the short sides was not connected to the existing structure, but only to the longitudinal ones. This helped to improve the performance of the structure in both directions to the detriment of an increase in costs countered by a small increase in useful area.

The last solution of the analysis phase provided a superior connection between the lateral additions, which produced a decrease in displacements against an increase in the period due to the rise in building height.

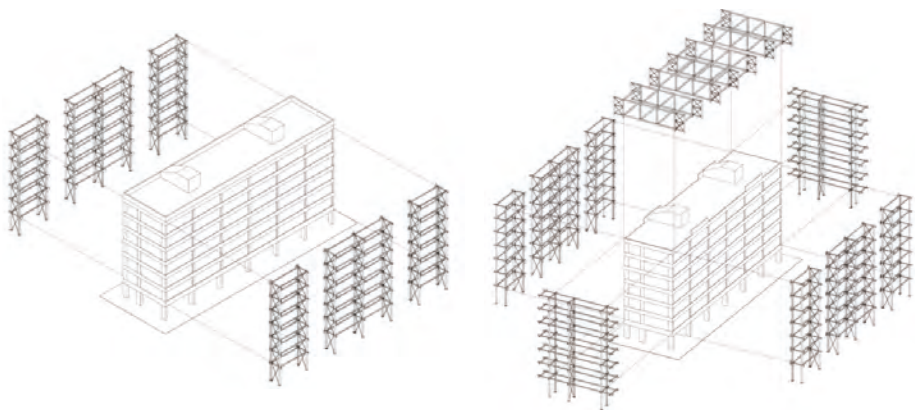
Finally, by also combining an assessment of the costs of the structure, a check of the elements of the new steel frame was carried out. In this phase, all the profiles constituting the new structure were defined and differentiated based on internal stress and on the cost calculation dependent on the weight of steel. The aim was to find a fair compromise between the construction costs and performance in terms of improvement achieved on the existing structure.

Another fundamental aspect was represented by a parallel evaluation of the added surfaces due to the volumetric external addition. The added value given by these areas reduced the expenses.

As reported at the beginning of the section regarding the verifications (Eurocode 3 and 8), the seismic load relating to Athens was used based on the EAK2000 [14].

Two structural solutions were considered due to different benefits:

- B1—Alternate addition to the longitudinal façades (Figure 14a). This solution involves the greatest performance benefit with minimal cost; however, it has a small contribution in terms of added area.
- E1—Alternate addition to the longitudinal façades, continuous addition on the transversals plus top connection with Vierendeel beams (Figure 14b). A different solution to the previous ones is illustrated below. Thanks to the possibility of raising the structure of a floor, this allows the greatest contribution in terms of added surface, a higher cost with equal performance benefit on displacements.



(**a**) (**b**)

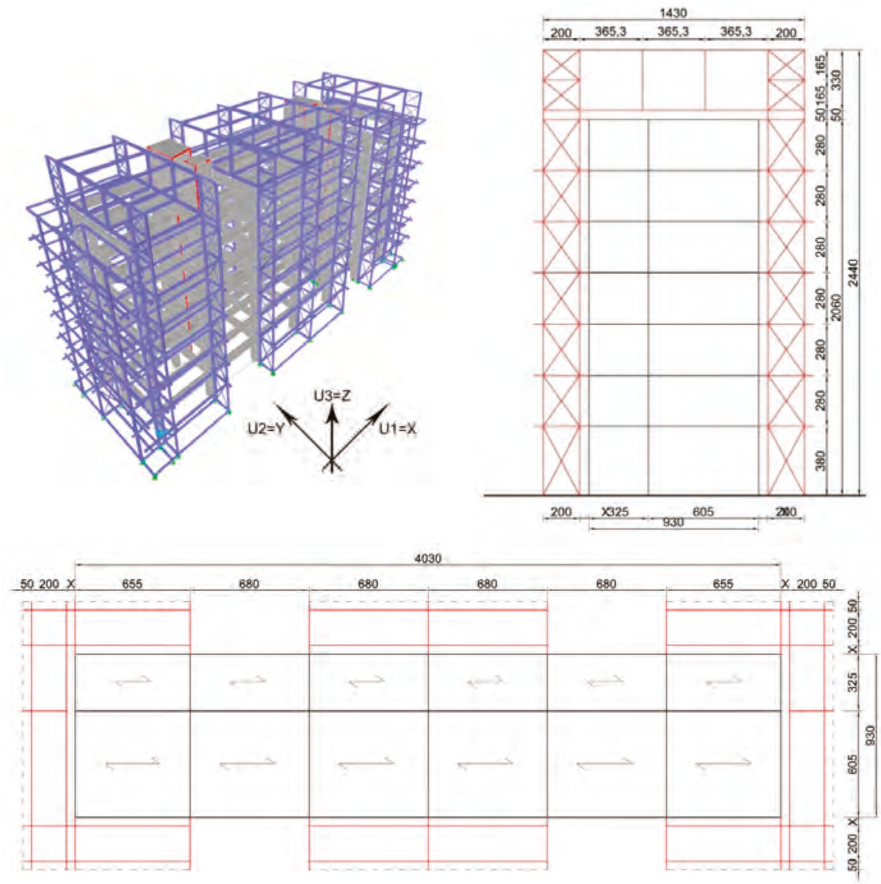
Figure 14. Axonometric drawings of the two selected solutions. On the left (**a**) is presented the alternate addition to the longitudinal façades B1, while on the right (**b**) there is the alternate addition to the longitudinal façades, continuous addition on the transversals plus top connection with Vierendeel beams E1.

Regarding the design solution E1, Figure 15 shows the schemes and the analyses output data.

Furthermore, the actual benefit that the Pro-GET-onE implies for the existing construction in terms of earthquake response was verified. Various design solutions were analyzed that involved variable quantities of added area, and used material (steel), which produced different responses to the earthquake. Overall, an improvement in terms of displacements was always obtained due to the increase in stiffness given by the addition of the new structure. The analysis carried out initially focused on the maximization of the benefits on the existing construction and afterwards, on the most valid design solutions (in terms of performance), a compromise has been proposed to ensure a seismic improvement at the lowest possible construction cost (considering only the structural components of the project).

Two proposals have been made (B1 and E1), which guarantee good performance in terms of transversal displacements (16–17% improvement), a substantial indifference for the displacements in the longitudinal development of the construction, and a large increase in added surface that reduced the cost of construction. Additionally, the assessments on the construction cost showed that both solutions had the same cost per square meter of added surface.

In conclusion, as far as regarding seismic safety, this case study verified that the GET system could provide improvements even for buildings that have already been designed with an adequate performance for horizontal loads. Certainly, the value of improvement for the previous buildings mentioned, was limited when compared to the structures that have been designed to withstand only vertical loads, in which cases the GET system could prove better safety results.



SD	U2 (m)	-Δ- U2 (%)	U1 (m)	-Δ- U1 (%)
I.S.	0.0305	**-**	0.0341	**-**
Sol. B1	0.0255	**16.40**	0.0337	**1.17**
Sol. E1	0.0253	**17.05**	0.0335	**1.76**

	T—Period	-Δ- T (%)
I.S.	1.004	**-**
Sol. B1	1.025	**−2.05**
Sol. E1	1.083	**−7.29**

Figure 15. Finite element model of solution E1, structural schemes of the new external structure, and results in displacements and periods.

3.2. Architectural Verification—The Abacus

Parallel to the seismic improvement conferred by the external steel structure, a series of possible architectural solutions have been developed to incorporate the skeleton initially formed by the single structural component. In this phase, it is necessary to consider several factors that determine the appearance and the way of using the additional space by choosing constructive solutions, materials, and the functional types. Highlights of this design typology include the versatility of the additional volumetric units in relation to the possibilities and the choices of the user, and the constant search of energy improvement aimed at the goal of bringing the existing building toward the nZEB.

Currently, one of the main shortcomings of deep retrofitting towards nearly zero energy is that they generally rely on separate clusters of technologies that are difficult to integrate. To overcome these barriers and create a roadmap for cost effective renovation through a well-balanced strategy of mass customization, the research project has envisaged an integrated modular system, composed of components manufactured off-site, that can be customized and optimized for different cases in a user-oriented perspective (by adding balconies, loggias, sunspaces according to the users' needs and expectations). The integration of the system will focus on the interfaces between the different components to ensure their collective performance according to the project requirements. Standardized interfaces will also ensure the flexibility of the system, as different components can be interchanged and adjusted as a function of different climate conditions and urban context, as well as according to the inhabitants' requirement.

Regarding the Greek building, different architectural hypotheses have been realized. In each of these solutions, several additional volumetric units were hypothesized and divided into three functional types: sunspace, extra-room, and balcony. Figure 16 shows a possible functional and therefore architectural variation of the same external volumetric addition.

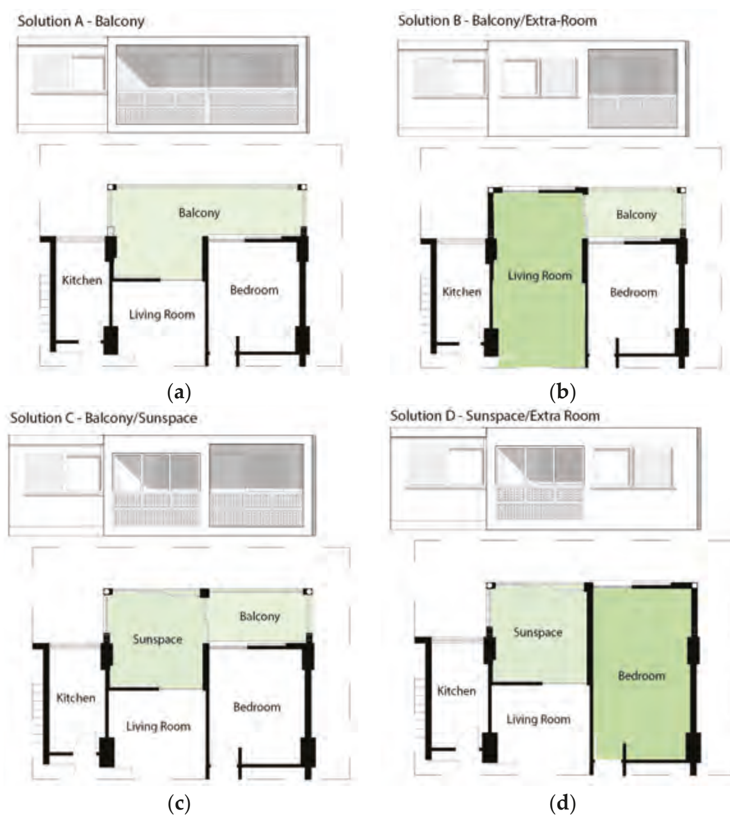


Figure 16. Possible functional variation of the same external volumetric addition made by the alternate combination of sunspace, balcony, or extra-room. Every plan solution determines a different façade conformation. Solution (**a**) refers to an extension with the option of a balcony, where (**b**) is a combination of an extra room with a balcony, (**c**) refers to the combination of a sunspace with a balcony and finally (**d**) is the combination of an extra room and a sunspace.

Performed cost-benefit analysis in a large set of reference buildings in the context of another EU project ABRACADABRA [16] that considered the hypothetic investment in additional units on top of GETs showed that the potential economic gains obtained through the sale would largely compensate the energy retrofit cost including RES to set the energy demand of the whole building to zero. The GET system, in fact, could be used to support additional loads on top of buildings that were not structurally conceived for addition. This aspect could implement and accelerate the market penetration of deep renovation within the private sector, which is the most challenging sector to overcome the existing barriers in energy retrofit market uptake. In fact, energy-retrofitting actions are very often implemented in over-imposed actions by the main ownership, with no direct benefits to the final users.

To overcome this limit, it is necessary to focus on the local private owners of real built environments where owners may directly benefit from the economic and spatial gains. Different options of façade adds-on to be integrated on the vertical surfaces of the existing buildings will be studied and categorized in a comprehensive abacus containing the different solution along with the variable measures/materials/technologies to be adopted. The possible modifications in the façade modules will be studied according the main structural frame and the residential units' utilities.

They will be grouped in one abacus of possibilities that will become one of the main design tools for planners and professionals involved in the GET process. In fact, the abacus can be tailored and customized as a function of different construction elements and architecture in the different case studies and it will represent the catalogue of a new production line for a possible joint participation between SME partners. The abacus is designed to define classification criteria, to launch an open energy performance and architectural repository to be used as an unlocked resource where energy professionals and major users like home-owners, tenants, condominium's administrators, etc. may find technical tools to deep renovate housing residential buildings.

In terms of the architectural solutions, the development phase of the technical solutions for the realization of the horizontal and vertical partitions of the GET system is under process. Therefore, the Peristeri case application is the first approach to this detailed phase of design that will lead to the definition of the integrated technical solution. Figure 17 shows drawings of another example of application.

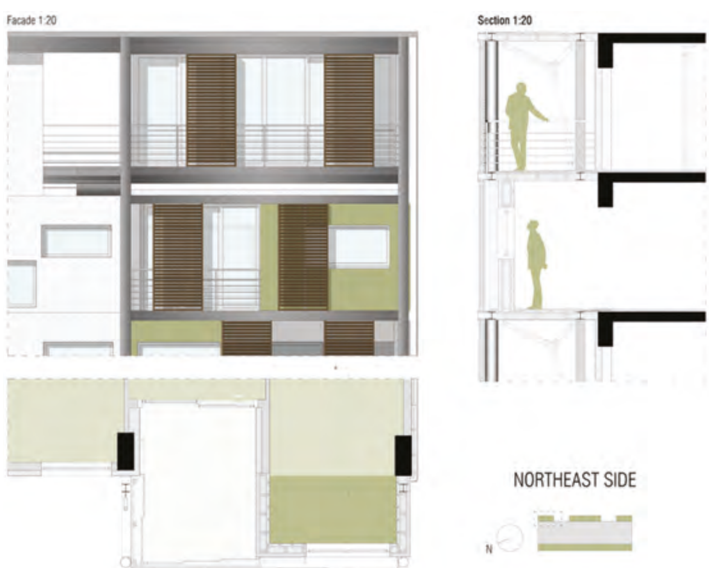


Figure 17. Façade, plan and detailed section of a typical application of the GET system on the Peristeri building.

Different material, technical, and functional choices involve different compositional solutions. On the basis of the design hypotheses carried out on the Peristeri case, perspective views have been made of what may result following the realization of the Pro-GET-onE (Figure 18).

Figure 18. Possible façade verification of the application of the GET system on the Peristeri building.

Outstanding examples in architecture building practice so far that could be considered as the inspiration behind the GET strategy include the transformation of the Tour Bois Le Pretre by the French architect Frédéric Druot [17,18]. This is a significant example of deep renovation combining energy retrofit with architectural quality and social sustainability. Another significant example is the extension and refurbishment of the residential Tower Weberstrasse, Winterthur, an existing 12 level apartment tower, built at the 1960s by the architect H. Isler. The project refers to an extension of the rear facade planned by Bulkhalter Sumi architekten [19].

In both examples, the additional space led to the variation of the existing apartments, the increase of a greater sense of security, and at the same time upgraded the social life of the community with the active participation of the owners during the whole procedure. New "envelopes" often consist of architectural spaces and units: the new volumes with the winter gardens, the extra balconies and galleries create a transition zone between the existing building envelope and the external climatic conditions and that results, as reported in the reference cases, in a consistent decrease in the initial energy consumption.

The architectural solutions here described, starting from a non-energy related objective like the increase of the rentable surface and, more generally, the increase of the asset value, prove that technological and architectural transformation in buildings do have the highest potential to decrease energy consumption in the existing ones. Regarding the case study of the Tower Weberstrasse [19], the measured energy consumptions calculated on the heated surface before the renovation (3887 m^2) was calculated up to 604,244 kWh/year. This resulted in 155 kWh/m^2 per year in terms of gas consumption. After the renovation, the calculated energy consumption accounted for a global 61.5 kWh/m^2 per year, considering a total increased surface of 4.830 m^2, thus, including the addition.

4. Field of Application and Potential Impact

The field of investigation and design is limited to existing buildings from the 1950s and 60s onwards. Indeed, this is not an actual limit, since these buildings represent the large majority of the EU building stock and are the biggest source of energy loss. Taking into account that today, only 1% per year of the existing buildings are renovated, it is obvious that these buildings embed a great potential in terms of impact on the building construction sector for energy, architectural, and economical reasons.

The project, by setting the ambitious target of achieving nZEBs in the most critical cluster of buildings (the building blocks from the 1970s onwards represent the most inefficient buildings located in the poorer and seismic areas of the Mediterranean) addresses:

- The large majority of urban areas in the EU; as reported in noticeable studies in the EU 27 the peri-urban areas represent the larger majority with respect to the central urban areas. Indeed, recent studies [20] have revealed how dense peripheral contexts preserve large areas for possible densification.
- The large majority of the EU building stock. As a matter of fact, about 70% of buildings in the EU have been built after the Second World War (60s to 90s) and well before the entry into force of regulatory measures on energy consumption reduction [21].
- The most inefficient buildings in all their different sizes and type (single family houses, multifamily houses and high-rise buildings);
- Buildings where change and transformation are feasible (due to free or available areas) and beneficial for energy, architectural, economical, and social reasons.

Furthermore, Pro-GET-onE aims at addressing a large sector of the residential stock: the ones owned by owner-occupiers, private landlords, and social housing companies. In particular, the proposal largely aims to address the accommodation of almost all EU citizens: indeed just over seven out of 10 (70.6%) people in the EU-28 lived in owner-occupied dwellings, while 18.5% were tenants with a market price rent, and 10.9% were tenants in reduced-rent or free accommodation.

The information required in the design, construction, and operation of facilities from their inception onward, will be based on computer-generated models containing accurate geometry and relevant data needed to support the whole lifecycle of buildings. This concept is referred to as Building Information Modelling, as pointed out by Charles Eastman [22] and by many other scientific works [23–29].

The production process of components in off-site factories, their supply to the construction site, and the onsite assembly procedures will have to be optimized by a BIM-based process to maximize the workflow and project efficiency.

Many firms are already using BIM design to collaborate with general contractors and construction managers, to automate production and prefabricate building components such as mechanical equipment and curtain-wall systems. In Pro-GET-onE, BIM will be exploited as a pipelined process among researchers, designers, managers, engineers, architects, and contractors, all sharing a common language made of digital representations. Three kinds of knowledge will be characterized to properly model the facility: knowledge about object shapes (survey), knowledge about objects identities (metadata implementing), and knowledge about the relationships between elements (BIM semantic modelling aimed at analysis).

This will enable both the minimization of the embedded energy of the system, and the minimization of its costs. The planning, simulation, and optimization of the different processes occurring in building construction will be enabled through the following tools and methodologies:

- A Building Information Modelling (BIM) software platform for pre-production design coordination, interface checking, and clash detection;
- A Process Information Modelling (PIM) framework that combines BIM with an applied kinematics assembly simulation system to simulate and optimize the production processes taking into account the material attributes and production speed. The PIM framework will be descriptive, prescriptive, and explanatory. While BIM is a good approach for these aspects, a wider system of connections has to be layered to become PIM-compliant, so during the executive stage, a proper BIM execution plan will be delivered to implement the advantages of PIM.

5. Expected Future Impact

The current impact of the research project is based on 24 dwelling units of about 100 sqm. each that will be renovated in the Groningen area. Other case studies consist of the project demo-building in Athens (about 2600 sqm.), and a building in the Reggio Emilia district (about 1000 sqm.). In the following years, more than 113 dwelling units will be used as regional specific buildings in the Groningen area. However, to calculate the large scale potential impact of the project, new calculation techniques and methods based on parametric modeling will be developed to improve the speed and efficiency of the calculations for individually different residential buildings and the surrounding available area for different seismic target regions.

The integrated and multi-purpose nature of Pro-GET-onE determines the high level of effectiveness of the proposal. Moreover, the consolidated knowledge used in the seismic technical solution proposed and its combination of different products already available on the market in the definition of a new system are the major outcomes. By assessing and answering—in one prefabricated solution—the energy, structural, and fire safety needs, together with the possibility of integrating the personalization of different components within the same mass-produced product, Pro-GET-onE opens a methodological revolution in the retrofitting practice. This highly innovative and effective technology offers the possibility of re-launching the renovation sector and foster its application on a broader scale in Europe.

The studied solutions aim at enabling the conditions to create attractive, self-financing schemes to support deep renovation actions; in fact, the GET system represents a possible standardized solution with a highly replicable strategy, especially for the Mediterranean countries of the EU and all the induced seismic areas of the EU. It is the authors' considered opinion that this strategy could more easily convince the users, the urban dwellers, and investors in the energy regeneration and major architectural revamp of the existing buildings. This ambitious idea is based on the willingness of creating completely retrofitted buildings that can be admired and looked-for from other condominiums in the surrounding areas and, from them, to many other buildings in the Mediterranean and EU. Moreover, Pro-GET-onE will put in place the legal/economic and social conditions where energy savings, combined with the increased real estate value, can be mobilized to repay a significant part of the energy investments.

The research project aims at ensuring the proper exploitation of a ground-based knowledge to boost the European strategic aim of mobilizing investment in the energy renovation of the existing building stock.

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Author Contributions: As project coordinator, Annarita Ferrante was responsible for the overall research concept, for the definition of the possible architectural choices and for the structure envelope of the GET system. She particularly dealt with the integration between, structural, energy and user oriented requirements related with the architectural improvement of the building. Giovanni Mochi participated in the development of the structural components of the façade addition and he also dealt with the economic viability of the GET System, providing a comparison of construction unit costs between a typical deep renovation and the new GETs. Giorgia Predari was responsible for defining the characteristics of the structural scheme to be adopted to achieve seismic improvement, as part of the multi-benefit solutions. Furthermore, she contributed to the modeling of the existing structure and the steel exoskeleton, with the interpretation of the results as regards the structural part. Lorenzo Badini dealt with the bibliographic research and the definition of the state of the art; additionally he worked on the structural simulations using the SAP2000 calculation software, applying the proposals of the structural schemes to the case study of the residential building in Peristeri. Anastasia Fotopoulou was responsible for defining the energy and user oriented requirements of the GET structure, and she contributed to the drafting of the abacus for the case study of Peristeri, with the definition of the possible functional variation of the same external volumetric addition made by the alternate combination of sunspace, balcony, or extra-room. Riccardo Gulli made its contribution in defining the applicability of the GET system to the existing building made by reinforced concrete and in its expected future impact. Giovanni Semprini was responsible of the plant integration in the volume of the

GET system and how to satisfy the nearly zero energy demand, with energy simulation implemented through calculation software.

Conflicts of Interest: The authors declare no conflict of interest.

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Renovation of a School Building: Energy Retrofit and Seismic Upgrade in a School Building in Motta Di Livenza

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Abstract: The main part of Italian building stock was built before the energy and seismic regulations, so most of buildings need comprehensive refurbishment to achieve the performance required by laws that are in force. This paper presents an experimental study for an energy and structural upgrade methodology, applied to an existing school building in the north-east of Italy. The methodology is based on the International Energy Agency–Energy in Buildings and Communities Programme (IEA–EBC) Annex 56 project guidelines. For the energy retrofit, a set of interventions is defined concerning the building envelope and systems. Among these interventions, the optimal cost is identified: this minimizes the energy demand and the CO_2 emissions, and reduces the financial commitment. The analysis of the seismic retrofit is developed using innovative techniques of intervention and high-performance materials. The proposed interventions are evaluated in terms of efficacy and cost. The results show that it is possible to identify a comprehensive energy retrofit at optimal cost, thanks to high energy saving and subsidies. For the seismic retrofit, the intervention with the higher cost-effectiveness ratio is determined, but the related investment does not have a payback time. The union of the two retrofits permits the combination of benefits and has a payback time for both the interventions. It is possible to state that the cost of a combined intervention is lower than the costs of two different interventions; therefore, when a single retrofit is needed, the possibility of a combined intervention should be evaluated.

