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Synergistic approaches to structural and thermal retrofitting via external envelopes for existing buildings: a state-of-knowledge

Silvia Calò [a], Alessio Cascardi [b,*], Marielisa Di Leto [c], Lidia La Mendola Prof, PhD [c], Maria Antonietta Aiello Prof, PhD [a]

[a] Department of Innovation Engineering, University of Salento, Italy
[b] Department of Civil Engineering, University of Calabria, Italy
[c] Department of Engineering, University of Palermo, Italy

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A B S T R A C T

Retrofitting existing masonry and *Reinforced Concrete* (RC) buildings remains a critical challenge in advancing both structural resilience and energy efficiency. This paper provides a comprehensive review of state-of-the-art techniques that integrate structural and thermal upgrades through interventions applied to the building envelope, with the main aim of classifying them. These multifunctional solutions may enhance structural performance while simultaneously improving thermal efficiency, particularly in regions with significant seismic risk and a rigid climate. Key innovations include – among the others – composite panels, externally bonded *Fabric-Reinforced Cementitious Mortars* (FRCMs), ventilated façades or with embedded insulation, and hybrid systems that combine mechanical anchorage with thermal layers. Special attention is given to the synergistic interaction between materials, emphasizing both their potential and their limitations. By coupling passive energy strategies with structural reinforcement, these approaches not only improve building performance but also contribute to sustainability objectives and compliance with evolving regulatory frameworks.

1. Introduction

The renewal of the building stock makes a significant contribution to the challenging target of a carbon–neutral society. In this context, the present study aims to report and discuss innovative solutions for improving the energy efficiency of existing buildings while enhancing structural safety. Most Italian buildings require deep renovation, especially in the southern regions; the investigation of new materials and technologies for a synergic structural and energy retrofitting may significantly contribute to environmental, economic, and social benefits, such as reduction of energy consumption and greenhouse emissions, resilience to climate change and environmental disasters, mitigation of energy poverty, and improvement of living conditions. A wealth of innovations has been recently developed in many European projects concerning technical methods, business models, and financing schemes for eco-renovation practices.

On the other hand, structural interventions have been largely addressed since our dated building stock generally manifests high vulnerability to natural and anthropogenic actions, due to degradation and poor maintenance. However, one of the main barriers remains the inertia of the market in reacting to innovations due to the complexity of the interventions, often related to separate solutions in solving energy or structural weaknesses. In recent years, the interest in novel materials and techniques for combined retrofitting has steadily grown, aiming to effectively contribute to the goal of safe, resilient, and sustainable cities. In addition, the re-use of waste material should also be considered and challenged to support the circular economy mission. The environmental focus has been crucial for several decades. The *Kyoto Protocol*, adopted in December 1997, first established a CO_2-emission reduction for the period 2008–2012. A further global agreement was reached in Paris in December 2015, for the period after 2020. The aim was to strengthen the global response to the threat of climate change by setting a threshold for global warming below 2°C. Accordingly, the EU's commitment to achieve climate neutrality by 2050 was included in the European Green Deal. This will enhance well-being and improve the health of citizens and future generations by offering, among others, refurbished and

* Corresponding author.
E-mail addresses: silvia.calo@unisalento.it (S. Calò), alessio.cascardi@unical.it (A. Cascardi), marielisa.dileto@unipa.it (M. Di Leto), lidia.lamendola@unipa.it (L. La Mendola), antonietta.aiello@unisalento.it (M.A. Aiello).

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energy-efficient buildings. Specifically, Italy generates 11.4% of the EU's total greenhouse gas emissions (EPRS – European Parliamentary Research Service, 2019); a large part of this contribution is from buildings. In fact, there are almost twelve million residential buildings in Italy, and 41% is in the southern regions (islands included). Among them, 51% are sited in climatic zone C, 25% in zone D, and 16% in zone B.