Keywords: energy retrofit; seismic analysis; nearly zero-energy buildings (nZEB); Annex 56; cost-effective; optimization

1. Introduction

The European Parliament approved the recast of the Energy Performance of Buildings Directive (EPBD recast) in 2010 [1]. As in the previous European Directive 2002/91/EU [2], this concerns the energy efficiency of buildings, but the new directive reinforces the requirements regarding the energy performance of existing and newly constructed buildings and fixes the target of nearly zero-energy buildings (nZEB) for new constructions by 2021. According to the EPBD recast, member states (MS) should consider cost-optimality to establish minimum energy performance requirements in buildings at the lowest cost. In Italy, the national school stock represents a strategic sector to promote interventions for energy retrofits and environmental impact reduction on existent buildings or to convert them into nZEB. In general, non-residential buildings are around 13% of the Italian building stock [3], where around 51,000 buildings are used entirely or partly as schools which, however, have higher energy consumption: in fact, schools use about 1 million TEP_{year} (70% for heating and 30% for electricity), representing 2% of the 50 million TEP of total civil use in Italy [4]. So, acting on schools does not have a huge effect from an energy-saving point of view, but from the point of view of training citizens [5]. Most of existing school buildings have inefficient heating systems and old technologies. Space heating is still the main end-use, with 43% of heating needs met using natural gas in 2012. In most school buildings, heating generation mainly uses gas-/oil-fired boilers [6] and radiator heating systems are installed. Moreover, the vast majority of schools are in public ownership and, as consequence, the possibility for comprehensive renovations is limited due to lack of funds for public administration. Howqever, national and European projects represent a way to find funding and incentives for the redevelopment of existing schools with the aim of spreading strategies and best practice among MS, such as the ENTRANZE, RENEW SCHOOL, ZEMeds, School of the Future [7] and VERYSchool [8] projects. Among these, a selection aims to achieve to a kind of retrofitting according to the nZEB target. The ENTRANZE project (2012–2014) supported policy makers by providing the required data, the analysis, and the guidelines to achieve a fast and strong penetration of the nZEB goal within the existing national building stocks by connecting building experts from European research and academia to national decision makers and key stakeholders [9]. The RENEW SCHOOL project (2014–2017) aims at retrofitting a large number of school buildings to highest nZEB standards, by promoting appropriate tools and measures, helping to downsize the energy use significantly as well as create and secure comfortable conditions for pupils and teachers [10]. The ZEMedS project (2013–2016) [11] focuses on the refurbishment of Mediterranean schools to nZEB. The project covers a complete renovation path, tackling strategies for the envelope, the systems and renewable-energy applications as well as the energy management and users' behavior. In this context, the first results are presented with case studies of school buildings that have been analyzed in terms of the energy efficiency and cost optimality so as to define a detailed renovation action plan [12].

Historically and in recent years, Italian territory has been the site of some seismic events that have affected ancient and newly constructed buildings [13,14]. Italian technical standards deal in depth with the procedures for the seismic analysis of buildings [15–21]. Mainly these are structures built in the past which have undergone various adaptation and expansion works, in most cases without considering the situation from a construction point of view, and in combination with techniques and materials that tend to weaken the overall response of the building in case of a seismic event. The study of the seismic vulnerability of existing buildings translates into a determination of the structure's ability to withstand horizontal stresses such as seismic events; in particular, as regards masonry constructions, it is important to study the non-linear behavior of the structure to know the level of safety and structural deficit [22–26].

The main part of the Italian building stock was built before energy and seismic regulations, so the majority of constructions need a comprehensive refurbishment in both these aspects to achieve the EU requirements. This paper proposes a method for defining and comparing different measures for energy retrofitting and seismic improvement, as interventions on the building envelope and the heating system, as long as the decision-making process advances those measures. The overall strategy consists in considering energy and seismic topics at the same time in order to achieve benefits from several points of views, such as economic, time-saving and logistics management during the building-intervention process.

2. Materials and Methods

2.1. Methodology

The methodology foresees a comparison in terms of costs [27] and energy performance [28] of construction alternatives; the aim is to define the cost-optimal level, i.e., to propose the solution presenting the lowest total costs. The solutions found are shown in a graph presenting a comparison between global costs (€ m^{-2}) and primary energy consumption (kWh $m^{-2} \cdot y^{-1}$).

The required benchmarks concern the achievement of nZEB targets and the calculation of incentives. The study to derive cost-effectiveness from a technical and economic perspective is carried out in accordance with the EPBD recast, the Delegated Regulation n. 244/2012 [29] and its Guidelines [30]. The methodology consists of several steps: definition of reference buildings; definition of energy-efficiency measures (measures based on energy from renewable-energy sources (RES) and/or packages and variants of such measures for each reference building); calculation of primary energy demand resulting from the application of the previously selected measures and/or packages of measures; calculation of global costs in terms of net present value for each reference building; sensitivity analysis related to cost data; and identification of cost-optimal levels in each reference building.

Subsequently, seismic retrofit interventions are based on the identification and analysis of the structural vulnerabilities of the building through modal and spectral analysis carried out with commercial finite element analysis (FEA) software. Required improvements are determined, and the best intervention is identified in terms of the cost–benefit ratio, aiming to find the cost-optimal seismic upgrade. The proposed method is divided into the several phases: definition of seismic action, load analysis, linear dynamic analysis, definition of interventions and cost–benefit calculation.

The methodology (Figure 1) described above is applied to a school building, as a case study, to verify its effectiveness: the school building was built in the 1930s and extended twice in the 1960s and 1970s. Thus, to date it presents non-homogeneous masonry and floors that need an energy retrofit and seismic upgrading.

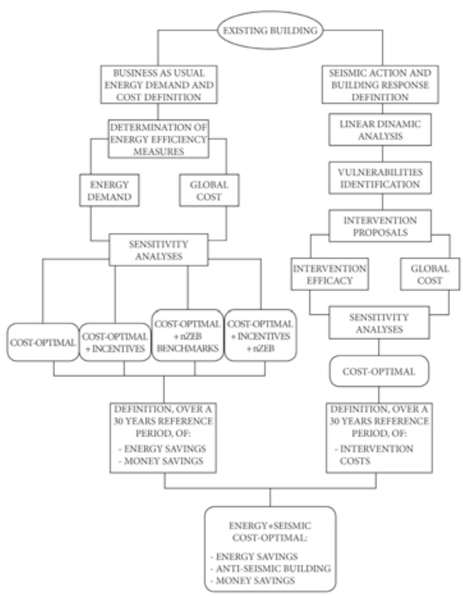

Figure 1. Flow chart showing the adopted methodology for the study.

2.1.1. Energy Retrofitting, Optimization and Nearly Zero-Energy Building (nZEB) Targets

A first step for the optimization process is the definition of a reference building and this study used the definition proposed by the IEA Annex 56 Cost-Effective Energy and CO_2 Emissions Optimization in Building Renovation [31]. In the reference case (Figure 2), the renovation consists only of measures carried out for maintaining the building and its functionality. In this kind of renovation, so called «anyway» measures strive for the renewal of building elements or building parts which have arrived at the end of their service life, not deliberately endeavoring to attain higher energy performance [32]. This anyway renovation solution, comprising the so-called anyway renovation measures, identifies a reference situation for determining and assessing the impacts of an energy-related renovation solution on energy use, carbon emissions, materials, costs and possible benefits. The energy-related solution comprises, on the one hand, those retrofit measures of the anyway renovation which are not changed by the energy-related measures. On the other hand, it comprises additionally the energy-related measures, which might be additional to the anyway measures or which might substitute some anyway necessary measures by measures which also improve energy performance and do not only restore the original functionality of the particular building element. Building renovation comprising energy-related measures is compared to the anyway reference case to determine the effects of the energy-related measures.

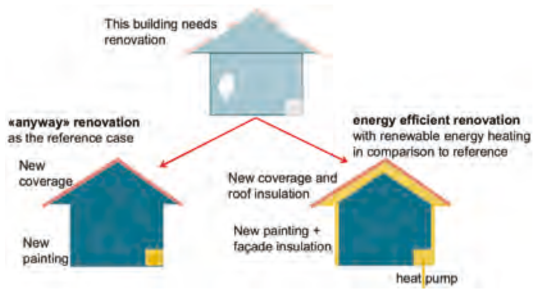

Figure 2. "Anyway renovation" vs. "Energy-related renovation" in the case of an anyway necessary building renovation due to functional reasons or building elements at the end of their service life, as defined by the International Energy Agency–Energy in Buildings and Communities Programme (IEA–EBC) Annex 56 Program.

The retrofit solutions are defined through different steps (Table 1). In the first step, the thermal envelope is analyzed: all the elements (external wall, roof, basement, windows) are considered in terms of thermal losses and percentage incidence of surfaces. Then, three groups of energy-efficiency measures (EEMs) are defined according to the standard values of thermal transmittance given by the Conto Termico 2.0 regulation (D.M. 16/02/16) [33,34]: interventions of thermal insulation on each technological element of the envelope; interventions on several technological components in accordance with their percentage incidence of thermal surface, first from higher to lower area and then from lower to higher area. In this way, 10 EEMs on envelope are defined and successively associated with the electrical lighting and wiring system interventions, for a total of 40 combinations: installation of photovoltaic system to cover the 50% of electrical need; and substitution of light bulbs with high-efficiency light-emitting diode (LED) lamps. Finally, all these solutions are combined with the substitution of the existent energy generator with three different boilers: installation of a gas condensing boiler; installation of a biomass boiler; installation of an electrical heat pump.

The EEMs, as they have been defined, number 120 and they will be analyzed in terms of primary energy use and annualized global cost for a lifecycle of 30 years.

After the definition of the reference buildings and the energy-efficiency retrofit measures, primary energy demand is calculated using software for an energy dynamic simulation, such as Energy Plus [35] with Design Builder [36] as a graphic interface. Heating, cooling, ventilation, domestic hot water, lighting and auxiliary demands have been estimated in accordance with the Italian technical specifications UNI 11300 [37], which implement the European standards [38,39]. The characteristics of energy production, distribution, emission and control, as well as the energy carrier, are inserted to derive the final primary energy consumption, according to the conversion factor given by the national normative [40]. The model is calibrated by means of the energy consumption of the last few years.

Table 1. List of energy retrofit interventions and their organization on different combined measures.

Measure Code	Envelope Interventions	Measure Code	System Intervention	Measure Code	Thermal Generator Substitution
M 1	First technological component (higher percentage incidence of thermal surface)	M 11 to M 20	Photovoltaic (PV) system installation	M 1.1 to M 40.1	Installation of condensing boiler
M 2	Second technological component				
M 3	Third technological component				
M 4	Last technological component	M 21 to M 30	Light-emitting diode (LED) installation	M 1.2 to M 40.2	Installation of biomass boiler
M 5	M1 + M2				
M 6	M1 + M2 + M3				
M 7	M1 + M2 + M3 + M4				
M 8	M4 + M3	M 31 to M 40	PV + LED	M 1.3 to M 40.3	Installation of electrical heat pump
M 9	M4 + M3 + M2				
M 10	M4 + M1				

In this study, the financial level is defined as the global cost: the sum of the initial investment, the sum of the annual costs for each year (energy, maintenance, operation and any additional costs), the replacement of systems and components, the final value, and the costs of disposal, as appropriate. All costs are actualized to the starting year, considering a lifespan of 30 years and the interest rate, through Equation (1):

$$\text{Annualized global cost} = \text{NPV} \times \text{r} \times [1 - (1 + \text{r})]^{\text{n}} \quad (1)$$

The equation for the annualized global cost (GC) calculation considers the NPV (net present value) (€), r as an annual real discount rate (%), and n as the lifetime (year).

The financing framework methodology is based on the net present value (global costs) calculation, carried out according to standard EN 15459:2007 [27], which provides a method for considering the economic aspects of the application of heating systems and other technical systems that affect the energy consumption of the building.

A sensitivity analysis is carried out considering the global cost and the primary energy consumption for each EEM compared to the reference scenario, to find out the optimal cost solution [41].

The main goal of the study is the transformation of a school building into nZEB. As defined by the EPBD recast, a nZEB is a building characterized by a very high energy performance; the nearly zero or very low amount of energy required should be largely covered by renewable energy produced on-site or nearby. A building is considered an nZEB when the following requirements are met: the energy performance (EP) is lower than the cost-optimal level, the differential GC with reference to the building before the refurbishment is negative (nZEB is cost effective) and the national minimum energy targets for nZEBs are achieved. Thus, the nZEBs should have a primary energy consumption lower than the cost-optimal range, and the GC in between the cost-optimal cases and the current reference building (Figure 3).

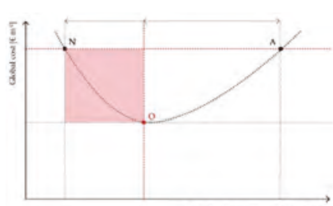

Figure 3. Global cost (GC) curve after renovation with energy-efficiency measures (EEMs) in comparison with reference situation; Identification of nearly zero-energy building (nZEB) solutions (red area) in sensitivity analysis of global cost and primary energy consumption. The graph shows the global cost curve after renovation (yearly costs for energy, operation and maintenance): the curve starts from the reference situation A (anyway renovation). Point O represents the cost-optimal renovation option and point N represents the cost-neutral renovation option with the highest reduction of primary energy.

The Italian law D. Leg. 63/2013 [42] and D. M. 26/06/2015 [28] defined minimum values to achieve nZEB targets for the following performance parameters: the overall heat transfer coefficient (H't), the solar transfer coefficient ($A_{sol,est}/A_{sup\ utile}$), the energy performance index ($EP_{H,nd}$, $EP_{C,nd}$, $EP_{gl,tot}$), the efficiency for generating thermal and electrical energy (η_H, η_W, η_C), and the integration of renewable energy sources, according to national minimal requirements [43]. With reference to the aforementioned parameters, this study considers the proposed EEMs which followed nZEB targets, identifying the cost-optimal solutions between them. Even if the EPDB Directive recast does not consider the application of financial incentives, this study considers the calculation of the Conto Termico 2.0 program, developed by GSE (Gestore dei Servizi Energetici, Rome, Italy), that regulates the incentive for interventions of small dimensions for increasing energy efficiency and for the production of thermal energy from renewable sources. Both public administrations and private owners are admitted, and the incentive duration varies from 2 to 5 years depending on the type of intervention. The characteristics of the envelope and system for retrofit measures are based on the benchmarks fixed by the Conto Termico 2.0 to evaluate the possible application of incentives to the different kind of interventions.

For solutions according to nZEB parameters, the bonus is equivalent to 65% of total investment cost of the intervention and conversion into nZEB (Table 2), where $I_{a\ tot}$ is the annual subsidy in euros, E_i is the yearly thermal-energy production; C_i is the thermal-energy valorization coefficient as prescribed by Conto Termico 2.0 in Table 7; while $I_{a\ tot}$ is the annual subsidy in euros; P_n is the system's rated power; h_r is system's functioning hours as prescribed by Conto Termico 2.0 in Table 10; C_i is the thermal-energy valorization coefficient as prescribed by Conto Termico 2.0 in Table 9; and C_e is the rewarding coefficient related to particulate emissions as defined by Conto Termico 2.0 in Tables 11 and 12. After defining the costs for each intervention with the calculation of incentives, the optimal cost is selected among all possible interventions and among those which comply with the nZEB parameters.

Table 2. Incentives regulation for small-scale energy-retrofit interventions.

Intervention Typology	Subsidies Related to Investment (%)	Maximum Investment (€·m^{-2})	Maximum Subsidy (€)
I-Horizontal opaque structures: roof insulation from outside	55%	200.00	
II-Horizontal opaque structures: flooring insulation from inside	55%	100.00	(I + II + III) ≤ 400,000.00
III-Vertical opaque structures: wall insulation from outside	55%	100.00	
Windows substitution with installation of thermoregulation systems	55%	450.00	100,000.00
Substitution of existing lamps with LED lamps	40%	35.00	70,000.00
Building modification in nZEB building	65%	500.00	1,750,000.00
Condensing boiler installation	55%	160.00	3000.00
Electrical heat pump installation	To be determined with the formula: $I_{a\ tot} = E_i \times C_i$		
Biomass boiler installation	To be determined with the formula: $I_{a\ tot} = P_n \times h_r \times C_i \times C_e$		

2.1.2. Definition of Seismic Action and Analysis of Structural Vulnerability

Seismic action is defined by several characteristics of the buildings as: its use, nominal life (V_N), reference period (V_R), the seismic hazard of the construction site, and other parameters related to the typology of the soil. These values are defined by the Italian Building Code, NTC 2008.

The seismic hazard of the site is defined by referring to the ultimate limit states (ULS) and the serviceability limit states (SLSs), as defined by the NTC 2008. The seismic hazard for ULSs, referring to the case study analyzed in this work, is characterized by the parameters shown in Table 3.

Table 3. Parameters used to define the elastic response spectrum of the case study of this work: T_R represents the period return; A_g is the maximum horizontal acceleration; F_0 is the horizontal acceleration spectrum amplification coefficient; and T_C* represents the period of the stroke at constant speed of the horizontal components.

Limit State	T_R (Year)	A_g (g)	F_0	T_C* (s)
SLSs	712	0.146	2.531	0.366
ULSs	1462	0.186	2.602	0.377

Based on these characteristics, the design response spectra for ULS, for both horizontal components, are calculated by NTC 2008 (Figure 4). For the determination of the spectra, a damping factor of 5% is assumed.

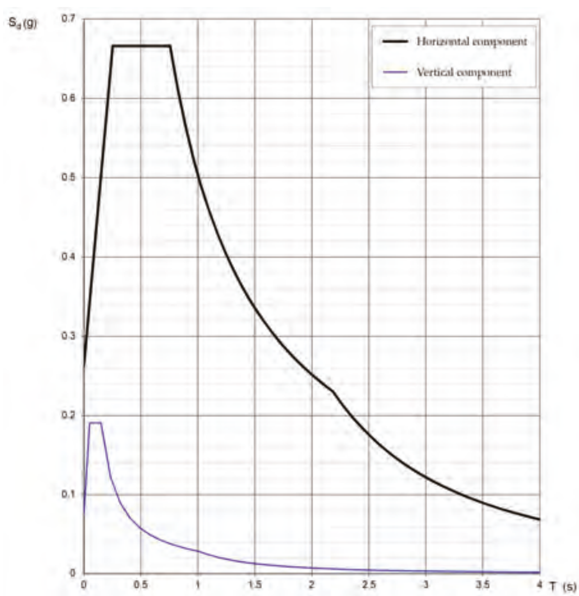

Figure 4. The design response spectra for ultimate limit states (ULS) along the horizontal and vertical components. The spectrum is defined related to the site and the characteristics of the case study in Motta di Livenza. S_d(g) is equal to the design seismic acceleration, while T (s) is the vibration period.

The elastic response spectrum allows identification of the elastic displacement response spectrum. Through the elastic displacement response spectrum, it is possible to compare the "displacement capacity" of the structure with the "displacement demand" required by the site, according to the reference state limit. The response spectrum is used to perform the linear dynamic analysis of the building. This analysis allows maximum displacement values to be obtained and the most stressed point of the structure to be located. Starting from these results, the intervention proposals are defined. The aim of the possible actions is to improve the critical aspects by lightening the horizontal elements, improving the resistance to stress of the vertical elements, and preserving the masonry box-like behavior.

Concerning energy issues, this research has achieved four cost-optimal solutions, selecting them among all proposed measures and among those that achieve nZEB targets, considering or not the calculation of incentives. All the outputs are summarized in charts representing the most efficient measure, considering primary energy use and the annualized global cost.

With regard to seismic assessment, intervention measures are simulated and compared with the behavior of a recent seismic event in the building. The value of performance and cost of intervention are collected to verify the effectiveness and validity of the proposal.

2.2. Applications—Case Study

The methodology is applied on a case study: the primary school A. Manzoni (Figure 5), located in the Italian municipality of Motta di Livenza (TV). The school was built in 1930 and later expanded in the 1960s and 1970s. The floor area of the building is 415.38 m^2. The thermal surface is 947.98 m^2 and the heated volume is 2070 m^3. The geometry is compact and regular, with a compactness surface-area-to-volume ratio (S/V) to 0.46. The building consists of several types of masonry and floor, corresponding to different construction phases; the features of the external envelope are summarized in Table 4 describing the thermal losses behavior and the relative percentage incidence.

Table 4. Area, thermal transmittance, thermal dispersion and percentage distribution of the envelope elements % by surface and % by thermal losses.

Element	Area (m^2)	Thermal Transmittance ($W{\cdot}m^{-2}{\cdot}K^{-1}$)	Thermal Dispersion ($W{\cdot}K^{-1}$)	% By Surface	% By Thermal Losses
Brick wall with 2 heads	213.79	1.76	376.27	22%	26%
Double brick wall UNI	143.34	0.90	129.00	15%	9%
Alveolar block wall	107.17	0.90	95.45	12%	6%
Total wall	464.30	-	601.72	49%	40%
Windows	68.30	3.19	217.88	7%	15%
Roof	207.69	1.75	363.46	22%	25%
Basement	207.69	1.93	288.69	22%	20%
Total	947.98	-	1471.75	100%	100%

The mechanical characteristics of the structural elements are derived from in situ test results [44] and are summarized as follows (Table 5):

Table 5. Mechanical characteristics of the structural elements: d represents the thickness of the element; γ the specific weight; E the elastic module; and G_1, G_2 and Q_k the permanent and variable loads.

Construction Year	Description	Mechanical Characteristics		
1930	Brick wall with 2 heads Concrete slab	d = 0.29 m G_1 = 3.00 $kN{\cdot}m^{-2}$	γ = 18.00 $kN{\cdot}m^{-3}$ G_2 = 1.25 $kN{\cdot}m^{-2}$	E = 2227 $Nm{\cdot}m^{-1}$ Q_k = 3.00 $kN{\cdot}m^{-2}$
1960	Double brick wall UNI Concrete and masonry flooring system	d = 0.29 m G_1 = 2.95 $kN{\cdot}m^{-2}$	γ = 12.00 $kN{\cdot}m^{-3}$ G_2 = 1.50 $kN{\cdot}m^{-2}$	E = 3600 $Nm{\cdot}m^{-1}$ Q_k = 3.00 $kN{\cdot}m^{-2}$
1970	Alveolar block wall Concrete and masonry flooring system	d = 0.29 m G_1 = 1.30 $kN{\cdot}m^{-2}$	γ = 15.00 $kN{\cdot}m^{-3}$ G_2 = 3.40 $kN{\cdot}m^{-2}$	E = 3500 $Nm{\cdot}m^{-1}$ Q_k = 1.20 $kN{\cdot}m^{-2}$

The structure is analyzed by the linear dynamic analysis carried out through the modal analysis to identify the potential failure mechanisms and the spectral analysis to define the maximum displacement values and to locate the most stressed point caused by the seismic action. The finite element calculation software SAP2000 [45] is used to undertake this structural analysis. A 3D model of the school is built in the software, based on the available data regarding the geometry of the structural components and the characteristics of the materials (Figure 6).

The vertical structural elements are divided into rectangular sub-portions that in the software correspond to two-dimensional shell elements. The shells are connected to each other by nodes in the corners. Three different types of shells are modeled to represents the three masonries of the building, as shown in Figure 7 through the use of different colors. The openings are represented as empty shells. Then, the flooring system is modeled as rigid diaphragms sealed to the masonry with full fixed constraints (black elements in Figure 6). The diaphragms are "thin" elements, without thickness, thus they are subjected only to bending deformations. At the base of the building, the nodes of the shells are tied with rigid constraints, represented in Figure 6 by the green elements, as foundations of the building. Every foundation element is connected to a node blocking its vertical and horizontal translation as well as its rotation. In this way, the whole base of the building is rigid: only the above-ground part is permitted to deform.

Figure 5. Front and back view of the A. Manzoni school.

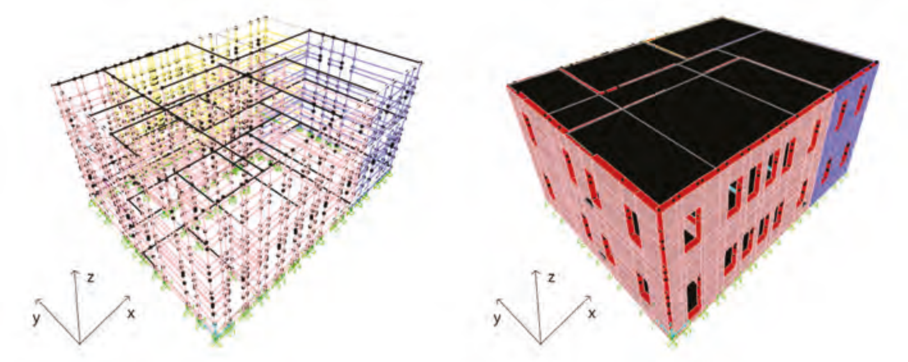

Figure 6. Finite element 3D model of the A. Manzoni school in the software SAP 2000; (**a**) wireframe view; (**b**) solid view.

The horizontal elements of the model are stressed with the load calculated through the load analysis. The load analysis defines the elementary load conditions of the structure and their combinations, as defined by NTC 2008. These loads are categorized as permanent (G) or variable (Qi) based on the variation of intensity over time.

Following the steps of the linear dynamic analysis, the modal analysis is carried out to define the proper vibration modes of the structure. The results of the modal analysis are shown in Figure 8.

Modes 1 and 2 show a torsional behavior of the structure, with a participant mass to the rotation of respectively 95% and 5%. Although the building is symmetrical, the torsion is caused by the asymmetry of the mechanical characteristic of the elements built in different periods. The torsion activates a considerable percentage of mass, even if the frequencies are low. The higher modes until the 7th do not activate a relevant quantity of mass. The 7th mode shows prevalent displacement in the *Y* direction. The displacement is larger in the oldest portion of the structure. Here, the walls are thinner and not braced because of the absence of internal partitions. The modes from the 8th to the 12th show displacement in both *X* and *Y* directions, with an activated mass of 66–72%.

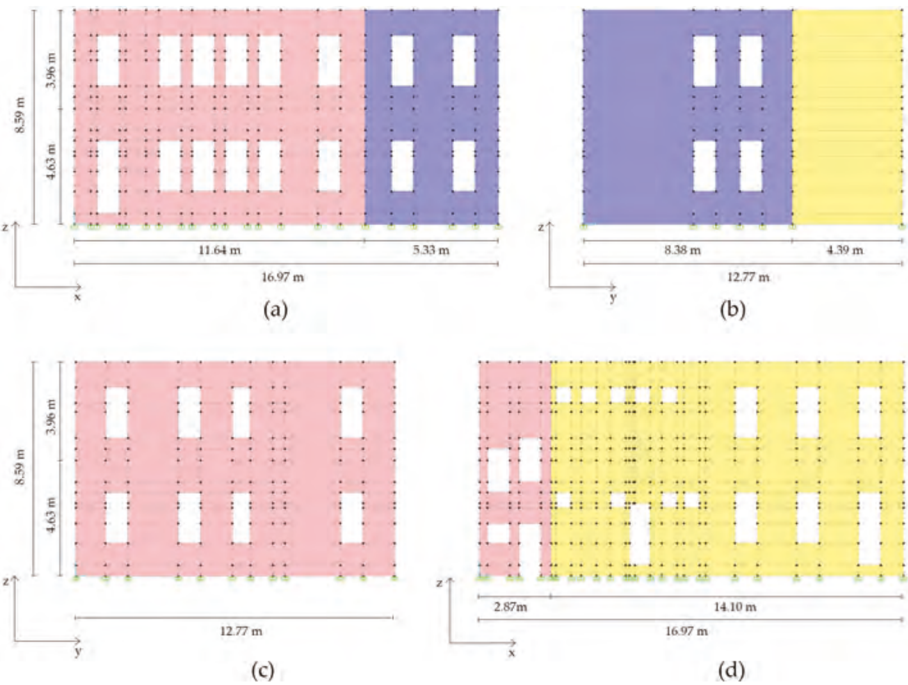

Figure 7. View of the model façades in the software SAP2000: (**a**) south façade; (**b**) west façade; (**c**) east façade; (**d**) north façade. The different colors represent the different kind of masonries: brick wall with 2 heads in pink, double brick wall according to the UNI specifications in yellow, and alveolar block wall in blue.

In succession, the seismic analysis is carried out. In the software, the seismic action is applied to the structure as a dynamic load. Two different load cases are defined for the two *X* and *Y* directions. The input data for the seismic analysis are the masses of the structure and their barycenter, the proper vibration modes defined by the modal analysis, and the spectral function defined by the acceleration values of the elastic response spectrum. Following the NTC 2008 indications, the acceleration values of the two *X* and *Y* directions are associated to scale factors to define the two different load cases, as shown in Equations (2) and (3):

$$X = F_x + 0.3\ F_y \quad (2)$$

$$Y = 0.3\ F_x + F_y \quad (3)$$

The F_x and F_y are the seismic component in both directions. For the analysis, the structural factor of 2 and the damping factor of 5% are considered.

The seismic combination in ULS is given, as prescribed by NTC 2008, by Equation (4):

$$F_d = E + G_K + \Sigma\ \psi_{2i}\ Q_{ik} \quad (4)$$

In the equation, G1 and G2 are the dead loads of the structural and non-structural elements respectively; Q is the accidental load; and E is the seismic action. The recommended value of the ψ factor is extracted by Table 2.5.1 of NTC 2008.

For the two load combinations, the maximum frame displacements (Figure 9), the maximum floor displacements (Figure 10), the intermediate shifts, and the maximum stress (Figure 11) values are defined. These values are then checked following the prescription of NTC 2008 to determine the most vulnerable elements of the building.

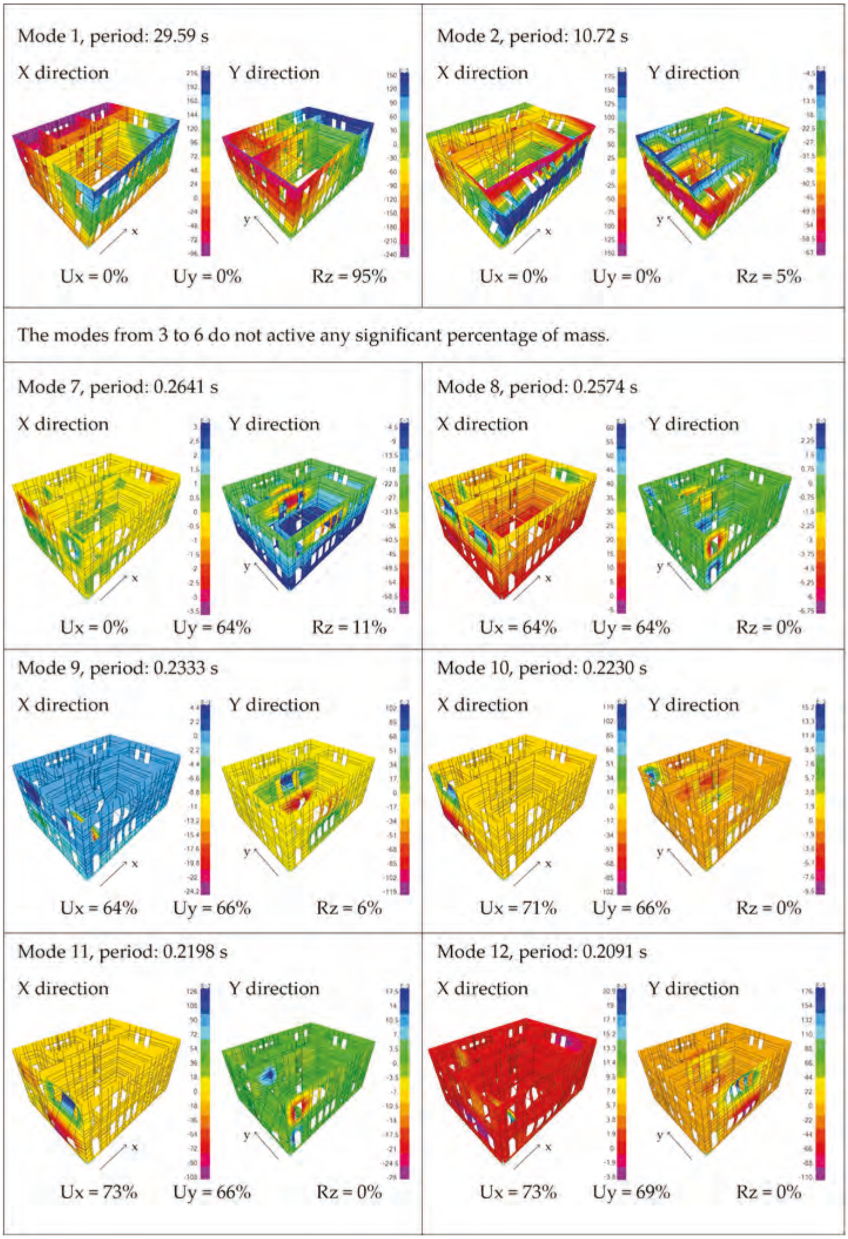

Figure 8. Results obtained by the modal analysis, for the most significant modes. Ux are the masses participating in the *X* direction. Uy are the masses participating in the *Y* direction. Rz are the masses participating in the rotation around the *Z* axis. The color scale shows the zone of greater reaction, and its values are expressed in mm.

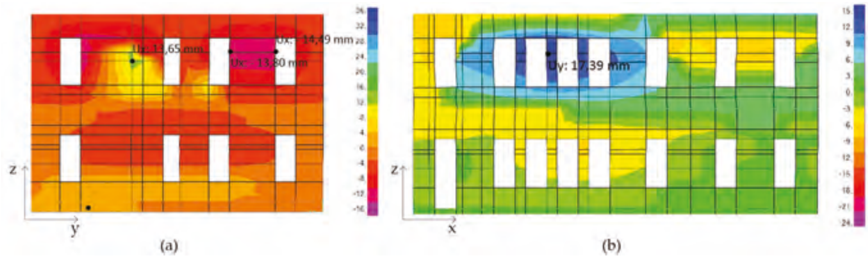

Figure 9. The maximum frame displacements for the load combination in the *X* direction (**a**) and in the *Y* direction (**b**). The displacement values are defined by referring to the quiet state of the structure.

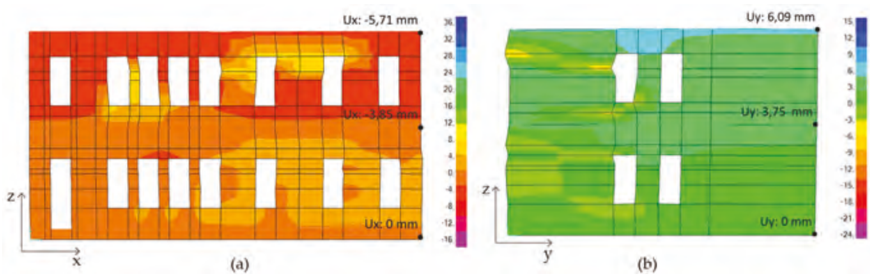

Figure 10. The maximum floor displacements for the load combination in the *X* direction (**a**) and in the *Y* direction (**b**). The maximum interpolation displacements are calculated through the difference between the floor displacements.

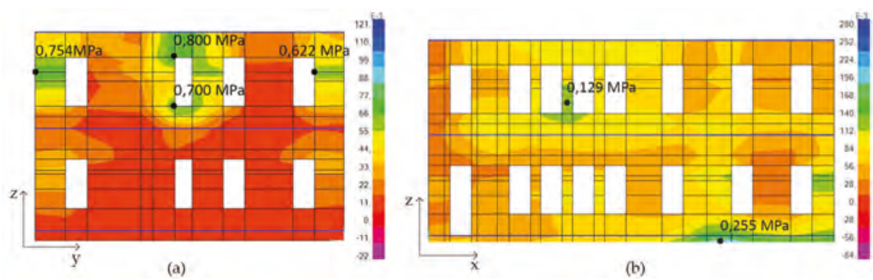

Figure 11. The maximum stress values for the load combination in the *X* direction (**a**) and in the *Y* direction (**b**).

Analyzing the results, the element of the structure that is more vulnerable is located on the second floor near the four openings of the south façade. This element is characterized by the maximum values of displacement and stress for the load combination in the *Y* direction.

To ensure the study is complete, some characteristics of the structure are identified for which a level of uncertainty was found about their mechanical characteristics. The foundation elements and the connection status of the different masonry present no comprehensive information, so different hypothesis of degradation of the elements are defined:

Hypothesis 1. *State of good conditions of the foundation system and a good connection between the different types of masonry;*

Hypothesis 2. *State of degradation of foundations and the consequent yielding support of the building on the ground;*

Hypothesis 3. *State of degradation of the foundation system as defined in the previous case, assumption of the loss of connection between the different masonry;*

Hypothesis 4. *Implementation of energy-retrofit intervention*.

In relation to these hypothesis, four different 3D models were built in the software. The linear dynamic analysis, as shown before, is carried out for each them. In this case, only the results of the four analyses are presented (Table 6).

The results of the linear dynamic analysis show the main weakness of the building: the high interpolation movement, the frame movement and the instability of one of the walls on the second floor, which is characterized by significant thinness. In Hypothesis 1, the building has a good response to the seismic action not presenting any particular fragility. The weaknesses are larger in Hypothesis 2. Hypothesis 3 presents slightly better behavior than the second hypothesis because of the loss of connection between the three different types of masonries that cause a better response to seismic action. Hypothesis 4 presents reduced fragilities over Hypotheses 2 and 3 because of the augmented mass of the vertical envelope elements given by the application of the insulating material. For all the hypotheses, the stress values are considered insignificant since those are lower than the minimum value admissible for the compressive strength of a brick wall ($f_{m,min}$ = 2.4 MPa) as prescribed by the instructions for the application of NTC 2008; they will not be examined in the following analyses.

Table 6. Results of the linear dynamic analysis of the different cases.

Hypothesis	T_1	Maximum Interpolation Displacement (mm)	Interpolation Displacement Test [1]	Maximum Frame Displacement (mm)	Maximum Stress (MPa)
1	29.59	3.85	Verified	17.39	0.80
2	38.77	16.07	Not Verified	23.69	0.44
3	38.77	15.98	Not Verified	23.69	0.44
4	33.94	19.67	Not Verified	23.01	0.44

[1] The admissible interpolation displacement is calculated through the formula $\Delta x_{max} = 0.003\ h_{floor}$, as prescribed by NTC 2008. For the case study, the admissible interpolation displacement values for the ground and first floors are 11.88 mm and 12.63 mm.

The definition of energy-retrofitting interventions is structured considering the envelope first. Following the methodology proposed in this paper, the interventions on the envelope are defined in this case according to the amount of thermal surfaces of the envelope (Table 7). For each intervention, the percentage of the envelope affected by the retrofit is shown.

Table 7. Definition of EEMs for energy retrofitting on building envelope.

Intervention Code	Description	Percentage of Envelope Considered for the Intervention
M 1	External wall	49%
M 2	Roof	22%
M 3	Basement	22%
M 4	Windows	7%
M 5	M 1 + M 2	71%
M 6	M 1 + M 2 + M 3	93%
M 7	M 1 + M 2 + M 3 + M 4	100%
M 8	M 4 + M 2	29%
M 9	M 4 + M 2 + M 3	51%
M 10	M 4 + M 1	56%

The adoption of characteristics for the envelope and heating system considers the benchmarks provided by the Conto Termico 2.0, developed by GSE (Rome, Italy). As previously described, EEM interventions have been combined with the replacement of the three generators and the installation of a photovoltaic system and LED lamps (Table 8).

Table 8. Description of proposed EEMs for the case study, with the characteristics for the envelope and heating system after the intervention according to what is prescribed by the Conto Termico 2.0.

Intervention	Description	Current State Value	After Intervention
External wall	External insulation of the wall of mineral wool 14 cm	U = 1.76 W·m^{-2}·K^{-1} U = 0.90 W·m^{-2}·K^{-1}	U = 0.22 W·m^{-2}·K^{-1} U = 0.22 W·m^{-2}·K^{-1}
Roof	External insulation of the second slab of mineral wool 16 cm	U = 1.75 W·m^{-2}·K^{-1}	U = 0.21 W·m^{-2}·K^{-1}
Basement	Insertion of insulating layer of mineral wool 14 cm below the floor level	U = 1.93 W·m^{-2}·K^{-1}	U = 0.20 W·m^{-2}·K^{-1}
Windows	Installation of double glazing with argon cavity and low-emissivity coating, polyvinyl chloride (PVC) frame with thermal break	U = 3.19 W·m^{-2}·K^{-1}	U = 1.21 W·m^{-2}·K^{-1}
Heating system	Condensing boiler with buffer storage tank	η = 0.62	η = 0.98
	Biomass boiler		η = 0.92
	Electric water-heating pump		COP = 3.9
Lighting system	Lighting substitution with 16 W LED lamps	Use = 7.05 kWh·m^{-2}	Use = 3.13 kWh·m^{-2}
RES production	Installation of photovoltaic panels with 2.4 kW peak power	-	Prod. = 1828 kWh·y^{-1}

The seismic retrofit consists of four possible interventions (Table 9) and the definition is based on the most vulnerable properties of the building: excessive displacement movements, deformations, and the instability of the sloping wall located on the second floor of the original building structure.

Table 9. Definition of the proposed seismic retrofit strategies of interventions for the case study.

Code	Intervention	Description	Characteristic
1	Roof relief	Replacing the existing soleplates with new elements composed of armored plates in autoclaved aerated concrete	Own weight= 1.44 kN/m^2, Thermal transmittance = 0.67 W m^{-2} K^{-1}
2	Anchorage with tie rods	Inserting a tie system to prevent the most vulnerable wall collapse mechanisms	Bar type: FeB32K, Tie diameter: 20 mm, Plate type: FeB32K, Plate dimension: 0.5 × 0.5 × 0.5 m, Installation height: 8.5 m
3	Reinforcement with fiber-reinforced polymer (FRP)	Stiffening of the slim wall at the openings with FRP bands with bonded carbon fibers in perfect adherence to the masonry	Tensile modulus= 240–640 MPa, Tensile strength= 4200–4800 MPa
4	Reinforcement with double layer of FRP	Stiffening of slim wall with double layer of FRP bands	Tensile modulus = 240–640 MPa, Tensile strength = 4200–4800 MPa

After the analysis of each energy and seismic retrofitting interventions, the assessment for the Manzoni school presents cost-optimal solutions as follow in the next section.

3. Results

With the application of the methodology described in the previous section, three different cost-optimal interventions are presented and it is possible to evaluate the results on energy performance and global costs in comparison to the reference case (Table 10).

Table 10. Energy use and cost for the business-as-usual building.

	Heating Primary Energy Use	Total Primary Energy Use	Investment Cost	Annualized Global Cost
Reference	50.66 kWh m^{-2}	121.93 kWh m^{-2}	200.42 € m^{-2}	21.00 € m^{-2}

3.1. Cost-Optimal Among All the Interventions

The intervention M 21.1, as presented in the description in Table 1, represents the optimal solution among all the interventions (Figure 12). It consists on the realization of the external insulation of mineral wool in the envelope and the installation of a condensing boiler and LED lamps. The outcome results of primary energy use and annualized global cost are, respectively, 57.32 kWh m^{-2} and 16.30 € m^{-2} (Table 11).

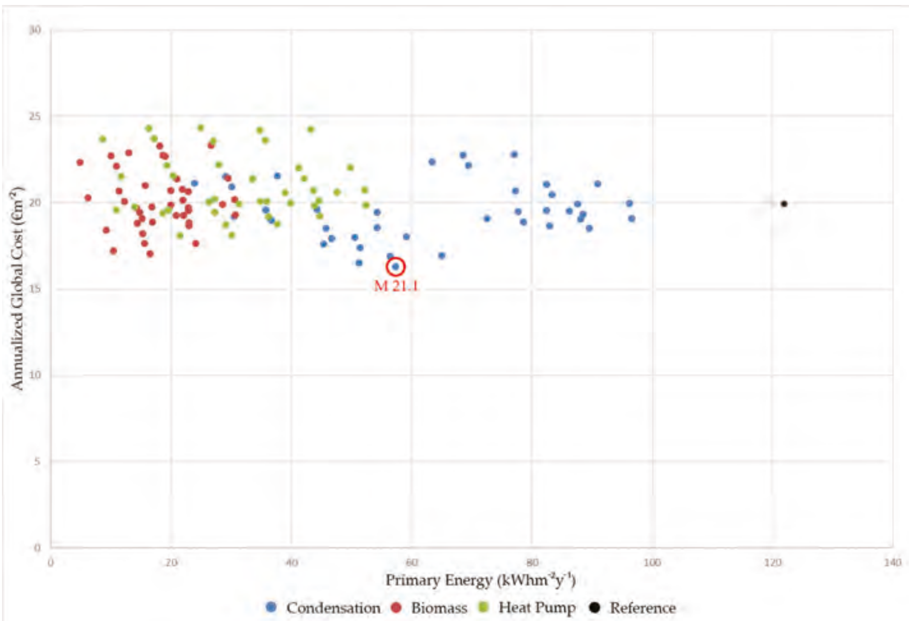

Figure 12. Cost-optimal solutions concerning primary energy consumption and global cost for the proposed EEMs, among all the interventions.

Table 11. Energy use and cost for the identified cost-optimal measure.

Measure	Heating Primary Energy Use	Total Primary Energy Use	Investment Cost	Annualized Global Cost
M 21.1	50.66 kWh m^{-2}	57.32 kWh m^{-2}	200.42 € m^{-2}	16.30 € m^{-2}

3.2. Cost-Optimal Among All the Interventions that Achieve the nZEB Targets

According to the nZEB benchmarks, the cost-optimal solution is M 31.2 (Figure 13), including the installation of a biomass boiler and LED lamps, the realization of external insulation, and the installation of a photovoltaic system. The results for M 31.2 show a primary energy use of 10.38 kWh m^{-2} for years and an annualized global cost of 17.23 € m^{-2} during the lifecycle (Table 12).

Table 12. Energy use and cost for the identified cost-optimal measure.

Measure	Heating Primary Energy Use	Total Primary Energy Use	Investment Cost	Annualized Global Cost
M 31.2	10.27 kWh m^{-2}	10.38 kWh m^{-2}	247.57 € m^{-2}	17.23 € m^{-2}

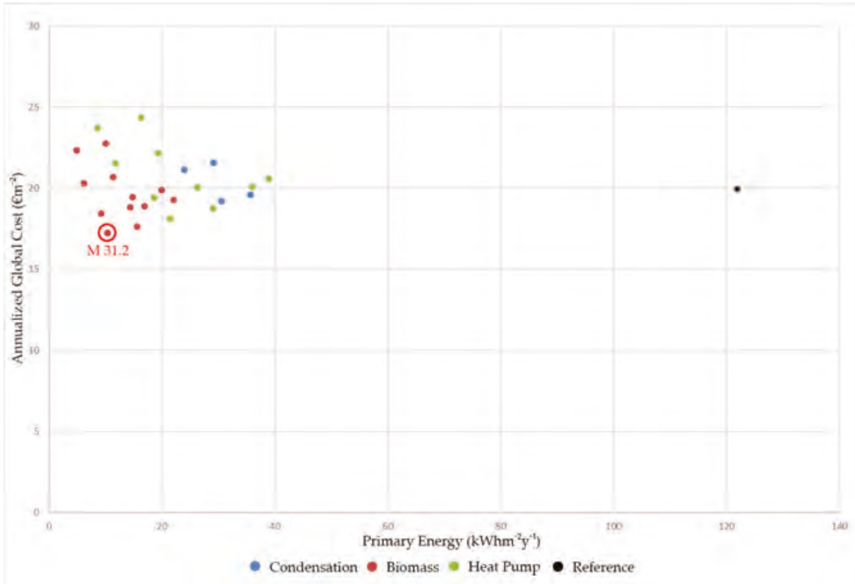

Figure 13. Cost-optimal solutions concerning primary energy consumption and global cost for the proposed EEMs, among the interventions that achieve the nZEB targets.

3.3. Cost-Optimal Among All the Interventions with Incentives

The incentive calculation (Table 13) gives evidence of the M 37.2 (Figure 14) as the cost-optimal solution among all the interventions: each envelope element is retrofitted (insulation on external walls, basement, roof, and replacement of windows), a biomass boiler and photovoltaic system are installed and a light system with LED lamps is considered, saving overall energy use and global cost during the lifespan. The measures allow a primary energy use of 4.85 kWh m^{-2} for a year and an annualized global cost of 9.10 € m^{-2} during the lifecycle (Table 14).

Table 13. Intervention price and incentive amount for every foreseen renovation action.

Intervention Typology	Intervention Price (€)	Subsidies Related to Investment (%)	Subsidies (€)	Maximum Subsidy (€)
I-Horizontal opaque structures: roof insulation from outside	41,146.06	55%	22,630.33	
II-Horizontal opaque structures: flooring insulation from inside	24,669.25	55%	13,568.09	(I + II + III) $\leq$ 400,000.00
III-Vertical opaque structures: wall insulation from outside	24,892.26	55%	13,690.74	
Window substitution with installation of thermoregulation systems	44,754.00	55%	24,614.70	100,000.00
Substitution of existing lamps with LED lamps	919.25	40%	367.70	70,000.00
Building modification in nZEB building		65%		1,750,000.00
Condensing boiler installation	9870.56	55%	5428.81	3000.00
Electrical heat pump installation	39,274.63	-	25,528.51	-
Biomass boiler installation	23,001.58	-	14,951.03	-

Table 14. Energy use and cost for the identified cost-optimal measure.