The main energy-devoting lacks are linked to the poor quality of the building envelope (whose upgrading is the focus of many recent research programs) and dated heating/cooling systems. According to Fig. 1, or rather, to ISTAT data (Italian National Institute of Statistics), the masonry buildings are almost double with respect to (reinforced concrete) RC-buildings in the south of Italy (which represent the 41% of the national building heritage), while a not relevant percentage is attributed to other typologies. Moreover, 60% of the building stock was built before the first seismic regulation (1974), and 88% before the first important energy provisions (1991). Unfortunately, the south of Italy is characterized by a territory affected by a consistent seismic hazard that, associated with the state of decay, defines a vulnerable building stock, due to the inadequacy of existing structures with respect to the seismic or even static over-stresses. Consequently, structural and thermal requalification is generally required to guarantee safety and energy-saving. To optimize costs and benefits when addressing a deep renovation of a building, the energy efficiency objective should be integrated with policies and measures aimed at other issues, such as those related to structural safety, functionality, maintenance, and durability.

Thus, it is of fundamental importance to adopt a *holistic approach* in restructuring the stock of existing buildings, able to evaluate the technological solutions required for the concurrent improvement of the heritage from an architectural, energy, and structural point of view, instead of addressing independently any of the mentioned issues. For example, the *Fibers Reinforced Polymers* (FRPs) have been largely adopted in the last decades with the aim of improving the strength and ductility of both RC and masonry structures. In fact, the valuable advantages, related to the low weight/strength ratio, easy and fast installation, durability, and negligible addition of thickness and mass, have pushed the market of FRP significantly in the field of structural upgrading. More recently, *Inorganic Matrix Composites* (IMCs) are gaining increasing success, because of their advantages in terms of higher compatibility with the substrate (mostly masonry substrates), their ability not compromising/altering the original breathability of the substrate, higher resistance to elevated temperatures, and minor limitations on the environmental conditions of applicability. Furthermore, the thickness of the IMCs commonly ranges between 10 and 50 mm when applied at only one side of the elements constituting the building envelope; thus, an insulating-oriented role is thinkable even if challenging.

This topic is highly relevant today and of great interest to the scientific community, which is why many different systems have been proposed over the years. In this context, this study aims to review state-of-the-art systems for building envelopes that simultaneously address the structural and thermal deficiencies of existing buildings. The growing need to reduce greenhouse gas emissions and increase the resilience of the building stock makes the development of "dual retrofitting" approaches, which can combine energy improvement measures with structural adaptations, highly topical. Attention is paid to masonry and reinforced concrete buildings, which are widespread, especially in southern Italy, many of which were built before the introduction of modern seismic and energy regulations.

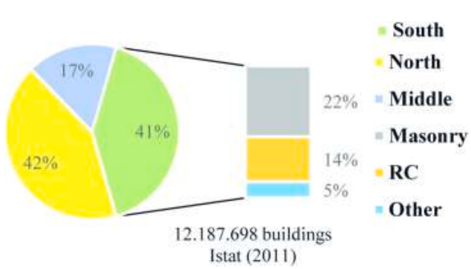

Fig. 1. Census of building typologies in Italy.

This review analyses the most innovative technological solutions developed in recent years, distinguishing them according to the type of approach (i.e., separate, combined, unified, and integrated) and evaluating their mechanical, thermal, and durability properties. Case studies and experimental investigations are also discussed to illustrate the effectiveness and critical issues of the currently available technologies. These examples highlight the actual performance of the systems, application challenges related to the complexity of the interventions, and the most effective design strategies for optimizing results in terms of safety, energy efficiency, and sustainability. The main objective of this study is to provide a critical overview of integrated systems, highlighting their potential, limitations, and prospects, with a preference to seismic risk mitigation, energy performance improvement, and support for the principles of the circular economy. This summary of the state of the art provides a reference point for designers, researchers, and policymakers, contributing to the definition of guidelines for integrated redevelopment projects that reconcile safety, energy efficiency, and environmental sustainability.