Measure	Heating Primary Energy Use	Total Primary Energy Use	Investment Cost	Annualized Global Cost
M 37.2	4.74 kWh m^{-2}	4.85 kWh m^{-2}	139.74 € m^{-2}	9.10 € m^{-2}

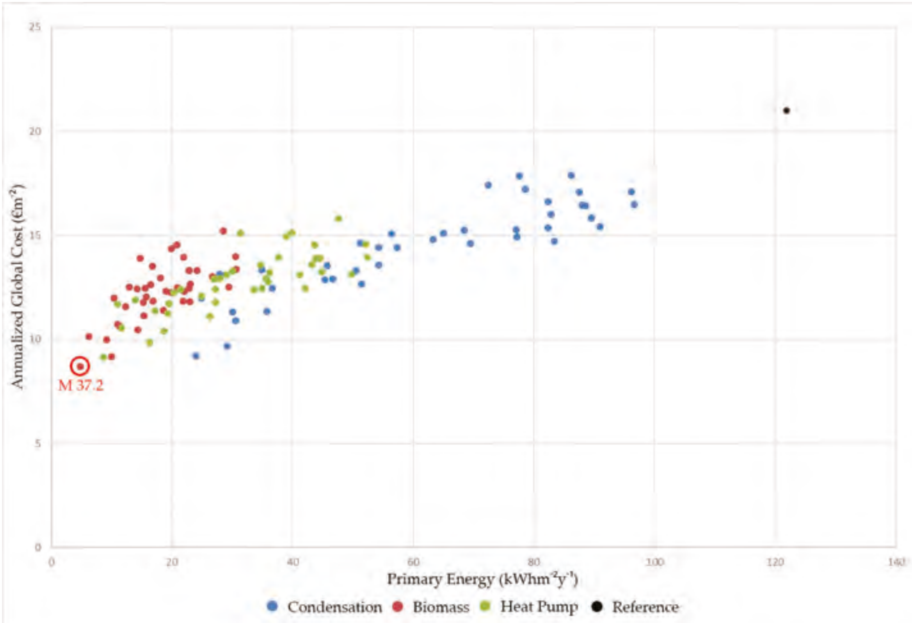

Figure 14. Cost-optimal solutions concerning primary energy consumption and global cost for the proposed EEMs applying incentives calculation.

3.4. Cost-Optimal Among All the Interventions that Achieve the nZEB Targets with Incentives

The same measure of the previous section, M 37.2, complies with the nZEB parameters, resulting as the best proposed solution that allows a primary energy use of 4.85 kWh m^{-2} per year and an annualized global cost of 9.10 € m^{-2} during the lifecycle (Figure 15).

In the case study, a single intervention of thermal insulation on the external walls is proposed as the cost-optimal solution, corresponding to the best compromise of energy saving at lower global cost. The conversion to nZEB allows higher energy saving in comparison to the cost-optimal solution (from 53% to 91%), showing a similar annualized global cost; the application of the current national subsidy program allows the global cost to be halved during the 30-year life span (−56%), even if the renovation measures regard all the building elements of the envelope, corresponding to the highest investment cost due to the number of technical elements and intervention areas.

3.5. Seismic Retrofitting Interventions

For the purpose of this study, the evaluation of seismic interventions considers only hypothesis number 4. This hypothesis permits examination of the effects of the combinations of the energy and seismic retrofit. The linear dynamic analysis is carried out for all the interventions described in the previous chapter. The results (Table 15) are expressed as a variation of the values compared to the current situation (Table 6), to show the structural benefits.

All the interventions allow improvement of the structural behavior of the building. The only exception refers to the acceptance criteria of the displacement, related to the load combination in the *Y* direction; in this case, the interpolation displacement values are referred to the nodes of the north façade, which is not affected by the interventions because it is in a good condition, and the values are the same as in the actual situation. Analyzing the results through a cost–benefit evaluation, the best solutions consider as interventions anchorage with tie rods (n. 2) and reinforcement with fiber-reinforced polymer (FRP) (n. 3). In fact, solution n.1 results in being very expensive and ineffective, and n.4 has the same benefits as n. 3 but with a doubled cost. So, the best solution for the seismic retrofit is the combination of the two interventions n. 2 and n. 3. For this solution, an annualized global cost of 22.48 €·m^{-2} during the 30-year life span is calculated.

Table 15. Results of the seismic analyses of the proposed interventions for hypothesis no. 4. The results are expressed in terms of variation from the values of the current situation. 1−2: values referred to the load combinations in the *X* and *Y* directions.

Intervention	Interpolation Displacement Value Variation	Interpolation Displacement Test (Dir. X^1)	Interpolation Displacement Test (Dir. Y^2)	Maximum Frame Displacement Value Variation	Investment Cost
1. Roof relief	−0.08 mm	Verified	Not verified	−0.15 mm	70,464.80 €
2. Anchorage with tie rods	−0.00 mm	Verified	Not verified	−33.62 mm	2205.58 €
3. Reinforcement with FRP	−0.43 mm	Verified	Not verified	−2.42 mm	9741.54 €
4. Reinforcement with double layer of FRP	−0.37 mm	Verified	Not verified	−2.44 mm	14,547.66 €

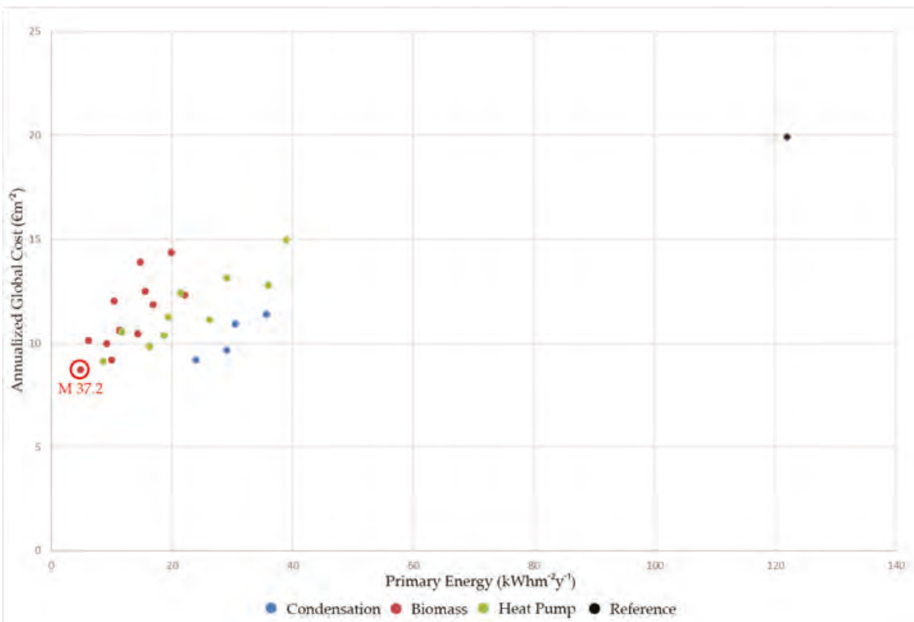

Figure 15. Cost-optimal solutions concerning primary energy consumption and global cost for the proposed EEMs applying the incentives calculation, among all the interventions that achieve the nZEB targets with incentives.

4. Discussion

This paper identifies the interventions to be adopted for the optimal energy and seismic retrofit of the A. Manzoni school in Motta di Livenza. From the energetic point of view, it is convenient to intervene in the envelope by creating an exterior insulation and finishing system, isolating the upper floor and the floor on the ground and replacing the window frames, and on the systems by means of the installation of LED lamps, a photovoltaic system, and the replacement of the existing generator with a biomass boiler.

Regarding the seismic upgrading intervention, it is assumed that the installation of two tie rods to the intrados of the last floor, and the reinforcement of the most vulnerable wall by installing FRP on the outer side of the masonry, will be undertaken.

The costs of intervention for the energy retrofit, and for the seismic renovation have been calculated (Figure 16). For the energy refurbishment of the building, the determined cost of intervention is 170.83 €·m^{-2}, the costs of intervention for the seismic retrofit is 5.31 €·m^{-2} for the tie rod intervention and 23.45 €·m^{-2} for the FRP intervention. To perform the interventions in a separate way, the expected cost is 199.60 €·m^{-2}.

Finally, the cost of intervention was calculated in the case of a joint energetic and seismic retrofit renovation, and the expected cost is 193.31 €·m^{-2}. The expected cost is slightly lower than that of separate interventions, thanks to the possibility of reducing site labor and construction costs.

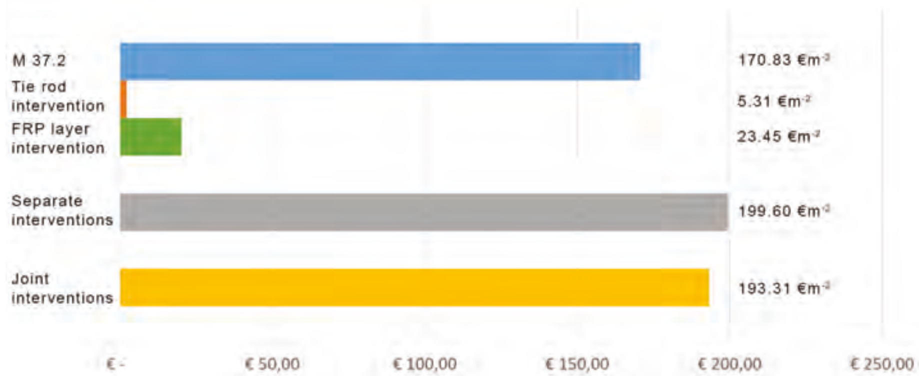

Figure 16. Cost of interventions graph. The blue bar represents the cost for the energy retrofit M 37.2; the orange bar is the cost for the seismic retrofit (tie rod); the green bar represents the cost for the seismic retrofit (one FRP layer); the grey bar is the cost for three separated interventions (M 37.2, tie rod, FRP layer); and the yellow bar represents the cost for three joint interventions (M 37.2 + tie rod + FRP layer).

The annualized global costs for the energy retrofit interventions, considering a lifecycle of 30 years, and the intervention costs for the seismic renovation have been calculated. After that, the cost of intervention was assessed in the event that the two redevelopment interventions were carried out jointly.

For the energy retrofit intervention, in the 30-year life span considered, the economic gain is 56%, and the energy saving 96%, compared to maintaining the current situation. For the seismic retrofit intervention, the annualized global costs, always referred to over 30 years, increase by 7% and the primary energy consumption remains unchanged.

Combining the two interventions, we obtain a reduction in the total annualized cost of 3%, thus passing from 56% to 53% of economic gain (the annualized global cost increases from 9.10 €·m^{-2} to 9.86 €·m^{-2}) with 96% of primary energy saved.

Eventually, the same considerations are made for the other two cost-optimal cases previously examined: with and without transforming the school into a nZEB building, both without considering any kind of subsidies.

Starting from the first energy retrofit identified, M 21.2, the cost for the seismic intervention is added to the annualized global cost. The results show that in this case the annualized global cost changes from 16.30 €·m^{-2} to 17.45 €·m^{-2} with 53% of primary energy saved. For the second energy retrofit, M 31.2, that which concerns the nZEB parameters, the annualized global cost changes with the addition of the seismic part from 17.23 €·m^{-2} to 18.38 €·m^{-2}, and the energy saving, instead, remains 91% (Figure 17).

It can be noted that even in those cases where the use of incentives is not foreseen, it is possible to aim at an economic saving in a 30-year life span even combining the energy and seismic retrofit action.

It can be assumed that the realization of an energy refurbishment can also provide the possibility to adapt the building from the seismic point of view, aiming at acceptable periods of return for the investment. Moreover, if a building needs a seismic retrofit it is possible to carry out an energy requalification that makes the investment economically viable, thanks to the reduction of energy consumption and operating costs.

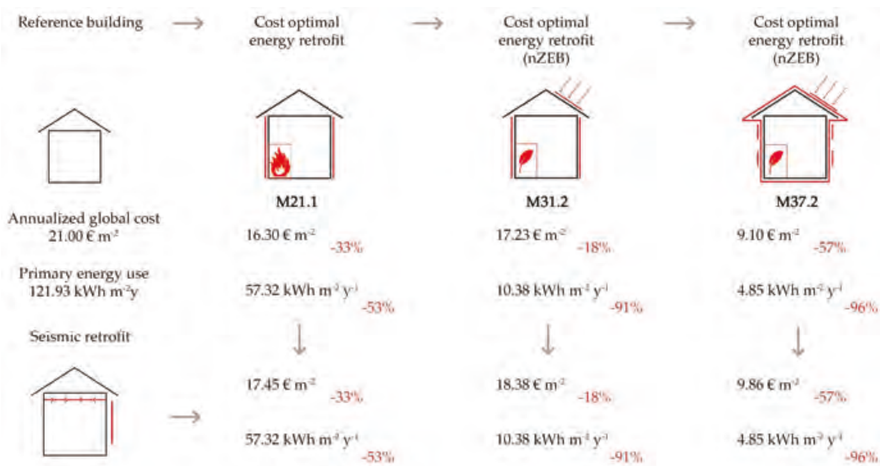

Figure 17. Cost-optimal and nZEB solutions compared with the reference case.

The data collected define the possibility of combining energy and seismic retrofit interventions in an effective and convenient way for investors, also referring to other buildings than the case study.

Considering the Italian building stock, it can be assumed that most of the artefacts still have high energy consumption or are not in compliance with the new seismic standards defined in recent years. It is, therefore, considered reasonable, both in one case or another, to evaluate the hypothesis of a joint intervention that can bring the buildings back to a suitable condition, aiming, in a brief time, for a total economic return on the investment.

In future renovation works, the designer of the building refurbishment should consider joining the retrofit works at the beginning of the project. In particular, the best choice should be retrofitting a single envelope element, from both seismic and energetic aspects, thus reducing the cost of interventions, materials and building-site impacts.

The seismic retrofit intervention that does not generate an economic saving and, therefore, a return on investment can be more economically sustainable if combined with an energy requalification.

5. Conclusions

The paper presents optimal measures of intervention in the cases of both energy and seismic retrofit for a public school building. The study is developed according to the application of the last European Union norm that concerns the achievement of nZEB targets for cost-effective energy-reduction measures, considering also seismic procedures.

The energy cost-optimal measure with subsidies allow an energy saving of 56% and an energy-use reduction of 96% in comparison to the reference situation during the 30-year life span. Analyzing the seismic intervention during the same period, the annualized global cost is calculated with an increase of 7% in comparison to the reference case while the energy consumption is unchanged. With the combination of energy and seismic retrofit, the cost saving is 53% and energy consumption is reduced by about 96%.

The methodology described in this paper points to several results. First of all, a cost-optimal measure for the energy retrofit of the case study could be found in different ways in relation to the conversion to a nZEB scenario and the application of subsidies. Considering these cases, the cost-optimal solution consists of a deeper upgrade with higher energy savings. The methodology could be applied to different building typologies in order to evaluate the different kinds of intervention in relation to the financial and economic availability and feasibility.

The cost-optimal measure for the seismic retrofit is based on the evaluation of several interventions on the building envelope; the paper compared structural benefits and costs for each intervention in order to define the best measure for a global seismic upgrade.

At last the two cost-optimal measures (energy and seismic) were combined. In this case, the results show that the economic saving in 30 years is far lower in respect to an intervention that considers only an energy retrofit. In fact, generally seismic retrofit measures do not create a money saving and a favorable payback time. In this case, the energy saving permits the seismic intervention to be paid back in 12 years (Figure 18).

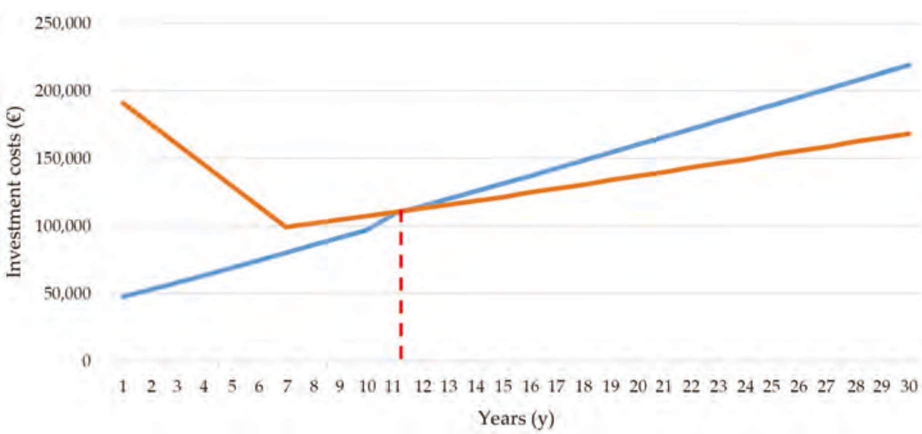

Figure 18. Return time graph for the investment cost of the energy and seismic retrofit. As prescribed in the Conto Termico 2.0, the subsidies are calculated to be provided during the first 6 years. Red line represents the payback flow M 37.2 investment cost in respect to the blue line of the Reference case.

The global cost of a combined intervention is lower than the costs of two different interventions. A single intervention reduces the period of the works and the consequent troubles for the school activities. When a single retrofit is needed, the possibility of a combined intervention should be analyzed.

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Abbreviations

EEMs	Energy-efficiency measures
EPBD	Energy performance of building directive
EU	European Union
FEA	Finite element analysis
FRP	Fiber-reinforced polymer

GC	Global cost
GSE	Gestore Dei Servizi Energetici
IEA-EBC	International Energy Agency–Energy In Buildings and Communities Program
MS	Member state
NTC	Norme Tecniche per le Costruzioni
nZEB	Nearly zero-energy building
RES	Renewable energy source
SLS	Serviceability limit states
TEP	Tonne of oil equivalent
TV	Treviso province
ULS	Ultimate limit states
V_N	Nominal life
V_R	Reference period

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Article

Seismic Retrofit Measures for Masonry Walls of Historical Buildings, from an Energy Saving Perspective

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Abstract: The planning of energy saving and structural retrofit interventions on masonry buildings are usually two separate projects; combined interventions are rare. Solutions tackling both aspects can reduce total refurbishment costs and improve global building performance. However, heavy interventions on the envelope have to be carefully designed in order to improve both seismic and energy performance whilst mitigating environmental impact. National energy saving regulations are generally less strict for historical buildings, making this category of buildings very interesting not only because of their widespread diffusion across Italy but also because of the possibility of planning interventions that will allow significant improvements by combining building efficiency and safety. This research looks at these aspects and proposes new methods for refurbishing masonry buildings combining seismic improvements and energy saving interventions. Among those mostly commonly applied on masonry buildings in Italy, and described in this paper, are various combined retrofit interventions, and we report the results of these interventions on thermal transmittance reduction and global costs.

Keywords: historical building; seismic and energy retrofit; combined interventions; U-value; historical masonry

1. Introduction

This article analyses the results of a wide-ranging study investigating the effects on energy performance of masonry buildings with historical/heritage value that have undergone typical seismic improvement interventions. The most frequently used techniques have been examined by analyzing, for each of them, the resulting effect on energy performances of the envelope in order to evaluate the variation of thermal properties of the materials employed for structures and finishes.

A significant part of Europe's building heritage is made up of old buildings [1–4] constructed using poor quality insulation materials. Therefore, recent regulations, such as the EU Directive 2010/31 [5] on buildings' energy efficiency, aim to increase energy efficiency standards, by considering both the single components and the entire building. In Italy, the energy improvement intervention regulated by the Legislative Decree [6] takes into account the European Directive 2002/91/CE [7]; actual regulations have been updated several times to comply with new European directives. The current energy saving standards have been recently integrated with a set of NZEB objective norms; last updates of 90/2013 law have been published in the Official Journal of the Italian Republic, 15 July 2015, n.39 [8]. However, the application of the aforementioned legislation is subordinate to Italy's own cultural conservation principles. Rules concerning the Italian energy performance certificate (APE), to check thermal installations, are still valid, whilst any other intervention must be evaluated by the local office of Ministry of Cultural Heritage and Activities and Tourism (MiBACT). The latter office evaluates, case by case, the adequacy of interventions. Despite their best intentions [5,8], current regulations have led to an increase in the gap in required performance between new buildings and historical buildings. Furthermore, a substantial absence of general rules about better compatibility among available energy retrofit technologies and other eligible interventions can lead to differences in treatment of similar cases in several contexts [9].

In recent years, a number of investigations have looked at energy saving and structural aspects. Different approaches have been adopted, ranging from holistic ones [10], dynamic simulations of entire buildings [11], to specific solutions such as the adoption of a thermal, vegetal based, insulating plaster [12].

An interesting multidisciplinary approach was investigated by Ascione et al., Mannella et al. and De Berardinis et al. [13–15]: they proposed a replicable methodology for improving the performance of historic buildings based on preliminary historical analysis, structural diagnosis and in-situ investigations. This multidisciplinary approach to building structural and energy diagnoses was applied to a case study obtaining a model to predict the structural safety of the building and its energy consumption. Tiberi and Carbonara [16] explored aspects relating to retrofitting interventions for energy saving and the financial costs, introducing a case study and finding four solutions for the envelope; Calvi et al. [17] presented an integrated approach to seismic resilience and energy efficiency assessments. Marques et al. and Calvi [18,19] performed an in-depth cost–benefit analysis of the strengthening solutions, comparing the economic benefit gained by reducing the seismic damage against the intervention cost. More recently, smart and innovative integrated systems have also been designed in order to achieve important energy and environmental benefits regarding historical buildings [20,21].

The state of the art approach leans towards combined interventions and multidisciplinary approaches in the refurbishment process; however, it is important to understand the interactions going on. This study highlights how the execution of some of the most adopted typologies of structural improvement intervention on the outer walls typically cause an increase of the envelope thermal transmittance and, consequently, a general worsening of the energy performance of the building. However, an appropriate selection of materials and the techniques employed, with a very small increase in working times and costs, allows a rebalancing and even, in some cases, a notable reduction in thermal conductivity whilst respecting the original historical values of the buildings. The analyses carried out permit us to evaluate the impact of current regulation on energy efficiency in buildings that constitute Italy's cultural heritage [22].

2. Materials and Methods

The impact on buildings' energy efficiency produced by structural improvement interventions is analyzed below focusing on conductivity and thermal transmittance of the envelope. This work analyzes some of the most common structural improvement interventions on various kinds of masonry and typically occurring in the historical buildings of central Italy (a territory characterized by important seismic events and by historical buildings, as shown in Figure 1).

The investigated interventions are often used for the seismic retrofit of buildings damaged by earthquakes [23]. In general, restoration projects that include seismic improvements use several different types of intervention. Figure 2 illustrates the distribution of the principal interventions carried out on masonry buildings located outside the historical center of L'Aquila after the earthquake (Mw = 6.3) that occurred in the Abruzzi region on the 6 April 2009 [24,25]. Figure 2a shows the distribution of the most diffuse interventions and Figure 2b shows the distribution of secondary interventions: main intervention, for each building, refers to more widespread and costly work typology; secondary interventions, on the other hand, are complementary to the main ones.

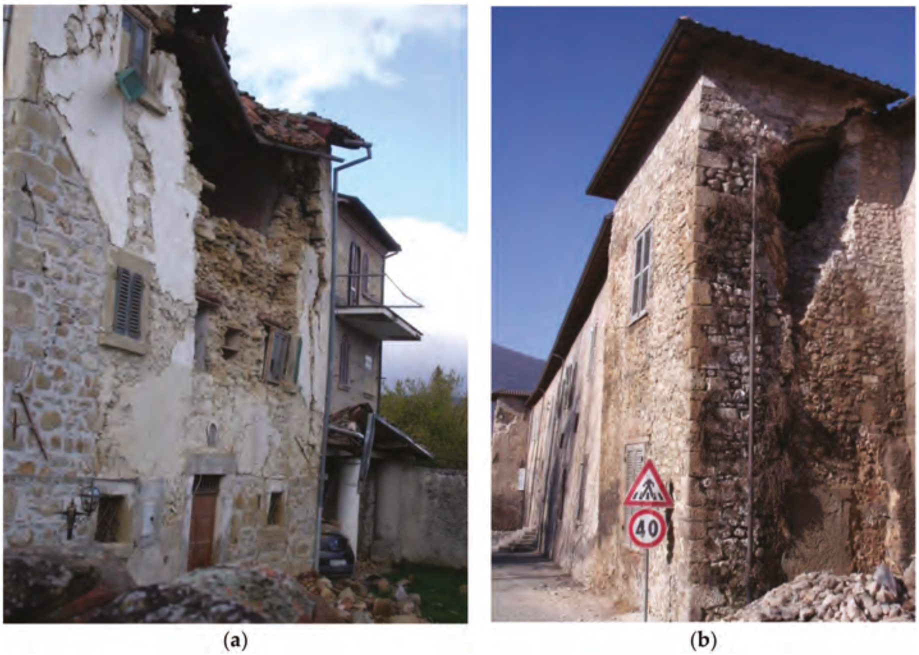


Figure 1. Historical buildings heavily damaged by the earthquake that occurred on 30 October 2016 in Central Italy: (**a**) Exterior view of the residential building; (**b**) Fortified residence.