2. Background and motivation

In upgrading the existing building stock, particularly in seismic-prone regions, structural strengthening and thermal (energy) retrofitting are often treated as separate operations, typically resulting in two sequential interventions. Structural interventions usually focus solely on the seismic safety and resistance of buildings, whereas energy retrofitting targets the building envelope with the sole aim of improving the thermal performance. While these approaches are well-established, their independent application can lead to limited synergy between structural and energy-related issues. Typical characteristics of this approach include high cost, greater invasiveness of the interventions, and increased disruption to occupants, particularly during the implementation phase. From a structural perspective, the most widely used techniques in our context include concrete jacketing, FRP/FRCM wrapping, and steel bracing, each of which is applied to address the specific vulnerabilities of the structure under seismic actions. Classical jacketing (e.g., steel or reinforced concrete jackets) remains a benchmark intervention, in which a steel shell or an additional concrete layer is cast or grouted around existing columns or walls to increase the confinement, cross-sectional area, stiffness, and ductility [1–3]. In concrete jacketing, reinforced concrete is added around the existing section, enhancing the confinement, compression, bending, and shear resistance. Steel jacketing involves the application of external steel plates or profiles, providing increased tensile strength and confinement, along with improved stiffness and resistance to cyclic effects, such as those induced by seismic activities. This type of intervention is often employed to upgrade existing structures to meet new load requirements or updated code provisions, although it often adds significant mass, modifies dynamic behaviour, and can lead to high costs and labour-intensive implementation [3–5]. Recently, to address some of the issues associated with classical jacketing, composite material solutions based on externally bonded or near-surface-mounted FRP or *Fabric-Reinforced Cementitious Matrix* (FRCM, also known as *Textile Reinforced Mortar*, TRM) wrapping have gained traction [6,7]. This is because such reinforcement systems do not significantly increase the mass or stiffness of the structure, thereby preserving its dynamic property. These systems offer various combinations of matrices and reinforcement fabrics, making them adaptable to different substrates. FRP and FRCM reinforcements consist of wrapping or coating structural elements with high-performance composite materials to enhance their strength, ductility, and durability. FRP systems (carbon, glass, basalt, etc.) provide a high strength-to-weight ratio, minimal added mass, and minimal geometric intrusion, improving axial load capacity, confinement, and ductility, particularly for columns, as documented in experimental campaigns that show up to approximately a 150% increase in load-bearing capacity for fully wrapped columns, depending on the number of layers and fibre orientation. In comparison, FRCM/TRM uses a bidirectional open-grid textile embedded into an inorganic cementitious (or lime-based) mortar, improving compatibility with irregular or historic masonry surfaces, allowing vapor permeability, better fire resistance, easier workmanship, and often lower cost than FRPs [8–12]. Steel bracing involves the insertion of diagonal or frame-shaped steel elements inside or outside an existing structure to increase the load-bearing capacity and lateral resistance, particularly against seismic or wind forces. Steel elements, connected to beams and columns via bolts or welds, transfer shear and moment forces, enhancing overall stiffness and reducing deformations and vibrations. This intervention is particularly effective for reinforced concrete or masonry buildings, allowing localized or global seismic upgrading without significantly altering the building geometry [13–15]. Considering the potential drawbacks, the installation of steel bracing can introduce additional internal or external bulk, potentially interfering with functional or living spaces. Moreover, exposed steel may require periodic maintenance to prevent corrosion, and in some cases, the intervention can alter the original flexural behaviour of the structure, generating stress concentrations at the connection nodes. Finally, the cost of materials and installation can be higher than that of less invasive reinforcement systems, such as FRP or FRCM.