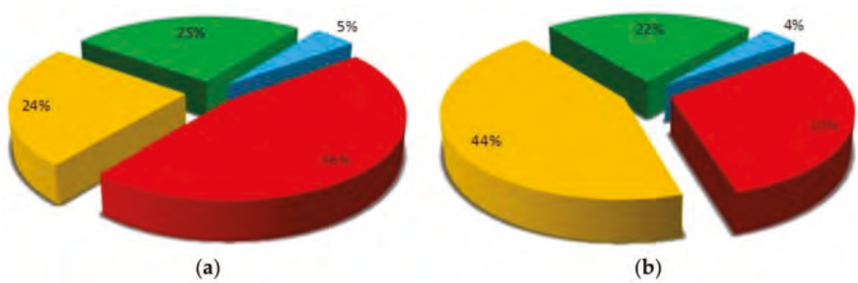


Figure 2. Type and frequency of techniques for (**a**) main and (**b**) secondary interventions to historical buildings after the Abruzzo earthquake of 6 April 2009 in Abruzzo. Red: strengthening of masonry walls (i.e., reinforced plastering mortar, injections, diàtonoi); yellow: single, individual interventions; green: application of tie-rods in connections and walls; blue: interventions related to the foundations.

2.1. Methodology

The methodology for this research involves seven steps and terminates with an optimization of the interventions carried out. The methodology of the study is the following:

- Step 1: execution of preliminary investigations on the morphology of the masonry and evaluation of the thermal physical state of the envelope;
- Step 2: application of the most common interventions for the structural improvement of the investigated masonries;

- Step 3: application of the most common energy efficiency interventions, compatible with the structural interventions chosen in the previous step;
- Step 4: determination of the new thermal-physical characteristics of the masonries using thermal equivalent conductivity (λeq);
- Step 5: comparison between the thermal transmittance (U-value) of the masonries after seismic retrofitting intervention and after energy retrofitting interventions combined with seismic retrofitting interventions;
- Step 6: economic analyses of each of the solutions analyzed, to show the advantages and disadvantages of using combined solutions;
- Step 7: evaluation of the design process to optimize the balance between cost and work, to achieve structural improvement as well as adequate energy saving.

2.2. Masonry Types and Thermal Properties

This research relates to the variations of the thermal properties of each material making up the walls after seismic retrofitting interventions: the analyses carried out aim to establish the new values of the U-value of the masonry.

In the case of heterogeneous materials, like masonry, it is not formally correct to use thermal conductivity because the flux is not solely due to conduction but also to convection and radiation in the internal cavities of the wall. For this reason, the study was conducted by varying the thickness of each layer of masonry analyzed (masonry cut stones with possible rubble in-fill). Table 1 shows the values of λeq for different value of thicknesses.

Table 1. Main properties of investigated masonries. The thickness values refer only to the thickness of the masonry, not the total wall section.

Material	ρ (kg/m^3)	λeq (W/mK)
Masonry 20 cm thickness	2100	2.4
Masonry 26 cm thickness	2100	2.28
Masonry 36 cm thickness	2100	2.14
Masonry 56 cm thickness	2100	2.02
Masonry 76 cm thickness	2100	1.94
Rubble	1500	0.7

To calculate the U-value of heterogeneous structures, reference was made to the UNI EN ISO 6946:2008 and EN ISO 12567-1 [26,27], that also specify a method to measure the thermal conductivity of homogeneous materials. For the reference values of thermal conductivity for common building materials, references used are in the following standards: UNI 10351:2015 (homogeneous materials) and UNI 10355:1994 (not homogeneous materials) [28,29].

The next step was to define the whole section of the wall using the equivalent conductivity of the masonries described in Table 1. Thus, it was possible to determine, in six typical configurations investigated, the impact of the most common structural improvement interventions on the masonry thermal properties. The most recurrent envelope thicknesses in the Italian historical buildings of the Central Apennines were considered. Table 2 shows the outer walls investigated in some selected different thicknesses. In the table below, the middle column refers to the wall section layout characterized in terms of the constituting layers: e.g., section "plaster (2) masonry (20) rubble (8) masonry (20) plaster (2)" refers to a section with five layers, namely a 2-leaf wall with main layers made of stone masonry, with 20 cm thickness for each one, a filling layer of rubble stone with 8 cm thickness, and the plaster on both faces with an average thickness of 2 cm.

The execution of seismic retrofitting interventions generally involves the removal and then remaking of one or both of the external finishing plasters. In this case, the new plasters are made with high mechanical performance pre-mixed materials based on pozzolanic binders or mixed lime/cement.

Then a final finishing layer, made of lime-based plaster for the interior surface of the wall and cement-based plaster for exteriors, is spread on the masonry surface. In Table 3, various types of most common used plasters are shown, including some high thermal performance plasters.

Table 2. Wall thickness composition (in cm) and the U-value for all the samples analyzed. The finishes are lime/gypsum plasters.

ID	Wall Section Layout (cm)	U (W/m^{2}K)
MS4	plaster (2) masonry (36) plaster (2)	2.485
MS6	plaster (2) masonry (56) plaster (2)	1.955
MS8	plaster (2) masonry (76) plaster (2)	1.598
MR4	plaster (2) masonry (20) rubble (8) masonry (20) plaster (2)	1.941
MR6	plaster (2) masonry (26) rubble (8) masonry (26) plaster (2)	1.734
MR8	plaster (2) masonry (26) rubble (24) masonry (26) plaster (2)	1.242

Table 3. Water vapor resistance coefficient μ and conductivity λ of finishes.

Material	μ	λ (W/mK)
Lime/gypsum plaster, interior side	10.7	0.7
Plaster (c = 1000 J/kgK), exterior side	22.7	0.9
Plaster (c = 840 J/kgK), exterior side	22.7	0.9
Lime or lime/cement mortar	22.7	0.9
Thermal insulating plaster 1 [1]	<9	0.09
Thermal insulating plaster 2 [1]	4.5	0.075
Thermal insulating plaster 3 [1]	4	0.045

[1] The thermal characteristics of the insulating plasters derive from the average of the values declared in technical sheets of the most used commercial products.

Often the plasters in Table 3 replace the historic lime finishes, generating a further change of the envelope thermal performance; for this reason, the choice of finishes with specific characteristics is very important in the refurbishment process. Planners must pay close attention to the choice of materials and their combination in the design phase of the retrofit intervention because this strongly determines the performance of the enclosure. Different combinations of the materials described above will be shown in the next sections in order to define the most frequent types of structural intervention on the masonry and their new thermal characteristics.

3. Case Study

The structural retrofit of historical buildings has achieved commendable results in the last few decades from both a regulatory and an applicative point of view [30] and is the result of research as well as historical and technical traditions, which have been fully adopted by practitioners and designers. Research suggests that when planning structural interventions, the one solution fits all approach is not effective and each intervention must be assessed with a case by case approach.

This methodology is the result of an interdisciplinary dialogue that has been taking place for some time among engineers, restorers and technicians. This interdisciplinary dialogue has not, unfortunately, been extended to the energy installations sector, which still today proceeds in a somewhat ad hoc style notwithstanding recent significant developments in this field. Indeed, an absence of specific studies on the relationship between restoration, structures and installations often results in a design that is aware of neither its own limits nor its potential.

3.1. Seismic Retrofit on Vertical Structures

The study focuses on the analysis of stone masonry that characterizes the building technology most often found in historical and valuable buildings. Although a variety of materials and techniques are used, masonry presents recurrent problems with regards to seismic vulnerability and the applicability of the reinforcement techniques most frequently used. Generally the vertical structures examined are constituted by irregular shaped, stone elements (unworked stone, often of irregular shape, of different dimensions and sometimes even of different materials) that have been used to build one or more leafs. The connections between single stone blocks constituting the wall are made with low quality mortar in terms of their composition and strength. For this type of masonry, often poorly connected to the horizontal structures, the effects of seismic forces may create conditions of instability. These are related to the disintegration of the wall or part of it (expulsion of the outer leaf), to activation of kinematic mechanisms (out-of-plane or other mechanisms of local collapse) or to second mode damage due to forces acting in the plane of the wall (in-plane shear or buckling).

Interventions on masonry vertical structures are designed to increase the mechanical strength and ductility of the walls, improving the behaviour of the building subjected to static and seismic loads. The materials used are selected so as to obtain the chemical-physical and mechanical characteristics as compatible as possible with the original materials. Technical standards, mostly normalized in EU, give specific instructions about the mechanical qualification and the durability of the materials treated, which can be used for structural applications only if CE marked. Specific procedures are also defined for the classification of materials with specific characteristics of thermal conductivity, employable in the context of energy efficiency interventions. However, commercial products for which the thermal characteristics are specified and also appropriate for structural purpose are very few, and in particular, until now, no grout or structural plaster fall into this category.

The most common structural interventions can be classified into three main categories: localized repairs; localized improvement interventions that interest single discontinuity of the wall structure (such as filling of the cavities); and general improvement of the masonry characteristics, with specific actions taken to mitigate vulnerabilities associated with the type of brickwork and/or its structural elements and mortar. These interventions range from local rebuilding methodology: scuci-cuci (substitution of damaged elements with new ones, reestablishment of the structural continuity), that aims to restore the wall continuity along cracking lines; to mortar bed-joint repointing that improves deteriorated joints (both reinforced or not); to insertion of artificial diàtonoi (= stones which run through the thickness of the wall and bind it together as described by Vitruvius in [30]), that consists in the improvement of the connection between multi-leaf masonry walls via the insertion of small tie beams across the wall in a regular pattern; and to external reinforcement (jacketing with Fiber Reinforced Polymers, Glass Fiber Reinforced Polymers or grids of steel) [31,32].

Particular attention is given to the consequences that interventions of mortar injections (Figure 3) facing of masonries with reinforced plaster and the insertion of artificial diàtonoi have on the thermophysical characteristics of the wall surface. The decision to focus on these kinds of intervention was because of their frequent use and massive and diffuse application.

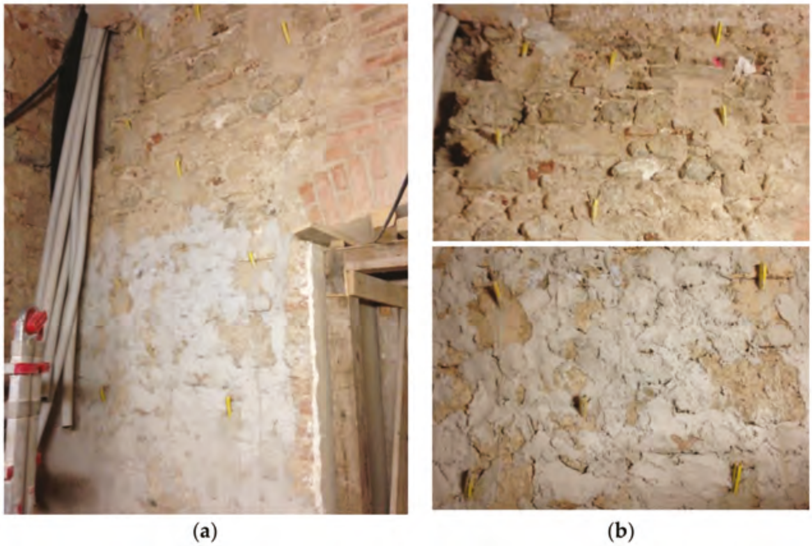


Figure 3. Example of grout injected masonry in an historical building in L'Aquila: (**a**) cannulae distribution on the wall; (**b**) details.

3.2. Energy Efficiency Interventions on Outer Walls in Historical Buildings

Preliminary evaluations of interventions for structural improvement allow us to define appropriate combined solutions for the energy efficiency of the building. In fact, the possibility of adopting solutions that are more or less invasive will depend on the degree of invasiveness of the structural intervention. Insulating materials can be used both inside and outside buildings, and external insulation, if carried out without interruption on the surface and with suitable materials, is capable of creating a continuous barrier to the heat transfer and hence controlling humidity on the internal side of the wall. It follows that where possible, the application of an external insulation is preferable to an internal insulation [22].

In the Table 4, all the retrofit interventions analyzed (either seismic and/or combined with energetic interventions) are described. The last intervention shows the characteristics of exterior insulation finishing system (EIFS) used in energy efficiency interventions. By way of comparison, Table 9 illustrates the results of applying EIFS in three different thicknesses: 3 cm, 6 cm and 10 cm.

Table 4. Definition of the seismic and energetic interventions.

ID	Interventions
GI1	Grout injections and 2 cm of finishing cement plaster (λ = 1)
GI + RP	Grout injections + reinforced plaster and 3 cm of finishing cement plaster (λ = 1)
RP	Reinforced plaster and 3 cm of finishing cement plaster (λ = 1)
D32	Artificial diàtonoi of 32 mm diameter and original finishing plaster
D100	Artificial diàtonoi of 100 mm diameter and original finishing plaster
TP1	3 cm of thermal insulating plaster (λ = 0.075), exterior side
TP2	3 cm of thermal insulating plaster (λ = 0.075), exterior and interior side
EIFS	Ext. Insulation Finishing System (λ = 0.04) and 1 cm of finishing plaster (λ = 0.7)

4. Non-Destructive Testing

The thermal characteristics of stone walls are directly related to the amount of voids in the masonry. This parameter is also related to the resistance of the masonry, in terms of bearing and shear strength. The amount of voids inside the masonry also affects its thermal characteristics, especially with an increasing regularity of the stone elements; thus with a minor percentage of voids, it is possible to observe an increase of the equivalent conductivity. Given the lack of specific experimental results, non-destructive testing was used to obtain velocity measurements and injectability measurements of different sample walls in order to estimate the voids' percentage and consequently the thermal characteristics variations of the masonry walls as a result of grout interventions.

4.1. Sonic Tests to Evaluate the Percentage of Cavities in Rubble Masonries

The sonic test is a non-destructive test that measures the speed of propagation of elastic waves within a wall. These waves are produced by a pulse generator (usually an instrumented hammer) and recorded by a receiver. The wave velocity increases with the bulk density of material. Thus, the tests are able to provide indications of a qualitative nature on the strength of the masonry and the presence of cavities, cracks or material heterogeneity intercepted along the wave path. For research purposes, knowing the percentage of injected voids is fundamental to estimate the physical properties of the wall, such as thermal insulation and breathability.

Results of the experimental testing by Artioli et al. [33] carried out on rubble masonry walls of historic buildings affected by the 2009 L'Aquila earthquake, in Italy, were used for the characterization of rubble masonry. That study has identified six severely damaged buildings in the urban centers of Onna, Tempera and Sant'Eusanio Forconese, in the Aterno Valley (L'Aquila, Italy). From these buildings 21 masonry portions were obtained and investigated with sonic tests before and after the injection of grout. These walls are representative of the rubble masonry widespread in Central Italy. The rubble between the two faces is of limited size, and consists of small pieces of stone mixed with the same mortar used for laying the stones.

During the interventions, the injection time of each single hole was monitored to estimate approximately the amount of grout injected and the percentages of injected cavities. Through sonic tests, a map of sonic speeds, made up of a square grid of measuring points with distances 0.20 m × 0.20 m, was obtained.

The research [33] shows that although the percentage of injected voids is placed between 7% and 18%, and on average 12%, the increases in terms of sonic speeds reach values of approximately 2000 m/s, corresponding to 380% of the original speeds. This result could depend on the sonic wave path that decreases substantially after the injections because the waves do not intercept cavities and the wave is propagated through the densest part of the masonry, regardless of the percentage of the injected voids. Seeing as it is possible to assimilate the propagation of the heat flow through the wall to the sonic wave, it is also right to suppose a very high increase of the conductivity values in the post-intervention. However, in this study the increase of the equivalent thermal conductivity of the injected rubble masonry has been determined by assigning to it the same value of the average amount of percentage of injected voids, equal to 12%.

4.2. Grout Injection Tests to Evaluate the Percentage of Voids on Irregular Stone Masonry

For the characterization of irregular shape, stone masonry, reference was made to the values provided by a grout injection test performed during the post-earthquake reconstruction in L'Aquila, in two buildings located in Via S. Marciano and in Via dei Vetusti (Tables 5 and 6). The injected masonry has a 60 cm thickness and is made of hewn stone in a single wall. The injection was performed by the execution of 1.4 cm diameter holes. The holes length was approximately 2/3 of the wall thickness and 1.2 cm diameter cannulae with 1 cm diameter internal hole were used (the cannula was inserted approximately 30 cm into the interior of the wall and sealed with mortar). The injections were planted 50 cm × 50 cm in the traditional staggered pattern. The testing allowed us to estimate that internal cavities were around three percent of the gross volume of the masonry; therefore, for this masonry typology the same value was assumed for the equivalent thermal conductivity increase.

Table 5. Sample 1 (3.20 m × 1.5 m), from a masonry wall reinforced with injections in the post-earthquake reconstruction. The building is located in Via S. Marciano, L'Aquila, Italy.

Sample 1, Via San Marciano	Survey Results
total area covered	4.8 m^2
number of holes	19
total injected material	150 kg
average material injected per unit area	30 kg/m^2 (approximately 60 kg/m^3 wall)
number of holes not responsive	5
number of little responsive holes	7
number of very responsive holes	7

Table 6. Sample 2 (1.9 m × 1.6 m), from a masonry wall reinforced with injections in the post-earthquake reconstruction. The building is located in Via Vetusti, L'Aquila, Italy.

Sample 2, Via Vetusti	Survey Results
total area covered	3 m^2
number of holes	14
total injected material	87.5 kg
average material injected per unit area	28 kg/m^2 (approximately 58 kg/m^3 wall)
number of holes not responsive	4
number of little responsive holes	7
number of very responsive holes	3

5. Results

The analyses on the walls were carried out by calculating the variation of the equivalent conductivity as a result of three main interventions: grout injections, grout injections and plaster reinforced with welded wire mesh, and insertion of artificial cement diàtonoi with a thickness of 32 mm and 100 mm. The new equivalent conductivity obtained from the analyses is related to the several masonry types investigated and is shown in Table 7. The subscripts refers to the intervention IDs defined in Table 4. All values have been obtained without considering the finishing.

Table 7. Values of λeq (W/mK) after different kind of interventions.

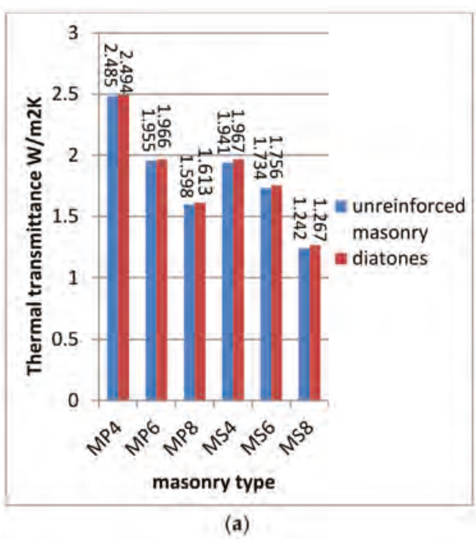
Masonry	λ_{eq}	λ_{GI1}	λ_{RP}	λ_{GI+RP}	λ_{D32}	λ_{D100}
MS4	2.14	2.20	2.145	2.204	2.16	2.149
MS6	2.02	2.08	2.025	2.085	2.04	2.025
MS8	1.94	1.99	1.96	2.002	1.97	1.95
MR4	1.71	1.91	1.724	1.914	1.75	1.75
MR6	1.75	1.96	1.764	1.974	1.79	1.79
MR8	1.331	1.49	1.34	1.502	1.37	1.38

The first case (GI1) is related to a retrofit intervention with grout injections: the new conductivity value was calculated according to the results provided by the experimental tests and in particular for the rubble masonry, reference was made to the non-destructive sonic tests (12% of the masonry volume is empty before the intervention and filled with grout after the intervention). For the irregular stone masonry, reference was made to the grout injection testing (three percent of the masonry volume is filled of air before the intervention and filled with grout after the intervention). The second case (RP) regards the strengthening of masonry with reinforced plaster. The third type of consolidation investigated (GI + RP) concerns combined interventions of grout injections and reinforced plaster: in this case the value of the post-intervention conductivity is higher than the two previous cases, because of both the injection and the steel roads inserted into the masonry. The latest investigated configurations are related to diàtonos interventions (D32 and D100): because of the lower invasiveness of the intervention the conductivity increase is small. For the cases D32 and D100, four diàtonoi per unit area were considered and, in the analyses of the thermal properties of the reinforced surface, the U-value was computed in parallel. Each diàtonos was armed with a ϕ16 bar. The conductivity of the reinforced masonry through RP was obtained considering the presence of five ϕ8 parallel bars per unit area of wall. The results of the analyses carried out in order to obtain the new masonry U-values corresponding to GI1, RP and GI + RP interventions and related to the whole section of wall, are shown in the table below.

Despite the seismic intervention analyzed in Table 8, diàtonos interventions do not modify the U-value significantly (see Figure 4); for this reason, in the next steps of the analyses carried out, no energy efficiency interventions were applied.

Once the equivalent conductivity of the structural part of the masonry was calculated (Table 7), the possibility of producing variations in the U-value relating to the whole section of wall (finishing included) was investigated (see Table 9).

In the first column of Table 9, the masonry type is reported; in the second column, the structural intervention applied to the wall combined with thermal plaster; the third column gives the new U-values; and in the fourth column another energy retrofitting intervention (EIFS) has been associated to the same structural intervention. The fifth column shows the thermal transmittance relative to the combined solution (seismic and energy retrofitting interventions) which has been calculated taking into account three feasible thicknesses of EIFS solution.



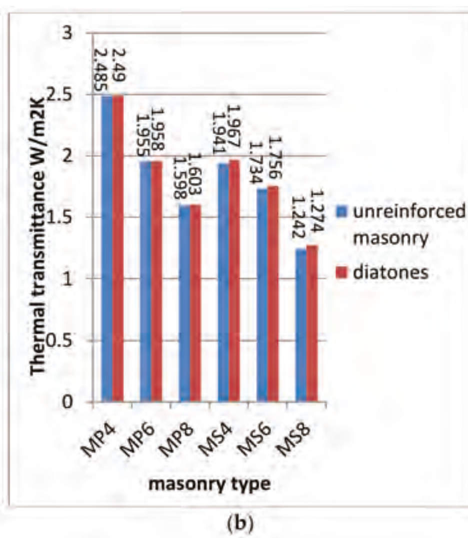


Figure 4. Effects of diàtonos interventions on U-value: (**a**) Diameter = 32 mm; (**b**) Diameter = 100 mm.

Table 8. Effects on U-value of the structural interventions GI1, RP and GI + RP.

ID	U-Value (W/m^2K) Pre-Intervention	Intervention	U-Value (W/m^2K) after Intervention
MS4	2.485	GI1	2.545
MS6	1.955	GI1	2.006
MS8	1.598	GI1	1.636
MR4	1.941	GI1	2.081
MR6	1.734	GI1	1.868
MR8	1.242	GI1	1.353
MS4	2.485	GI1 + RP	2.658
MS6	1.955	GI1 + RP	2.077
MS8	1.598	GI1 + RP	1.688
MR4	1.941	GI1 + RP	2.160
MR6	1.734	GI1 + RP	1.935
MR8	1.242	GI1 + RP	1.391
MS4	2.485	RP	2.627
MS6	1.955	RP	2.043
MS8	1.598	RP	1.665
MR4	1.941	RP	2.036
MR6	1.734	RP	1.808
MR8	1.242	RP	1.282

Table 9. Effects on the energy efficiency interventions on the U-value.

ID	Intervention	U-Value (W/m2K)	Intervention	U-Value (W/m2K)		
				3 cm [1]	6 cm [1]	10 cm [1]
MS4	GI1 + TP1	1.564	GI1 + EIFS	0.859	0.522	0.344
MS6	GI1 + TP1	1.342	GI1 + EIFS	0.788	0.495	0.332
MS8	GI1 + TP1	1.166	GI1 + EIFS	0.723	0.469	0.320
MR4	GI1 + TP1	1.375	GI1 + EIFS	0.799	0.500	0.344
MR6	GI1 + TP1	1.279	GI1 + EIFS	0.765	0.486	0.328
MR8	GI1 + TP1	1.014	GI1 + EIFS	0.662	0.442	0.308
MS4	GI1 + RP + TP1	0.882	GI1 + RP + EIFS	0.859	0.523	0.344
MS6	GI1 + RP + TP1	0.807	GI1 + RP + EIFS	0.788	0.495	0.332
MS8	GI1 + RP + TP1	0.741	GI1 + RP + EIFS	0.725	0.469	0.320
MR4	GI1 + RP + TP1	0.820	GI1 + RP + EIFS	0.800	0.500	0.334
MR6	GI1 + RP + TP1	0.785	GI1 + RP + EIFS	0.767	0.487	0.328
MR8	GI1 + RP + TP1	0.678	GI1 + RP + EIFS	0.664	0.443	0.308
MS4	RP + TP1	0.879	RP + EIFS	0.856	0.521	0.344
MS6	RP + TP1	0.802	RP + EIFS	0.783	0.493	0.331
MS8	RP + TP1	0.737	RP + EIFS	0.720	0.568	0.320
MR4	RP + TP1	0.801	RP + EIFS	0.782	0.493	0.331
MR6	RP + TP1	0.763	RP + EIFS	0.746	0.478	0.325
MR8	RP + TP1	0.651	RP + EIFS	0.638	0.432	0.302

[1] The values refer to the thickness of EIFS.

It is worth noticing that not all the types of finishes analyzed in Table 3 and not all the energy efficiency solutions adopted in Table 9 are always compatible with the protection needs of historically important buildings. In Section 6, the aspects concerning the choice of better solutions will be discussed taking into account that restoration issues are a real restriction in case of high value finishes. The impact of the different finishes on the inner side, outside or on both faces of the wall for each intervention analyzed, was evaluated and is shown in Figures 5–7.

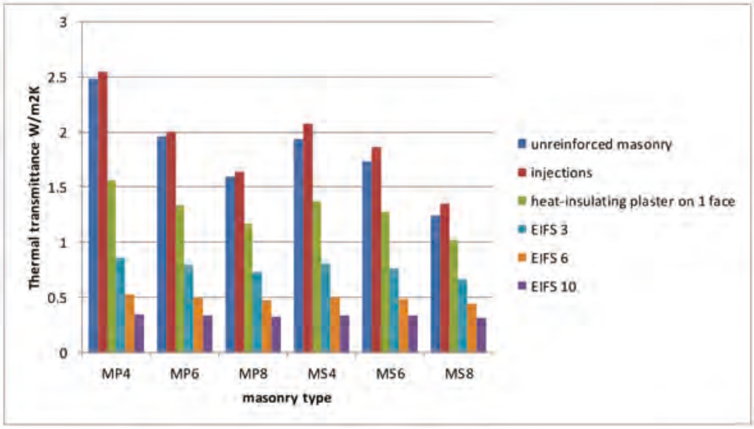


Figure 5. Comparison of the masonry thermal U-value before the interventions, after grout injections and after the application of finishing solutions for energy saving.

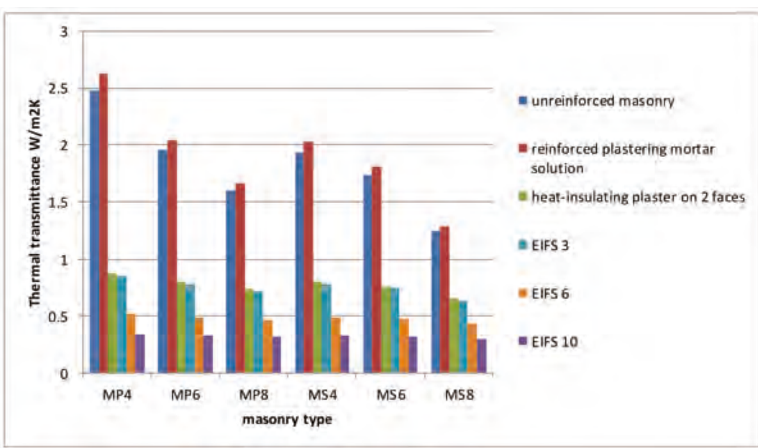


Figure 6. Comparison of the masonry thermal U-value before the interventions, after the steel mesh reinforced plastering mortar and after the application of finishing solutions for energy saving.

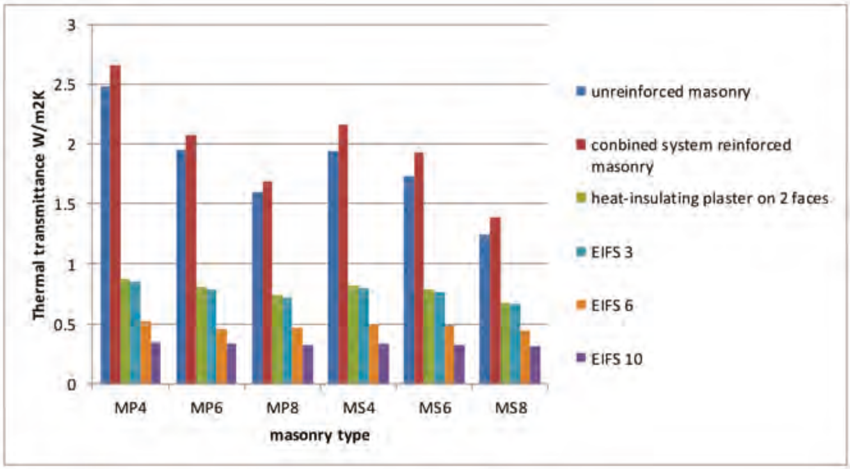


Figure 7. Comparison of the masonry thermal U-value before the interventions, after the combined reinforced system and after the application of finishing solutions for energy saving.

Finally, the intervention cost variations, caused by the use of more high performance materials in place of those used in current practice, were evaluated. These assessments were made using the regional list of Price Guidelines for Construction work in the Abruzzo Region "Prezzi Informativi Opere Edili della Regione Abruzzo". The prices indicated in this document are automatically applied in the execution of public works carried out in the Abruzzo region and, in particular, in the seismic retrofit interventions following the earthquake of 6 April 2009. The cost increment, due to the use of more high performance materials and to the different techniques adopted in the execution of finishes, was determined for each masonry analyzed, according to the following:

- Identification of all the techniques necessary for the execution of the structural improvement intervention; the cost of these techniques is constant and independent of the type of finishes adopted. The possibility of using structural materials with a higher energy performance in place of the traditional ones was not considered because it was not possible to find structural materials for which these performances were suitably certified in commerce. Lacking a reference performance standard, it is also difficult to justify the differences in cost of the materials themselves;
- Identification of the finishing techniques for the completion of the intervention, adopting finishing materials that do not possess particular energy performances;
- Application of high performance materials in place of standard materials. The possibility of adopting special plasters or EIFS of different thicknesses was considered. In Figures 8 and 9, the increment in cost relative to the use of more thermally performing materials is compared to the reduction of the U-value of the wall examined. The variation of the cost of the interventions only refers to the structural intervention.

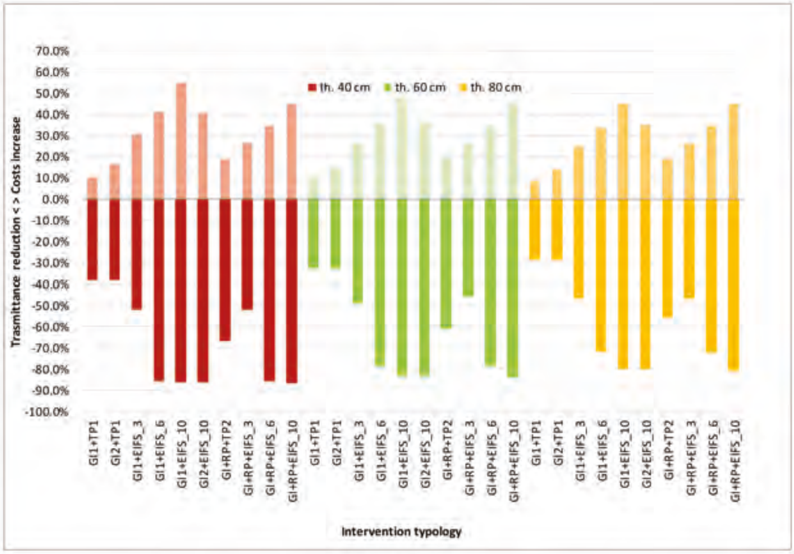


Figure 8. Transmittance reduction vs. costs increase for stone masonry.

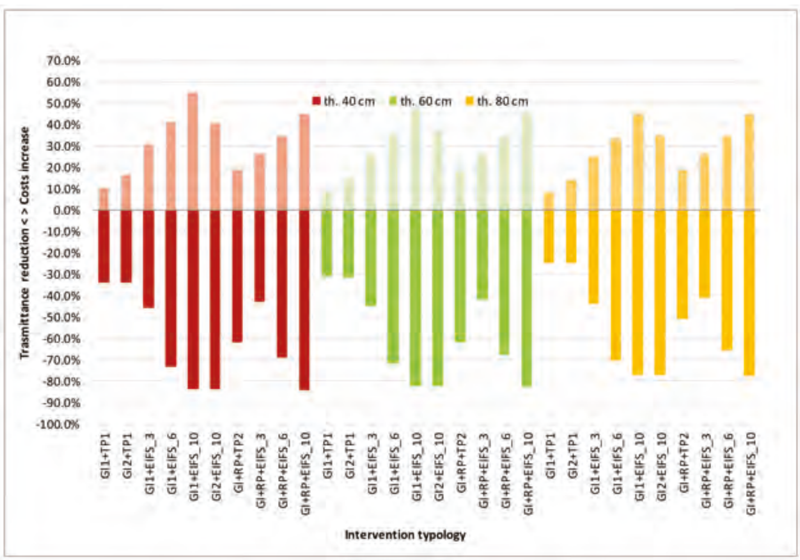


Figure 9. Transmittance reduction vs. costs increase for rubble masonry.

6. Discussion

In the previous analyses, the impact of structural interventions on masonry buildings was looked at from an energy efficiency perspective and in fact, the thermal characteristics of the structural materials analyzed are strictly connected to the building energy performance. This research demonstrates that these kinds of intervention can contribute to a worsening of the thermal performance of a wall, as Tables 8 and 9 highlight. The technological solutions suggested by this research are the adoption of thermal insulating plaster and exterior insulation finishing system (EIFS) to compensate this worsening: the use of thermal insulating plasters or EIFS on the reinforced masonry allows an improvement of the thermal characteristics of the opaque outer walls, considerably reducing the heat flow through the wall.

The analyses carried out also show that the use of diàtonoi in the masonry does not significantly worsen the thermal characteristics of the envelope: this means that energy saving can be achieved by optimizing heating and cooling systems rather than carrying out work specifically on the envelope. This evaluation is very useful in the case of historic buildings with valuable finishes that need to be conserved. On the contrary, the injection of grout and the reinforced plaster, applied separately or in a combined solution, have a significant impact on the thermal characteristics of the masonry, leading to an increase in terms of thermal transmittance, as shown in Table 8.

Table 9 shows the reduction of the U-value through the use of thermal insulating plaster ranges from 25% to 39% in the case of grout injection interventions, from 49% to 67% in the case of reinforced plaster and from 51% to 67% in the case of combined solutions (GI1 + RP). The use of EIFS solution can even reduce the U-value from 86% (10 cm thickness) to 50% (3 cm thickness). It is worth pointing out that the application of heat-insulating plaster delivers better results in masonry of less thickness, while the performances of EIFS only varies according to the thickness with which it is applied and almost independently of masonry type.

In the case of historically valuable buildings in which finishes often have to be preserved on one or on the two sides of the wall, the structural intervention has to be designed accordingly and the use of more extreme solutions such as EIFS are not always possible: the best architectural solution has to be arrived at by following a knowledge process that includes historical and non-destructive surveys to identify the valuable elements to be preserved [15]. The applicability and the compatibility of these more invasive interventions (GI1 + RP) must be verified case by case. It is evident that where an invasive structural intervention on the masonries that includes diffuse grout injections or even the removal of the historical plaster in favor of a mesh-reinforced plaster or FRP is adequate, other more advantageous solutions for the energy performance of the envelope are equally applicable.

The graphs in Figures 8 and 9 show the transmittance variations percentage and the relative costs increase, highlighting the variation of the combined intervention (structural and energy) with respect to the structural intervention alone. The examination of the diagrams shows the economical sustainability of combined interventions: for example thermal plaster application together with a structural injection and reinforced plaster, results in a reduction in the masonry U-value of 66%, compared to a cost increase of less than 20%. Similar results characterize other combined solutions such as the application of thermal insulating plaster and mortar injections (−32% U-value reductions, 10% costs increment) or a limited thickness of EIFS application (−45% U-value, +30% costs increment) in the case of rubble masonry.

In general, the execution of energy efficiency interventions, in conjunction with structural improvement interventions, results in economic savings linked to the reduction of demolitions and restoring of the finishing components. However, it should be noted that as the insulating capacity increases, the ratio between costs and benefits is reduced because the cost of raw materials gains an ever increasing weight in the overall burden of the intervention.

7. Conclusions

From the analyses carried out on the masonry typology considered, structural interventions inevitably result in an increment of the thermal conductivity of the wall. This increment is significant in those cases (that are often very frequent) which utilize grout injections or grout injections and reinforced plaster. However, it is negligible when using reinforcement techniques that include insertion of artificial diàtonoi for increasing the connection between multi-leaf masonry walls.

It was possible to constitute a catalogue of outer walls that have up-to-date thermal properties in function of the structural intervention and of the energy efficiency improvement associated with it.

From the analyses, it is evident how an increment in U-values, due to the intervention of structural improvement, is drastically reduced by the use of technological solutions that are energy saving, such as EIFS or thermal insulating plaster. The use of structural materials with specific thermal properties that are currently little used would also reduce intervention costs.

Often solutions for finishes capable of compensating the increase of conductivity caused by the structural intervention or structural material with certified thermal characteristic are not frequently adopted because availability on the market is still limited. However, the use of lime, grout and mortar with low thermal conductivity could greatly reduce the thermal U-value of walls undergoing interventions to improve seismic vulnerability.

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Seismic and Energy Retrofit of the Historic Urban Fabric of Enna (Italy)

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Abstract: This paper exemplifies several methods for retrofitting existing housing through four case studies, representative of the historical centre of Enna, a small town in Sicily, according to the requirements of static safety, typological adaptation and indoor comfort. These buildings were mostly built in the nineteenth century, up to three floors based on load-bearing masonry, iron joists and hollow tile floors and wooden roofs. A typological and construction analysis of these buildings was carried out to identify the stratigraphy of the different technical elements. Static and energy audits had been previously undertaken to understand the gap between the current state of the buildings and Italian standards and to develop appropriate interventions taking into account the site characteristics and the energy and seismic risk class pre- and post-retrofit intervention. The analyses and the retrofit interventions were performed in compliance with Italian standards and laws and strove to reach the minimum level. The study supports the planning of structural and energy retrofit interventions designed for historic load-bearing masonry buildings. Finally, the study simulates a strategy of action to provide subsidies and tax relief related to effective seismic and/or energy improvement that could be relevant for owners/builders as well as for local authorities.

Keywords: seismic retrofit; energy retrofit; historic urban fabric

1. Introduction

The static safety of existing buildings in Italy is increasingly important, especially due to the intensity of recent earthquakes (L'Aquila, 6.3 magnitude on the Richter scale, in 2009; Emilia Romagna, 6.0 in 2012; and Umbria, 6.6 in 2016), that caused the loss of human lives [1]. This is true also in other countries (Sumatra, 9.1, 2004; near the coast of Sendai, Japan, 9.1, 2011).

Compared to other earthquakes of higher magnitude, which occurred in areas where constructions were built according to anti-seismic criteria, the number of victims was considerably higher due to the vulnerability of the Italian buildings in historical centres impacted by the seism. For example, as a result of the 1968 Belice earthquake in Sicily, which had a magnitude of 6.1, 296 people were killed and 563 injured, compared to the last eight earthquakes that occurred in California from 2000 to 2014, with magnitudes between 5.0 and 7.2, where seven people were killed and less than 500 people were injured [1].

Of the 7.7 million residential buildings built before the first Italian anti-seismic law—Law No. 64 of 2 February 1974 [2]—almost 55% were built using the load-bearing masonry technique and mainly placed in historical centres [3].

Energy efficiency is also a relevant subject of current debate, considering the European regulations, e.g., Directive 2012/27/EU, and the proposed revision that was discussed and presented on 30 November 2016, proposing energy targets for 2030, including a revised Energy Performance of Buildings Directive (EPBD) [4].

On 19 December 2017, a provisional political agreement was subscribed to by negotiators from the Council of the European Union, the European Parliament, and the Commission, to update the EPBD and introducing new measures, particularly oriented to the renovation of existing buildings [5].

The preservation of buildings in historical centres from damage due to earthquakes, the need to make these buildings safe, especially for their historical value, became essential, to allow their repopulation. The current seismic, energy and functional inefficiency, in fact, has led to the abandonment of some of these historical centres.

Only in Sicily, there are sixteen "ghost" villages and in Italy overall the last census showed 190 abandoned villages [6]. Together with the abandonment of whole villages, the historic urban fabric, which is the core of the cultural identity of the Italian countryside, does not meet the current standards. The south of Italy shows the largest number of abandoned buildings. Table 1 provides some details. Milan has a similar number of abandoned residential buildings as the cities of the south of Italy [7].

Table 1. The most populous cities of Italy with data on residential buildings and abandoned buildings.

Municipality	Population	Residential Buildings	Abandoned Residential Buildings	Abandoned Buildings Percentage
Palermo	672,398	44,499	2068	4.65
Catania	315,769	26,755	1272	4.75
Reggio Calabria	182,323	26,368	2010	7.62
Naples	969,490	40,344	1107	2.74
Rome	2,874,529	107,332	2365	2.20
Milan	1,353,467	42,628	1791	4.20
Turin	885,651	35,814	1119	3.12

This has often led to degenerative instabilities and collapses and an increasingly widespread architectural and urban deterioration.

The intervention into these buildings supports the conservation of local territory, both in terms of reducing the risks of decay and collapse and abandonment [8,9]. It is also a tool to avoid the loss of cultural and technological knowledge of a place.

It is becoming increasingly important to incentivize and study methodologies and techniques for the regeneration of these buildings that are able to combine the achievement of current performance standards with the preservation of their peculiarities.

The two above-mentioned approaches are often planned and performed separately, considering the seismic aspect a priority, thus ignoring the importance of having energy-efficient spaces to live, or vice versa, considering the energy aspect first, and ignoring the importance of having safe spaces to live.

Besides this, the interest of communities is more frequently pointed towards monuments or public buildings due to their social value, such as town halls [10], schools [11], and churches [12], not considering the two approaches combined.

Even when the interest is focused on vernacular architecture, the analysis is carried out of building types and spatial organization, not considering seismic and energy improvement interventions [13].

Belleri and Marini strongly recommend integrated interventions, combining structural, architectural and energy improvement interventions, resulting in a more sustainable approach [14].

Integrated interventions, particularly energy-efficient interventions, reduce the environmental impact of buildings (in terms of energy consumption, operating costs and CO_2 emissions) and even it increases the life expectancy of the building.

Some recent studies of the "minor historical centres"—with historical buildings of little value, often located in small towns—of the Abruzzo area, in the centre of Italy—particularly of the village of Sant'Eusanio Forconese [15]—focused on both seismic and energy improvements, and on the importance of the conservation of the characteristics of the vernacular architecture.

This study, consistent with the work carried out by several research groups in recent years, especially in Italy, aims to further enrich technical knowledge and to demonstrate that it is possible to meet the essential requirements of structural safety and energy improvement, with the preservation of cultural values [11,16–18].

Particular attention was paid to the choice of interventions adopted in the various cases, choosing, where possible, non-invasive, reversible techniques compatible with traditional materials. The approach to intervention was that of "minimal intervention", according to the basic principles of the NIKER project (2010–2012) [19], co-funded by the European Commission, which sees in "minimum intervention" the only intervention method to guarantee compatibility and low intrusion.

The study, therefore, aims to develop integrated seismic and energy intervention strategies for the minor construction of historic centres, starting from the analyses performed on the selected case studies.

Thus, the selected target was the historic centre of Enna, and among this building stock, the regeneration of four representative buildings was studied.

Several intervention methodologies were identified, being potentially standardizable for similar building types, in other similar historical centres, to obtain those requirements according to "contemporary" use (static safety, typological adaptation, environmental comfort).

These intervention methodologies require a deep knowledge of the building in its current state from a typological, construction and energy point of view.

Through the application of recent Italian regulations on energy efficiency and seismic improvement, published respectively in 2015 and 2017, the seismic risk class and the energy class were identified before and after the intervention, which was necessary to formulate optimal strategies.

2. Methods and Case Studies

To define an intervention methodology for the historic urban fabric, it was necessary to carry out an analytical phase, which led to knowledge of the typological, construction, seismic and energy characteristics of the current state of the building. The next step was calculation, taking into account the different alternatives for seismic and energy improvement intervention, leading to the development of the various intervention strategies.

The methodology for the analytical phase was performed on two different levels. On the urban scale, it concerned the urban fabric, the shape and orientation of the blocks and their relationship with public spaces and contiguous buildings. At the architectural scale, the study provided a systematic collection of relevant data on the building techniques, materials and finish, state of conservation, use and spatial organisation [20]. Interest was focused on the four main technical elements of these buildings (walls, slab-on-ground floor, roofing and doors and windows).

2.1. Seismic Analysis

Since most of the buildings in the historic centres mainly consist of private residential buildings (not protected by law), in order to carry out a large-scale seismic improvement interventions, an Italian law was necessary to encourage private people to carry out these types of intervention.

In accordance with these objectives, the guidelines for the classification of the seismic risk of buildings (Decree of the Minister of Infrastructure and Transport no. 58, dated 28 February 2017, as modified by the Decree of the Minister of Infrastructure and Transport no. 65, dated 7 March 2017) were approved, combining the seismic improvement of buildings and economic incentives, called "sismabonus" [21].

These guidelines are important because they define for the first time the subdivision into classes of the seismic risk of buildings (from A+ to G), before and after any anti-seismic interventions; the seismic risk is defined as a measure to assess the expected damage following a possible seismic event. This depends on the interaction of related factors, namely the seismic hazard of the area, divided into high (zone 1 and zone 2), medium (zone 3) and low (zone 4), the vulnerability of buildings and the exposure of the various contexts.

The seismic risk class depends on two parameters: the average annual expected loss (PAM, the Italian acronym reported in the abovementioned law), which takes into account the economic loss associated with the damage and refers to the cost of reconstruction of the building; the IS-V safety index of the structure, defined as the ratio between the peak ground acceleration (PGA), which determines the achievement of the limit state for safeguarding life, and the value of the PGA that the law indicates for the site where the building is located.

The PGA represents the maximum acceleration value of the soil measured during an earthquake. It takes into account the influence of any amplification effects of the seismic motion, depending on the subsoil characteristics or topography.

The guidelines include two methods of seismic diagnosis, the "simplified" method, applicable only to load-bearing masonry constructions and local reinforcement surveys and interventions, taking into account only the PAM parameter, and the advanced method, the so-called "conventional" method.

The simplified method was applied to the selected case studies, introduced in §2.3, namely those built using load-bearing masonry.

Based on the type of masonry, which is divided into seven classes by the EMS-98 [22], the average vulnerability class is individuated by a table provided by the abovementioned Italian law.

Once the average vulnerability class is known and the seismic hazard area is identified, according to the ordinance of the Italian Prime Minister No. 3274 on 20 March 2003, the risk class is defined by the provided table and the PAM class is assigned consequently.

2.2. Energy Audit

The energy analysis was carried out through analytical calculations, as it is not possible to perform an in situ experimental analysis (e.g., thermal resistance measurement by means of guarded hot plate and heat flow meter methods), because the analysed buildings are abandoned, with partial collapses, and lacking doors and windows, and therefore there is no difference in temperature between the inside and outside.

Two types of energy analysis were conducted simultaneously. The first considered the entire building according to Italian standards, thus calculating the energy class of the buildings. The second considered the local type through the calculation of the thermal transmittance of the technical elements of the envelope according to UNI EN ISO 6946:2008.

While in order to be able to connect the thermal loss to the building types, the surface percentages of the various technical elements of the envelope were calculated with respect to the total surface.

The energy audit for the determination of the energy class of the buildings in the historic centre of Enna consisted of two parts: the analysis of energy performance in the current situation and the analysis of energy performance after the interventions.

All the characteristics (typological, geometrical and construction) found in the first phase were summarized in a mathematical model that shows the energy performance of the building.

The building energy simulation was performed by means of the open access software DOCET 3 ITC—ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development). This software conforms to the set of Italian technical standards UNI/TS 11300 series [23], which implements the European standards EN 15316 series and EN 15243:2007 [24], and is appropriate for evaluating the energy class.

Performing the energy analysis before and after the intervention, the software verifies how much each intervention influences the energy performance of the building. Only interventions on the elements of the envelope that could increase the energy performance were considered, neglecting any improvements in the performance of the plants, considering the absence of the latter in the selected case studies.

In the discussion part of this study, the choice of the energy performance improvement intervention is evaluated in relation to the interventions necessary to improve the seismic efficiency.

2.3. Four Case Studies in the Historic Centre of Enna

Enna is the highest Italian provincial capital at 931 m above sea level, a small town in the hinterland of Sicily, south of Italy, and due to this position it earned the nicknames *Urbs Inexpugnabilis* (unassailable town) by Romans, *belvedere* (panoramic viewpoint) and *ombelico* (navel) of Sicily.