On the thermal side, envelope-oriented retrofit strategies such as *External Thermal Insulation Composite Systems* (ETICS), ventilated façades (rainscreen/double-skin claddings), or internal insulation have been widely used. ETICS involves fixing insulation boards to the exterior wall, followed by rendering or finishing to provide continuous insulation and reduce thermal bridges. This solution improves the internal thermal and hygrothermal comfort while simultaneously renewing the façade's aesthetic without invasive interior interventions. The main issues associated with ETICS are adhesion problems, rising dampness or infiltration, and architectural constraints. The critical design aspects include durability, impact resistance, and overall mechanical behaviour of the system [16–18]. Another commonly used system is the installation of ventilated façades, which introduces an air cavity between the structural wall and external cladding, exploits airflow for heat exchange, reduces conductive and convective heat losses, and enables moisture regulation. When intervention on the exterior envelope is not feasible, thermal retrofitting can be achieved with internal insulation directly applied to the building's perimeter walls. Internal insulation may improve energy performance, but at the cost of reducing usable internal volume, complicating interfaces with existing finishes, and risking interstitial condensation, especially in older or masonry buildings [19–22]. This approach aims to reduce heat loss through the envelope and enhance indoor comfort. Unlike external insulation systems or ventilated façades, this intervention acts from the interior without altering the building's external appearance, making it particularly suitable for historic or protected buildings. Commonly used materials include rigid or semi-rigid panels of polystyrene, polyurethane, mineral wool, or natural materials such as wood fibre or cork, often completed with finishing layers such as plasterboard or plaster. Internal insulation of perimeter walls improves energy efficiency and hygrothermal comfort, reducing the perception of cold walls, but presents some critical aspects, including reduced usable internal area, risk of interstitial condensation if not properly designed, and continued exposure of exterior walls to climatic variations, which may limit its effectiveness compared to external interventions. Therefore, careful design, with particular attention to moisture control and internal ventilation, is essential to ensure the durable performance and effective functioning of the system [23–25].

Despite the effectiveness of each intervention, when structural and thermal retrofits are executed separately (see Fig. 2), the drawbacks accumulate: high overall cost (two distinct interventions), extended construction times, significant disruption for occupants, possible incompatibility or conflict between structural reinforcement (e.g., jacketing or wrapping) and thermal layers (e.g., ETICS or insulation panels), and in many cases, suboptimal performance because each intervention does not consider the constraints or requirements imposed by the other (e.g., structural anchors conflicting with insulation continuity; increased stiffness/mass altering seismic behaviour; moisture or breathability issues due to incompatible coatings). This multiplicity of issues underlines the clear need for integrated multifunctional retrofit solutions, that is, systems engineered to simultaneously provide increased structural safety (seismic resistance, ductility, confinement) and improved thermal performance (insulation, energy efficiency, comfort) in a single intervention cycle. In this respect, recent studies have proposed combined systems, for example, a multilayer coating integrating a "structural mortar + thermal insulation + finishing layer" applied on façades, to meet both structural and energy code requirements simultaneously. Such integrated approaches promise reductions in cost, construction time, and occupant disruption, improved compatibility among layers, and a more sustainable, holistic upgrade path for existing buildings.

3. Typologies of synergistic envelope systems

Composite panel systems, generally developed as preassembled envelope modules, integrate a structural layer (e.g., *Cross-Laminated Timber* (CLT), *Oriented Strand Boards* (OSBs), or thin reinforced concrete) with high-performance insulation and an external finishing layer. Their conceptual strength lies in the simultaneous upgrade of lateral stiffness and thermal resistance, obtained with external-only installation that minimizes disruption for occupants. In [26], the use of CLT infill panels is proposed as a dual seismic-and-energy retrofit strategy for RC

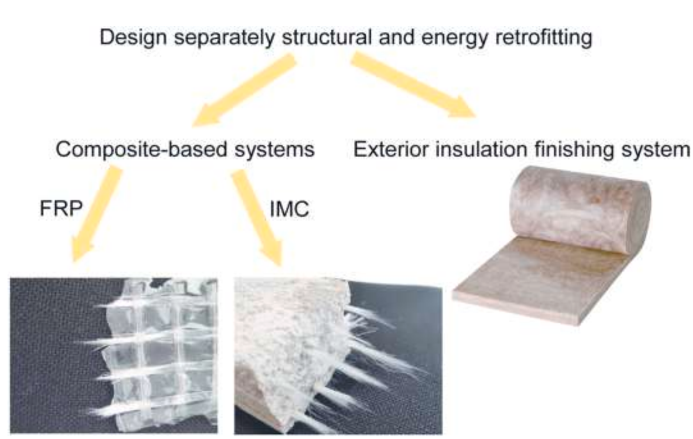

Fig. 2. Schematic illustration of the separate design in structural/energy retrofitting.

buildings, showing that the increased lateral stiffness provided by the engineered timber panels can effectively reduce inter-story drift, while the addition of external insulation (e.g., polyurethane boards or a ventilated cavity) enables a parallel improvement in energy performance. Diagonal-compression tests further demonstrated their high shear capacity ($\tau_{max} \approx 4.46$ MPa), considerably higher than typical masonry infills (~0.66 MPa) and even those strengthened with expanded steel plates (~3.54 MPa) [27], confirming their suitability as structurally efficient components for integrated retrofitting. In [28], the prefabricated CLT-based retrofit system was applied to a reinforced concrete residential building from the 1960s located in Catania, in the south of Italy, which serves as a case study to evaluate its effectiveness. From an energy perspective, the intervention consists of cladding the external envelope with CLT panels integrating bio-based insulating materials, combined with the replacement of the existing windows with high-performing ones, to enhance the thermal resistance of the façade and reduce thermal bridging effects. Dynamic energy simulations show a remarkable reduction in the wall transmittance U, from approximately 1.15 W/m^{2}K in the existing state to 0.27–0.29 W/m^{2}K after renovation, resulting in an overall improvement of the hygrothermal behaviour of the building envelope. These enhancements lead to a significant reduction in energy demand, with heating needs decreasing by about 65–70% and cooling needs by 7–22%, corresponding to an overall annual primary energy savings of up to 56% compared to the original configuration of the building. However, these results are limited to a single climatic context and rely on idealized boundary conditions (e.g., airtightness and perfect thermal bridge correction), meaning that further studies are required to validate long-term performance, economic feasibility, and scalability to different building typologies and climates.

Alternatively, hybrid systems combining FRPs with thermal insulation boards represent a conceptual strategy for integrated retrofitting, aimed at improving both the structural response of infill walls and the thermal performance of the building envelope. In fact, epoxy-bonded FRPs are traditionally appreciated for their high strength-to-weight ratio, corrosion resistance, and minimal increase in wall thickness, making them attractive in retrofits where architectural constraints are significant. However, their practical application is often limited by drawbacks such as high installation costs, sensitivity to elevated temperatures, incompatibility with wet substrates, and the need for specialized protective equipment due to the use of epoxy resins. Only a limited number of studies in the technical–scientific literature document the combined use of FRP systems and thermal insulation layers as a truly integrated solution for improving both seismic and energy performance. In this context, the study by [29] provides a significant contribution, as it develops a systematic assessment of different energy and structural retrofit strategies for an existing school building. The authors first analyse several energy-based retrofit scenarios, based on combinations of envelope insulation, Heating Ventilation and Air Conditioning (HVAC) system replacement, and lighting upgrades; they subsequently evaluate various seismic improvement options, including, among others, roof lightning, tie-rod systems, and localized strengthening by means of FRP. On the basis of these analyses, an integrated cost–benefit comparison is carried out with the aim of identifying the optimal configuration over the building life cycle. The results show that the most advantageous solution, both from an economic and a performance standpoint, consists of the combination of an external thermal insulation system with 14 cm mineral wool and structural strengthening with carbon FRP, applied in one or two layers on the slim walls at the openings, which are identified as the most vulnerable elements. It is important to note that this configuration does not correspond to an experimentally implemented intervention on the case-study building, but rather to the outcome of a comparative assessment based on performance and economic modelling. The fact that this combined solution emerges as the optimal option confirms the potential of integrated retrofit strategies, in which adequately coordinated energy and seismic interventions can generate synergies such that the overall investment becomes more efficient and sustainable than separate, non-integrated actions.

A reinforced ventilated façade is an external cladding system composed of an insulation layer and an outer finishing skin, installed with a ventilated air gap to enhance moisture control and summer thermal performance. When combined with an auxiliary structural frame, the system also provides local strengthening of the façade, preventing detachment or instability of existing cladding materials. In [30], this approach is applied to degraded marble façades of a multi-storey reinforced concrete school building, integrating rock-wool insulation with a tubular steel structure that supports a new ventilated cladding and mechanically secures the existing panels, ensuring adequate safety against out-of-plane failure of the envelope. The proposed solution achieves a local structural improvement, as the steel frame eliminates the risk of façade detachment under seismic or accidental actions, while being hinged to the RC structure so as not to significantly modify the global seismic behaviour of the building. From an energy perspective, the addition of a continuous insulated layer and ventilated cavity leads to a strong enhancement of thermal performance, reducing the wall U-value from 0.987 to 0.211 W/m^{2}K and cutting the heating energy demand by 57%, upgrading the building's energy class to a B after retrofit.