The historic centre of Enna presents features common to many other Sicilian and Italian historical centres, such as a narrow street network, load bearing masonry buildings of not more than three levels, plaster and/or fair-faced stone masonry, Sicilian tiles as the roofing finish and green or brown wooden doors and windows.

Large parts of the historic centre still maintain their identity and the original typological and morphological characteristics of the building fabric, not altered by new construction.

This is also due to the orography of the land, with the historic centre of Enna on a mountain (so-called "Enna Alta") and a consequent expansion of the city downstream ("Enna Bassa"), as shown in Figure 1, dating back to 1950.

Figure 1. View of the historic centre of Enna.

However, this expansion has in part caused the abandonment of some buildings in the historic centre.

Many people preferred to move to new buildings better suited to current housing needs.

The lack of use of most building in the historic centre eventually caused partial collapses (Figure 2).

Figure 2. Examples of abandoned and partially collapsed buildings in the historical centre of Enna.

The last census of residential buildings in Enna showed 4791 buildings, of which 3376 were built with load-bearing masonry (937 were in a bad condition, partly abandoned, while 144 were in complete decay and abandonment) before 1970, thus without anti-seismic criteria [25].

From the historic urban fabric of Enna, four case studies were identified with different morphological, typological and construction characteristics. The buildings were chosen in the historical fabric of "Enna Alta".

The typological analysis followed a procedure that considered only the morphological characteristics detectable from the outside and from the cartography [26].

The survey started with research into archival documents on related similar studies and on the contribution made by the present and past urban plans. In particular, we followed the same method of subdivision into building types used by the Detailed and Recovery Plans of the Municipality of Enna from 1990.

The urban morphology of the historic centre of Enna is very complex. Its urban fabric is characterized by a great variety of building types, presenting very different configurations within the different urban meshes in which they are set.

The building types that can be found are linked to the urban hierarchy deriving from the road relationship and the morphology of the site, distinguishing buildings of "major" and "minor" importance.

According to this hierarchy, terraced buildings of considerable consistency were found, overlooking the main streets and monumental buildings (churches, convents and noble palaces) or the squares.

In addition, along the cross streets of the main axes and behind the squares, other significant building typologies were identified: "corner buildings", almost exclusively single-family, "at court" and some cases of "tower" houses.

Excluding the recent and large volume residential buildings (4–6 floors), present in a limited number, residential buildings are characterized by buildings with two or three levels above ground.

In order to gain knowledge of the typology examined, axonometric schemes were produced reproducing the fundamental aspects of the four building types: a corner building (Figure 3a), terraced building (Figure 3b), tower building (Figure 3c) and at court building (Figure 3d).

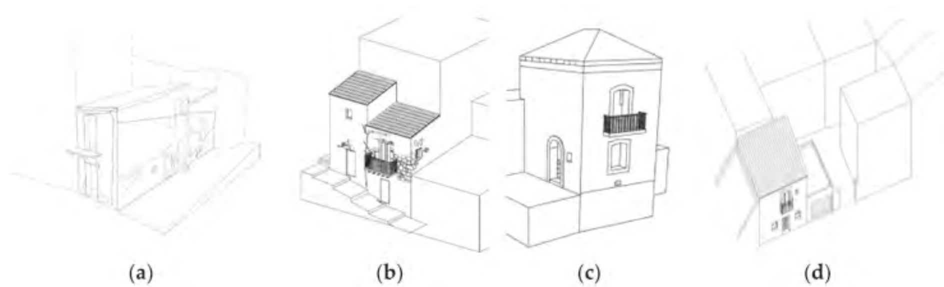

Figure 3. Axonometric scheme of the four building types.

From these schemes, such characteristics emerge as, for example, the ratio between horizontal and vertical development, the division into living cells and the contiguity between the buildings.

Plans and schematic sections were produced, showing how the typology is generally inserted within the urban fabric and whether, usually, this type is placed inside or on the front portion of a building block, whether it has a courtyard or not and whether it faces a road axis.

The selected case studies are representative of the following types (Figure 4):

1. Corner building: a building consisting of the union of two contiguous living cells, placed at the corner of a quarter, constituted by irregular plots. The plots at the rear saturated the space. (Case No. 1 located in Orfanotrofio St.).
2. Terraced building: the building is placed on the front portion of a building block (Case No. 2 located in Portosalvo St.).
3. Tower building: the building is defined by its height and it breaks the alignment of the block to which it belongs. It is characterized by one single room for each floor, all connected by stairs to each other (Case No. 3 located in Zacche St.).
4. At court building: the building is set on the edge of a "court" building block (Case No. 4 located in Colajanni St.).

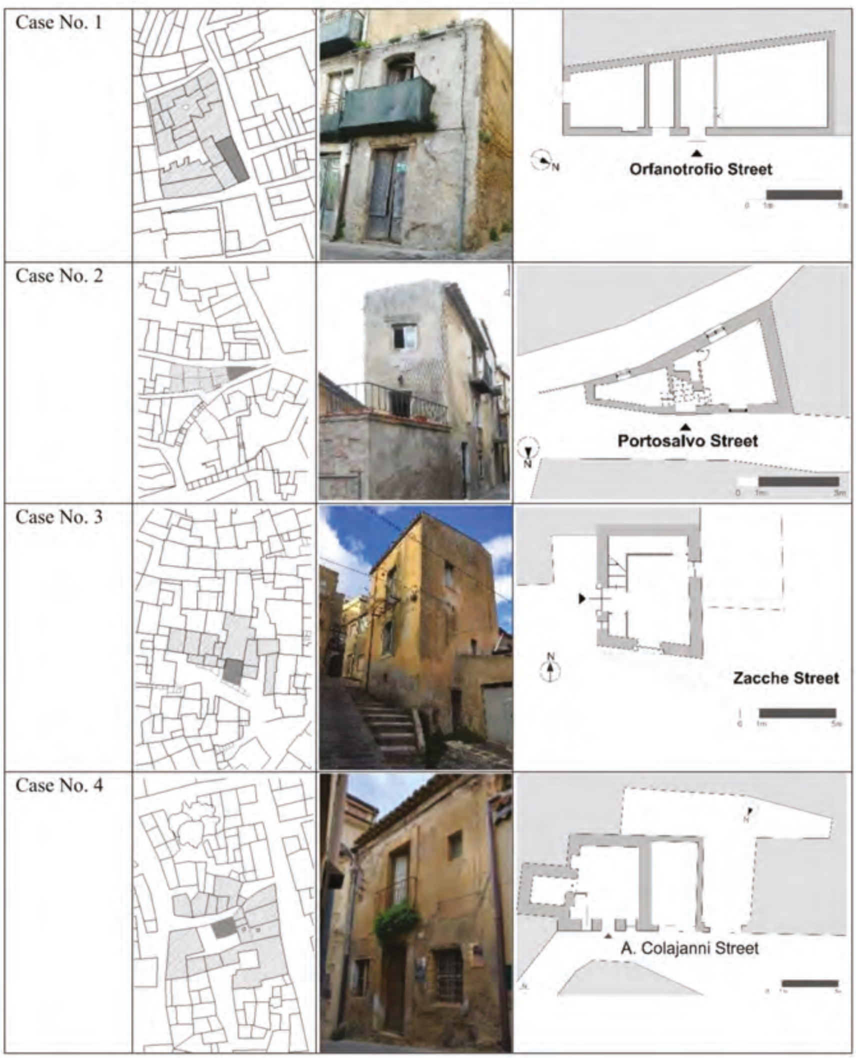

Figure 4. Four case studies in Enna (Sicily).

As is common for Italian minor centres, Enna is characterized by a spontaneous "architecture without architects" style [27] developed by local builders, according to local topography and climate.

These were mainly built between the end of the 19th century and the beginning of the 20th century [28], with load-bearing masonry (mainly irregular stones), girder and hollow brick floors or wooden beams with gypsum vaults floors and wooden roofing. All the buildings selected were not currently in use and in a state of abandonment [29].

In relation to the size and shape of the stone elements and the quality of the mortar and the stone, the walls present several textures with different strengths, lacking an effective connection between them and the horizontal elements. In addition, floors and roofing mainly made of iron and wooden elements have low in-plane stiffness and strength. These buildings have very limited resistance to seismic actions for both horizontal stresses in the masonry (shears stress) and out-of-plane (buckling stress), therefore requiring seismic retrofitting. Besides, the lack of structural integrity due to a poor connection between structural elements is one of the main causes of earthquake damage in vernacular buildings, where the "box-behaviour" is not guaranteed [13].

The Case No. 1 building is in a state of abandonment and presents the partial collapse of the roof and floors. It consists of load-bearing irregular stone masonry, consisting of 34 cm for external walls and 20 cm for internal walls, finished outside with 2 cm cement-based plaster and inside with 1.5 cm gypsum plaster, wooden floors with gypsum vaults, according to traditional construction techniques. It has non-thrusting roofs with wooden beams arranged parallel to the eave line, completed with planks and curved tile roofing as shown in Figure 5a.

The Case No. 2 building is in a good state of conservation and has undergone some energy improvement interventions in recent years. It is also made of irregular stone load-bearing masonry with an average thickness of 70 cm, with an insulating inner layer made of 4 cm extruded polystyrene panels, an internal finish of 1.5 cm gypsum plaster and an external finish of 2 cm hydraulic lime plaster. The first floor was rebuilt in the 70s and is a hollow brick floor. The internal space is divided into three levels, one of which is the basement, and the two original floors consist of wooden beam floors to support the bedding mortar and the flooring; the intrados are plain with a cane mesh ceiling finished with plaster mortar. A similar construction technique with wooden beams and an upper and lower layer of 1.5 cm cane mesh was found in the roof, finished with Sicilian curved roof tiles, as shown in Figure 5b.

The Case No. 3 building is abandoned and shows collapse of the inter-floor slab. The load-bearing structure is made of irregular stonewalls, 60 cm thick, finished externally with hydraulic lime mortar and internally with gypsum plaster. The inter-floor slab is made of iron beams and bricks, the roof of wooden beams, joists and Sicilian curved tiles as shown in Figure 5c.

The Case No. 4 building is in good condition. It shows a load-bearing structure of irregular stone, 85 cm thick, an inter-floor slab with iron beams and brick tiles and a wooden roof, finished with Sicilian curved tiles and wooden beams covered by 1.5 cm of plasterboard as shown in Figure 5d.

All the case studies show similar characteristics: the slope of the roofing is between 35% and 40%, the height of each floor is between 375 cm and 420 cm, and the shape of the interior rooms is polygonal.

In order to develop adequate seismic and energy improvement interventions, static and energy checks were performed accounting for the characteristics of the site—geographical coordinates lat. 37.34, long. 14.16, seismic zone 2 and climate zone E, degree-day 2.248—identifying the seismic risk class and the energy class.

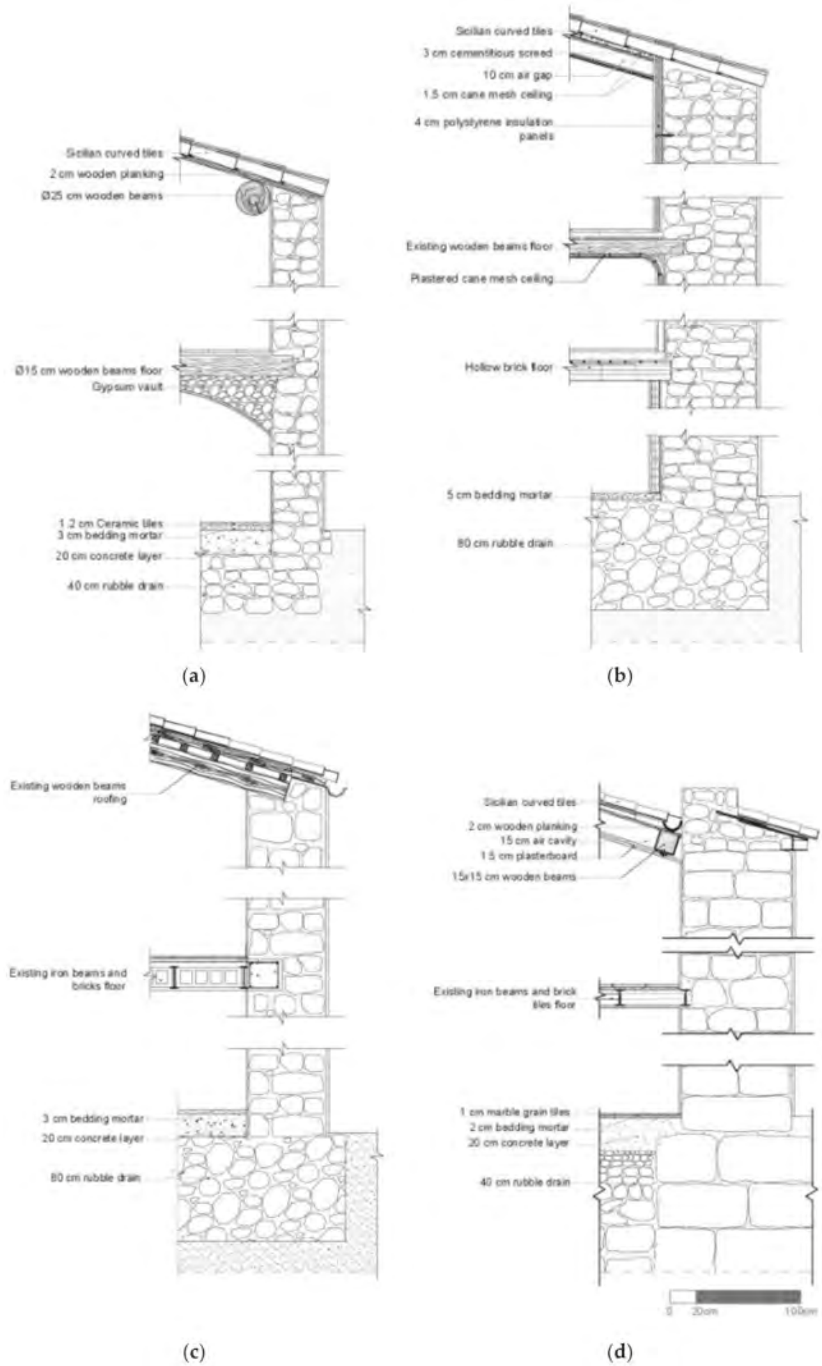

Figure 5. Structural cross section of the case studies.

3. Results

3.1. Seismic Analysis

For the case studies analysed, the simplified method was applied for the calculation of the seismic risk class, suitable for masonry buildings, considering the PAM parameter.

For each case study, by applying the guidelines the vulnerability class of the structure was identified based on the European Macro-Seismic Scale (EMS), which includes six classes of vulnerability from V1 to V6, based on the type of masonry, as reported in Figure 6. In all the four case studies, based on "irregular stone masonry", the most probable class of vulnerability (mean class) is V5. However, in cases No. 1 and No. 3, there is a deviation from the mean class with an increase in vulnerability to V6, due to the conditions of high degradation and collapse (collapse of the floors and part of the roof).

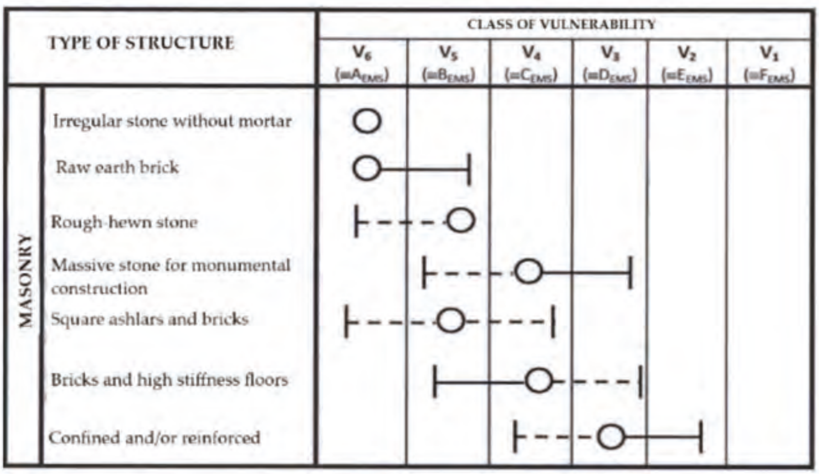

Figure 6. Class of vulnerability of the structure [21].

By relating the vulnerability class and the danger of Enna's location (seismic zone 2), the seismic risk class was defined among the eight classes provided by the guidelines. According to the table of guidelines shown in Figure 7, the buildings of case No. 1 and No. 3 can be classified within the F risk class, while the buildings of cases No. 2 and No. 4 can be classified within risk class E.

Risk Class	PAM	Zone 1	Zone 2	Zone 3	Zone 4
A+*	PAM ≤ 0,50%				$V_1 \div V_2$
A*	0,50%<PAM≤1,0%			$V_1 \div V_2$	$V_3 \div V_4$
B*	1,0%<PAM≤1,5%	V_1	$V_1 \div V_2$	V_3	V_5
C*	1,5%<PAM≤2,5%	V_2	V_3	V_4	V_6
D*	2,5%<PAM≤3,5%	V_3	V_4	$V_5 \div V_6$	
E*	3,5%<PAM≤4,5%	V_4	V_5		
F*	4,5%<PAM≤7,5%	V_5	V_6		
G*	7,5%≤PAM	V_6			

Figure 7. Seismic risk class from the Italian guidelines [21].

From these examples, it is clear that for existing buildings with load-bearing masonry it is not possible to obtain a seismic risk class higher than E or D for areas with high seismic risk, not adding into the calculation the geometric and construction characteristics of the building.

3.2. Energy Analysis

The energy analysis performed before and after the various recovery interventions allowed us to develop optimal energy intervention strategies. From the global thermal analysis, considering the various buildings without winter and summer air conditioning systems and accounting only for the energy required for lighting and domestic hot water, it was found that all the buildings studied were in class G.

Since the buildings in the case studies are single family residences, the energy improvement interventions affect the entire building envelope and therefore a percentage higher than 50% of the gross surface of the entire building.

These interventions fall in the typology defined by the D.M. of 26 June 2015, important first level renovations [30], and therefore the energy performance requirements to be verified concern the entire building.

The verification of the thermo-physical characteristics of the various elements of the building envelope, on the other hand, was useful to identifying the elements where the heat loss was higher, based on the thermal conductivity of every layer, calculated according to UNI 10,351:2015 [31], UNI EN ISO 10,456:2008 [32] and UNI EN ISO 13,370:2008 [33] (Tables 2–5), and thus guiding the energy regeneration strategies.

Table 2. The layers of the envelope's elements and their relative thermal resistance for Case No.1.

Type of Structure	Original Layers	Thickness [m]	λ [W/mK]	R [m^{2}K/W]	U [W/ m^{2}K]
Façade wall	Internal hydraulic lime and gypsum plaster	0.015	0.70	0.021	
	Solid brick	0.340	1.30	0.226	
	External cement-based plaster	0.020	0.90	0.022	
				0.440 *	2.271
Roofing	Fir plank	0.020	0.12	0.167	
	Sicilian curved tiles	0.010	1.00	0.010 0.317 **	3.158
Slab-on-ground floor	Ceramic floor tiles	0.012	1.00	0.012	
	Bedding cementitious mortar	0.030	1.30	0.023	
	Concrete layer	0.200	1.90	0.100	
	Rubble drain	0.400	1.80	0.220	
				0.355 ***	0.876

* indicates the values of thermal resistance, R, for walls, considering the addition of the superficial internal thermal resistance equal to 0.13 m^{2}K/W and the superficial external thermal resistance equal to 0.04 m^{2}K/W; ** indicates the values of R, for roofing, considering the addition of the superficial internal thermal resistance equal to 0.1 m^{2}K/W and the superficial external thermal resistance equal to 0.04 m^{2}K/W; *** indicates the values of R_f, the thermal resistance of the slab-on-ground floor.

Thermal transmittance in the case of the slab-on-ground floor was calculated in accordance with UNI EN ISO 13370:2008:

$$U = \frac{2\lambda}{\pi B' + dt} ln\left(\frac{\pi B'}{dt} + 1\right)$$

$B' = \frac{2A}{P}$, characteristic dimensions of the floor, being A its surface and P its perimeter;

$dt = w + \lambda\left(R_{si} + R_f + R_{se}\right)$, being w the total thickness of walls;

λ = 2 W/m^{2}K, the thermal conductivity of ground (sand or gravel);

R_{si} = 0.17 m^{2}K/W, the internal superficial thermal resistance for descending flux;

R_f, = the thermal resistance of the floor;

$R_{se} = 0.04$ m^{2}K/W, the external superficial thermal resistance.

In order to be able to connect the thermal loss to the building types, the surface percentages of the various technical elements of the envelope were calculated with respect to the total surface, as in Figure 8a.

Table 3. The layers of the envelope's elements and their relative thermal resistance for Case No.2.

Type of Structure	Original Layers	Thickness [m]	λ [W/mK]	R [m^2K/W]	U [W/ m^2K]
Façade wall	Internal hydraulic lime and gypsum plaster	0.015	0.70	0.021	
	Extruded polystyrene panels	0.040	0.04	1.000	
	Calcarenite irregular stone masonry [34,35]	0.700	1.50	0.467	
	External NHL plaster	0.020	0.90	0.022 1.680 *	0.595
Roofing	Internal hydraulic lime and gypsum plaster	0.010	0.70	0.014	
	Cane mesh ceiling Cavity Cane mesh ceiling Cementitious screed Sicilian curved tiles	0.015 0.100 0.015 0.030 0.010	0.06 0.25 0.06 1.30 1.00	0.273 0.400 0.273 0.023 0.010 1.132 **	0.883
Slab-on-ground floor	Bedding cementitious mortar	0.050	1.30	0.038	
	Rubble drain	0.800	1.80	0.444 0.482 ***	0.638

Table 4. The layers of the envelope's elements and their relative thermal resistance for Case No.3.

Type of Structure	Original Layers	Thickness [m]	λ [W/mK]	R [m^2K/W]	U [W/ m^2K]
Façade wall	Internal hydraulic lime and gypsum plaster	0.015	0.70	0.021	
	Calcarenite irregular stone masonry	0.600	1.50	0.400	
	External NHL plaster	0.020	0.90	0.022 0.614 *	1.630
Roofing	Fir plank	0.020	0.12	0.167	
	Sicilian curved tiles	0.010	1.00	0.010 0.317 **	3.158
Slab-on-ground floor	Bedding cementitious mortar	0.030	1.30	0.023	
	Concrete layer Rubble drain	0.200 0.800	2.00 1.80	0.100 0.444 0.567 ***	0.589

Table 5. The layers of the envelope's elements and their relative thermal resistance for Case No.4.

Type of structure	Original Layers	Thickness [m]	λ [W/mK]	R [m^2K/W]	U [W/ m^2K]
Façade wall	Internal hydraulic lime and gypsum plaster	0.015	0.70	0.021	
	Calcarenite irregular stone masonry	0.850	1.50	0.567	
	External NHL plaster	0.020	0.90	0.022 0.780 *	1.282
Roofing	Plasterboard false ceiling	0.015	0.21	0.071	
	Cavity Fir plank Sicilian curved tiles	0.015 0.020 0.010	0.25 0.12 1.00	0.600 0.167 0.010 0.988 **	1.012
Slab-on-ground floor	Marble grain floor tiles	0.010	2.80	0.004	
	Bedding cementitious mortar Concrete layer Rubble drain	0.020 0.200 0.400	1.30 2.00 1.80	0.015 0.100 0.222 0.337 ***	0.762

The reduced percentage of door and window surfaces between 3% and 8%, typical of traditional buildings of historic centres, which should make it possible to consider them negligible for the calculation of thermal transmittance.

Calculations show that under more unfavourable conditions, the increase found—considering the thermal input of doors and windows—never exceeded 2.21%.

From the comparison of the thermal transmittances obtained for the various technical elements of the envelope with the performance requirements, according to the current regulations, the thermal transmittance values were found to be considerably higher than the threshold values, as shown in Figure 8b.

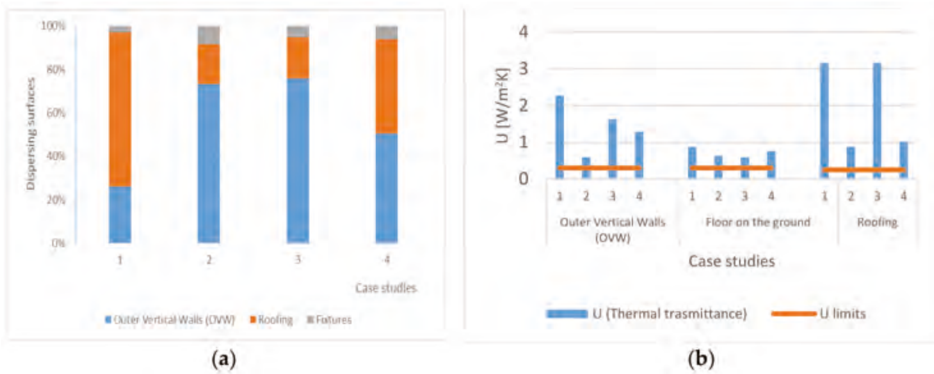

Figure 8. (**a**) Surface percentages of the various technical elements of the envelope on the total surface; (**b**) Thermal transmittance of the technical elements of the envelope of the considered case studies.

The elements with higher heat losses were the roofing (maximum value 3.22 W/m^{2}K for cases No. 1 and 3) exceeding from 4 to 15 times the threshold thermal transmittance, equal to 0.25 W/m^{2}K, and the walls (maximum value 2.25 W/m^{2}K for case No. 1), exceeding from four to seven times the threshold value of 0.3 W/m^{2}K. Only in case No. 2, for the walls (0.61 W/m^{2}K), which exceeded by only two times the threshold value, as this building had experienced energy improvement interventions with internal insulation.

Dealing with the walls of all of the case studies, a reduced thickness determined an increase in thermal transmittance.

The maximum value was U = 2.271 W/m^{2}K, for case No. 1 this was s = 0.375 m. The U percentage reduction for case No. 2 was equal to 73.80%, with an increase in the wall thickness of 106.67%. For case No. 3, the U percentage reduction with respect to case No. 1 was equal to 28.25%, with an increase in the wall thickness of 69.33%. For case No. 4, the U percentage reduction with respect to case No. 1 was equal to 43.57%, with an increase in the wall thickness of 136.00%.

For the floors on the ground, the thermal transmittance was calculated between 0.589 W/m^{2}K and 0.876 W/m^{2}K (according to UNI EN ISO 13370:2008).

3.3. Strategies for Seismic and Energy Improvement of Historical Buildings

Once the risk class of the case studies was defined, it was possible to evaluate any risk improvement and mitigation measures. However, using the simplified method it was possible to choose only local interventions, which do not produce substantial changes in the behaviour of the structure as a whole, addressing only the passage to the higher risk class.

Following the indications of the interventions provided in the guidelines, on the basis of similar solutions adopted in other European countries [36] and the findings regarding recent seismic events in central Italy, a list of possible actions for the case studies analysed was derived (Table 6). These seismic improvement interventions are directed to pursue an overall "box" behaviour, which eliminates or rather reduces local mechanisms outside the plane of the walls. Thus, these interventions aimed at the improvement of the relative mechanical resistance and the strengthening of mutual connections between them and the horizontal elements (floors and roofs).

The interventions on the walls consisted of the improvement of the mechanical strength in two ways: consolidation by means of mortar injections or glass fibre reinforced polymer (GRFP) net and hydraulic lime or thermally insulating mortar (with perlite or polystyrene), 3 cm thick [37].

To increase the wall-to-wall connection, tie-rods were considered on both sides of the wall (Figure 9a), while in the case of adjacent buildings, the solution chosen was the realization of an internal iron hooting (Figure 9b). The effectiveness of the tie-rods connecting the walls to each other was also demonstrated by the analysis of the damage undergone by a building in L'Aquila during the 2009 earthquake, since it was a seismic retrofit intervention in 2003, as demonstrated in the study by Lucibello [38].

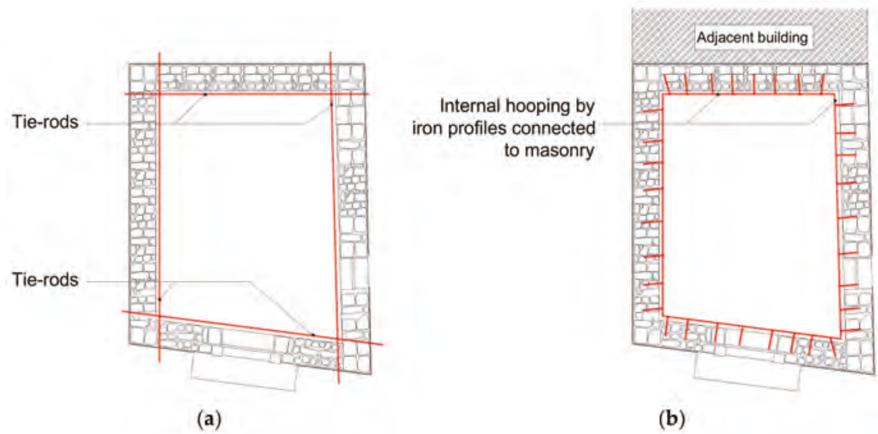

Figure 9. (**a**) Intervention in an isolated building by tie-rods and (**b**) on a terraced building by iron hooping.

Table 6. Possible actions provided for the selected case studies.

Site of Intervention	Retrofit Solution	Description
Walls	S_{W1}	Mortar injections
	S_{W2}	GRFP
	S_{W3}	Wall to wall connection improvement through tie-rods or internal hooping by means of iron profiles
Floors	S_{F1}	Stiffening and connection with the load-bearing walls
	S_{F2}	Reconstruction
Roofing	S_{R1}	Steel or reinforced brick bond-beam with steel tie-rods or carbon fibre
	S_{R2}	Stiffening of the existing roof with steel tie-rods in the intrados
	S_{R3}	Connection of the existing roofing with the masonry through tie-rods or internal hooting by means of iron profiles

Interventions on the floor depend on its static conditions. If in good status, the intervention consists of the stiffening of the existing floor and the connection with the load-bearing walls. Steel ties are the recommended intervention. The intervention with steel ties is less invasive, not requiring the demolition of the existing pavement, as reported by Branco and Guerreiro [39].

Chaining with steel profiles, moreover, has been implemented every time it has been necessary to reconstruct floors or roofing, with glued laminated timber or cross-laminated timber panels. These "C" or "L" steel profiles make it easier to set up new floors as well as creating a connection between vertical and horizontal elements. The connection between parallel walls and the floor/roof, using steel plates and wooden beams as connecting elements is one of the techniques of seismic reinforcement proposed by Diz and Costa for supporting masonry buildings in the Azores [40].

In the case of the maintenance of existing steel floors, stiffening interventions have been provided from the extrados by means of reinforced concrete slabs, connected to the masonry through injections with stainless steel bars (Figure 10a).

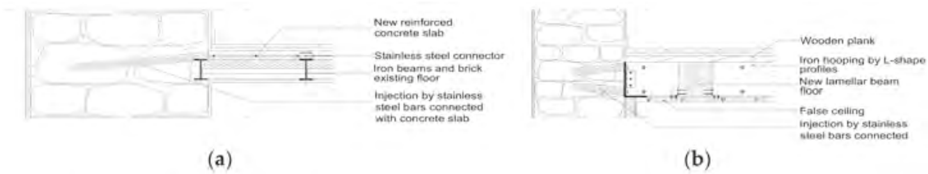

Figure 10. Connection interventions between walls and slabs.

All the selected interventions were compatible with the chemical–physical characteristics of natural stone materials and were in most cases reversible [41–43].

Otherwise, the reconstruction of the floor is provided for with lamellar wood beams or cross-laminated timber panels, both making a connection to the walls with steel profiles (Figure 10b).

The lamellar wood beams reproduce the original static scheme, which also acts as a chaining, facilitating its installation; the cross-laminated timber panels ensure greater stiffness of the plane.

Interventions into roofing consist of the stiffening of the existing roof with steel tie-rods in the intrados and its connection with the masonry through similar interventions to those proposed for the floors or the steel or reinforced brick bond-beam with steel tie-rods or carbon fibre in the case of roofing reconstruction.

The results of the energy analysis demonstrated the need for energy improvement. Considering the climatic conditions of the place, it was more important to provide interventions to reduce consumption related to winter heating. Excluding an intervention on the plant, only passive insulation measures (internal and/or external) of the envelope with traditional and innovative materials, with high-energy performance and small dimensions were considered.

In order to provide optimal energy performance intervention strategies [44], checks and calculations were carried out, through the combination of the following four interventions on the insulation of external walls, roofing and slab-on-ground floor, doors and windows.

From the various simulations performed for the four case studies, the best performance was found to occur either on the walls or the roofing or both, in relation to the percentage extension of one or the other with respect to the entire surface.

Dealing with energy interventions on walls, the choice between external and internal insulation was basically dictated by the presence or absence of the external plaster or any stone elements in the façade, as it was permitted to intervene from the outside if the building was finished by plaster.

It was preferred, if possible, to use the system with the external insulation, guaranteeing better living comfort both in summer and in winter.

The choice of the insulating materials, using the current technological solutions available, was carried out in compliance with the studies carried out by De Bernardis on a series of buildings in Abruzzo with characteristics similar to those of Enna [15].

From these studies we found that there were about 50% energy savings using vacuum insulation panels (VIP), better set outside than inside; about 44% energy savings using aerogel; about 42%

using EPS (extruded expanded polystyrene); and 30% with external TIM (heat reflective materials), considering the same thickness of the insulation material.

For cases No. 1, No. 2 and No. 3, dealing with plastered masonry buildings (λ = 1.3 W/mK), where the walls were available for seismic improvement, an external 12 cm cladding insulation (*L* = 0.04 W/mK) was provided (cases No. 1 and No. 3), thus enhancing the limits of the law, and 8 cm in addition to the 4 cm existing internal insulation (case No. 2). For case No. 4, due to the presence of fair-faced stone around the doors and windows, a different choice was made.

Internal insulation was provided with 80 mm spray polyurethane foam (λ = 0.035 W/mK) directly to the back of the existing masonry, the application of a 50 mm calcium silicate sheet (λ = 0.094 W/mK) and 20 mm NHL plaster.

This solution was able to reach the performance standards required by law (U = 0.279 W/m^{2}K) and did not cause condensation problems in winter and mould growth.

To verify this, a calculation by means of a Glaser diagram was performed and Figure 11 shows the results.

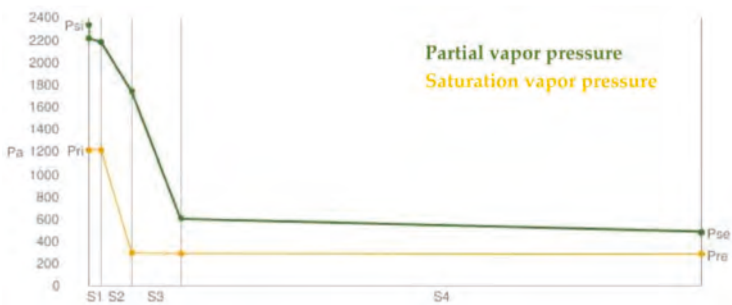

Figure 11. Glaser diagram of the proposed retrofit solution for Case No. 4.

This solution was also validated by Straube et al. in a report sponsored by the U.S. Department of Energy [45].

Strategy 1 requires intervention on only one of the four technical elements of the envelope identified (external walls, roofing, floor slab and doors and windows). Strategies 2–4 provide for the combination of two interventions on two technical elements of the envelope. Strategies 5 and 6 provide for the combination of three interventions on the technical elements of the envelope. Table 7 summarizes the six retrofit strategies and for each case study, indicated in subscript, the relative energy class is reported.

Table 7. Retrofit strategies of the selected case studies and relative energy class.

Strategy	Walls	Roofing	Slab-on-ground Floor	Doors and Windows
1	F_1 E_2 E_3 D_4	G_1 G_2 G_3 G_4	G_1 G_2 G_3 G_4	G_1 G_2 G_3 G_4
2 (Walls)	-	D_1 D_2 D_3 D_4	E_1 D_2 D_3 D_4	E_1 D_2 D_3 D_4
3 (Roofing)	D_1 D_2 D_3 D_4	-	G_1 G_2 G_3 G_4	G_1 G_2 G_3 G_4
4 (Slab-on-ground floor)	E_1 D_2 D_3 D_4	G_1 G_2 G_3 G_4	-	G_1 G_2 G_3 G_4
5 (Walls + roofing)	-	-	D_1 D_2 D_3 D_4	D_1 D_2 D_3 D_4
6 (Walls + slab-on-ground floor)	-	D_1 D_2 D_3 D_4	-	E_1 D_2 D_3 C_4

In case study No. 1, the best combinations always provide an intervention on the walls. We moved from energy class G, detected in the actual state, to energy class F, by means of only interventions on walls (26%), and to class D by intervening on the walls and roofing (71%), and to class E by intervening on the walls and floors on the ground or on the doors and windows. Combining three interventions between them, in no one case was the energy class higher than D.

In cases No. 2 and No. 3, on the other hand, by only intervening on the walls, it changed from class G in the actual state to class E, since the walls had a high percentage extension over the entire surface (75%). By intervening both on the walls and on any other closing element (roofing, slab-on-ground floor, doors and windows), it passed from class G to D. As regards the combination of several interventions, similar observations can be made to those of case No. 1.

In case No. 4, by only intervening on the walls, it passed from class G to D, and adding an intervention on another element of the envelope did not produce any class increase. Only using strategy 6 was class C obtained.

4. Discussion of the Results

The choice of interventions, accounting for the peculiarities on a case-by-case basis, was made by preferring interventions that involved the same technical element to produce both seismic and energy improvement. By means of the analyses in the previous paragraphs, the elements that showed the best performance were the walls and the roofing.

In fact, the sixth energy strategy, on the basis of the increase in energy class, led to the exclusion of the energy improvement of both the slab-on-ground floor and doors and windows.

For the walls, thin reinforced plaster interventions were planned for walls with limited thickness (30–40 cm), allowing an increase of the shear resistance in the plane and the flexural strength with limited thickness (about 3 cm) reducing the masses and weights on the structure.

For walls between 60 and 80 cm thick, mortar injections were planned to increase the mechanical resistance and the connection of the wall panels to each other by means of steel C-shaped profiles.

Table 8 shows the seismic and energy improvement interventions selected for the various case studies and the related class increases that can be obtained.

Table 8. Seismic and energy improvement interventions.

Case Studies	Seismic Improvement Interventions	Energy Improvement Intervention	Seismic Risk Class	Energy Class
No. 1	S_{W2} S_{R3}	External insulation, 12 cm thick, and L = 0.04 W/mk Roofing insulation, 15 cm thick, and L = 0.04 W/mk (Figure 12a)	$F \rightarrow E$	$G \rightarrow D$
No. 2	S_{W1} S_{R2}	External insulation, 8 cm thick, and L = 0.04 W/mk and integration of internal insulation, 4 cm thick Roofing insulation, 11 cm thick, and L = 0.04 W/mk (Figure 12b)	$E \rightarrow D$	$G \rightarrow D$
No. 3	S_{W1} S_{W3} S_{R2}	External insulation, 12 cm thick, and L = 0.04 W/mk Roofing insulation, 15 cm thick, and L = 0.04 W/mk	$f \rightarrow E$	$G \rightarrow D$
No. 4	S_{W1} S_{R1}	Internal insulation, 8 cm thick SPF, and L = 0.035 W/mk + 5 cm thick calcium silicate sheet, and L = 0.094 W/mk Roofing insulation from outside or intrados with insulation, 12 cm thick, and L = 0.04 W/mk	$E \rightarrow D$	$G \rightarrow D$

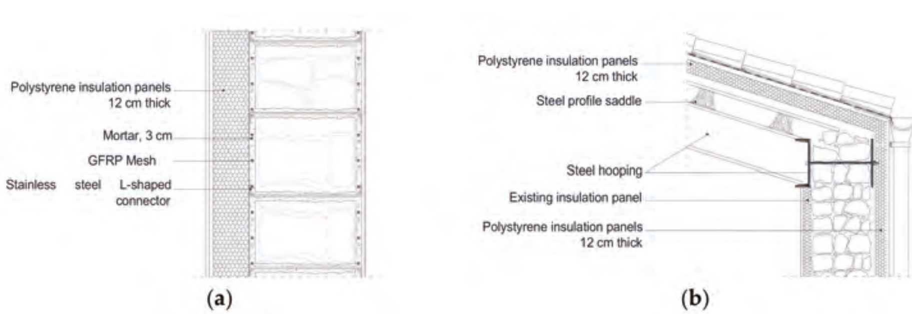

Figure 12. Detail of seismic and energy interventions on roofing and outer vertical walls (**a**) Case No. 1; (**b**) Case No. 2.

5. Conclusions and Future Research Lines

This research proposes a design tool to improve the energy efficiency and the seismic resistance of historic buildings, considering their own architectural value, thus using a "case-by-case" approach.

Through the analysis of the case studies, based on a deep knowledge of their peculiarities, we found that it is possible for existing buildings in the historic centres to develop intervention methodologies on the same technical elements—generally walls and roofing—that combine seismic and energy improvements. These strategies allow the optimization of interventions and above all the possibility to obtain relevant tax relief, combining the two incentives: "sismabonus" (for seismic improvement) and "ecobonus" (for energy improvement) [Italian law No. 205/2017]. While the "sismabonus" is proportionate to the seismic improvement obtained with the intervention, equal to 70% in the case of a single class improvement and 80% for an improvement of two classes, the "ecobonus" refers to the mere total cost of the intervention without accounting for the results of the energy improvement obtained. With the application of the simplified method of the Italian guidelines, we found that for existing masonry buildings, a seismic risk class higher than E or D could not be achieved for areas with high seismic risk, except through the application of the conventional method and the single seismic class improvement, corresponding to the 70% incentive. Besides this, the simplified method for buildings in historic centres is much cheaper than the more conventional and complex method, which only allows an additional 10% financial incentive. It would be desirable that the economic incentive for energy efficiency would be proportionate to the energy class obtained. In particular, the incentive for single-family buildings, as are most buildings in historic centres, would be equivalent to that provided for condominiums that can reach up to 70% for interventions on the envelope with an incidence of more than 25% of the building's surface, and to 75% for improving winter and summer energy performance. Moreover, the possibility for single-family buildings to obtain credit from banks would also make retraining interventions accessible to low-income people.

Further analysis of other case studies is needed both in the town of Enna and in other historic centres to support this methodology.

Furthermore, the authors consider it important to perform a quantitative seismic analysis, e.g., based on the interpretation of the data provided by the limit states design methods, to verify the real improvement of the seismic class, which is assumed to be superior to that obtained with the qualitative method.

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A Methodology for an Integrated Approach for Seismic and Energy Refurbishment of Historic Buildings in Mediterranean Area

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Abstract: Energy savings and seismic risk mitigation are the main issues regarding the refurbishment of traditional buildings. Referring to historic buildings, we have to take into account, as design requirements, the cultural sustainability, which means the respects of the cultural value of the built heritage. Therefore, for historic buildings is not acceptable to adopt the conventional design choices applied to newer buildings on energy efficiency and seismic risk mitigation. Generally, the design on the built heritage requires a careful cognitive phase for firstly to identify the performance deficits and subsequently to define which actions are compatible with the cultural value of each building, according to a "case by case" approach. In Italy, specific guidelines have been elaborated on cultural heritage but such guidelines are not integrated into a single methodological process. This paper, through the study of two historic buildings, aims to identify the relationship between the two specialisms, seismic and energy, within an integrated approach. As a result, this study proposes an innovation process characterized by the integration of these two protocols within the cognitive phase and, especially in the pre-diagnosis phase; this phase is identified in the standard diagnosis (Energy approach) and in the LV2 knowledge (Seismic empirical approach).

Keywords: historic massive envelope; cultural value; energy performances; damage mechanisms; pre-diagnostic process; seismic improvement; energy savings; Eastern Sicily

1. Introduction

Built heritage tells of the close relationship between man and environmental resources; this has defined the image of our historic cities in the material and formal aspects. According to ISTAT data (Italian National Institute of Statistics), the residential historic buildings (built before 1919) account for 19.2% of the Italian built heritage. Considering the masonry buildings, this percentage increases to 61.5%, if we think that this type of construction had also been used up to the 1950s.

Every building is an open system that interacts with its environment continuously. We refer to the climatic conditions, which, in the past, determined the shape of the urban fabric and the effects of earthquakes. Within the Mediterranean climate environment, we have directed our attention to Catania, whose seismicity degree is very high; in fact, the city was rebuilt after the violent earthquake of 1693. Its historic centre is therefore made up of massive buildings, with a loadbearing masonry structure.

Traditional buildings are characterized by vertical opaque closures with high thermal transmittance (U), which do not guarantee a good energy performance in the winter season [1].

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Energy and Seismic Recovering of Ancient Hamlets: the Case of Baia e Latina

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Abstract: This research proposes the development of a diagnostic tool to separately inspect the energetic and seismic behaviour of buildings in the small hamlet of Baia e Latina (district of Caserta) in order to evaluate and implement retrofitting interventions from seismic, energetic, and functional points of view. Methods, approaches, and tools relating to the minimisation of seismic vulnerability and energy consumption have been increasingly used and tested in order to ensure both sustainability and safety, with a connection that may improve the performances of both cultural and environmental heritage. The diagnosis method, stemming from the energy audit and the energy imprint evaluations of the buildings system (and the envelope above all), aims to redesign the whole construction or some of its parts within an energetic framework. With reference to the seismic behaviour of building aggregates, the basic methodology that has been conceived for isolated masonry buildings through a survey form has represented the starting tool for the application of an appropriate quick evaluation form considered for the aggregated structural units of historical centres. Finally, the methodology employed is aimed at obtaining an Energy Performance Certificate for the structural units of examined masonry aggregates without neglecting their seismic behaviour, which has been assessed in terms of vulnerability and damage.

Keywords: technological design; energy performance; seismic vulnerability assessment; risk analysis; masonry building aggregates

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1. Introduction

In the latest ICOMOS document: "Guardians of Heritage, Finders of Meaning" (February 2017), the value of choral architectural heritage, in its global conception of human, social, economic, and environmental ecosystems, is reaffirmed with wise attention to its resilience and safety features. The future development model of historic urban tissue can change its individual units by responding to functional needs; however, it must keep its form and identity intact. In fact, the urban landscape, including buildings and their relations with external open spaces (streets, avenues, squares, courtyards, gardens . . .), is a "system" that we have to preserve with its authenticity and integrity, in order to maintain the perception of its history and of social and economic urban changes through the times.

The Italian territory has been significantly damaged by many seismic events over the last 10 years; the seismic issue is finally becoming a priority in the country. Affected populations asked for the preservation of ancient hamlets, and not just for emergency solutions: timber houses offered and

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Mechanical Tests on Innovative BIPV Façade Components for Energy, Seismic, and Aesthetic Renovation of High-Rise Buildings

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Abstract: The paper shows the results of mechanical tests carried out on prototypes of a new Building Integrated Photovoltaic (BIPV) component developed by the author and SBskin Smart Building Skin s.r.l. This patented innovative component is able to merge structural function, insulation proprieties, and production of clean energy for retrofit actions and/or the construction of translucent façades in high-rise buildings located in different climatic contexts. Due to colored PV cells integrated into 3 Dimensional (3D) glass components and the dry-assembly system used for assembling them into precast and pre-stressed panels, an easy and creative customization of the product is allowed. Green energy production, safety, and energy efficiency of buildings can be assured in accordance with the environmental conditions and users' needs. The pre-stressing force used to improve the mechanical resistance of the panel toward horizontal forces due to winds and earthquakes guarantees the construction of secure translucent and active building envelopes. The paper summarizes the features of this innovative and patented BIPV product by focusing on its mechanical behavior. Laboratory tests are described and commented for underlining the benefits derived from the use of the dry-assembly system and of the supporting structure made of plastic for the construction of the panels. Bending and breaking strength tests have been carried out on two sq.m of panel prototypes, which have been dry-assembled through a supporting structure made of Polypropylene (PP) in order to compare the results with the theoretical calculations derived from the Finite Element (FE) simulations. Cyclic mechanical testing of the panel has been also carried out to verify its behavior under cyclic loading and understanding its ability to counteract the actions of the wind and earthquake.

Keywords: building envelope; innovative product; translucent panel; multifunctional component; energy efficiency; BIPV (Building Integrated Photovoltaic); dry-assembly system; mechanical resistance; high-rise building; façade

1. Introduction

SBskin. Smart Building Skin s.r.l. (www.sbskin.it) is an innovative start-up and academic spin off of the University of Palermo co-founded by the author (the CEO) with the aim to give a small and ambitious contribution to make our planet greener and our buildings sustainable and beautiful at the same time. By spreading the use of Renewable Energy Sources (RESs) and, in particular, of third generation PV technologies as well as by improving the building sector in Europe and abroad through the use of an innovative solution for the construction of translucent, active, and safe building envelopes even in high-rise buildings.

Buildings account for about 40% of the European Union's and the world's CO_2 emissions largely due to the operations of air conditioning, heating, and electricity systems [1]. The "2020 Climate and

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