Retrofitting solutions based on the combination of TRM/FRCM and thermal insulation layers represent one of the most advanced and versatile approaches for the integrated upgrading of building envelopes, intending to simultaneously enhance structural, energy, and potentially fire performance within a single composite system. TRM was extensively investigated in the field of seismic and energy retrofitting [31–34].

The integration of TRM/FRCM with thermal insulation materials—such as EPS, XPS, polyurethane foam, aerogel panels, or mineral wool—results in a composite system capable of simultaneously improving the seismic response of buildings and the energy performance of the envelope. TRM may be applied directly over the insulation layer, underneath it, or in a sandwich configuration (TRM–insulation–TRM), and is compatible with advanced solutions such as aerogel-based insulators or capillary tube radiant systems embedded within the mortar [32]. This design versatility allows for application in both frame structures (reinforced concrete or steel) with masonry infills and load-bearing masonry buildings, thereby broadening the system's applicability.

From a structural standpoint, extensive experimental evidence confirms the effectiveness of the TRM–insulation approach. The authors in [31] demonstrated that, for one- or two-sided TRM jacketing, with the insulation placed either externally or between TRM and masonry, the relative positioning of the layers does not significantly affect the in-plane structural behaviour, provided adequate bond between layers is ensured. One-sided application leads only to a marginal reduction in performance while offering the important practical advantage of enabling external retrofitting with minimal disruption to occupants. The authors in [33] further showed that the integrated TRM–insulation system markedly enhances out-of-plane structural capacity, exceeding the performance of TRM-only solutions due to the increased lever arm contributed by the insulation layer. In some cases, debonding of the insulation was observed, indicating that the insulation-to-masonry interface governs the upper limit of force transfer to the textile reinforcement. At the building scale, numerical analyses conducted within the iRESIST+ project [34] confirmed that such systems reduce inter-storey drifts, mitigate both local and global damage mechanisms, and lead to significant reductions in expected annual losses. From an energy perspective, building energy modelling simulations have shown that the combined application of TRM and insulation can substantially reduce heating and cooling energy demand [35]. Energy savings vary depending on the envelope's initial characteristics and local climatic conditions, ranging from approximately 37% for relatively recent buildings located in mild climates to nearly 78% for older buildings in cold regions. The inorganic and vapour-permeable nature of TRM helps reduce interstitial condensation risks, enhancing durability. While

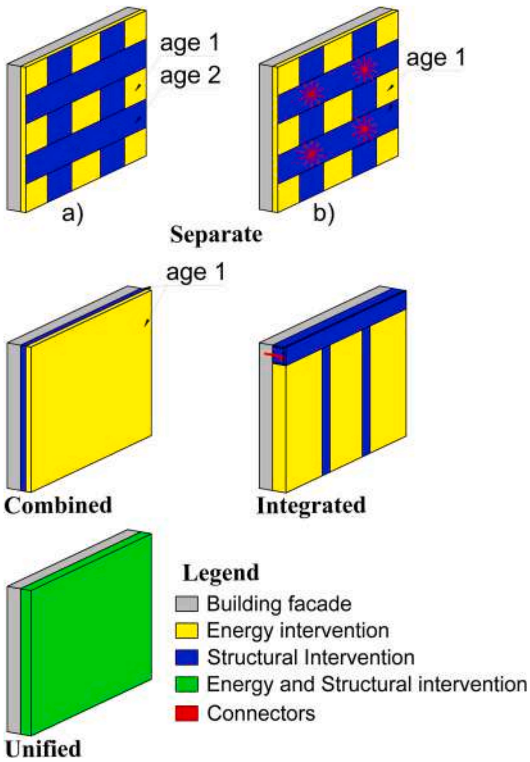

Fig. 3. Progression of façade retrofit solutions from independent layers to fully unified structural–energy systems.

external application is generally preferred due to minimal impact on indoor space and building occupancy, internal installation is technically feasible, albeit associated with limitations related to reduced usable space and more complex implementation. Overall, available evidence consistently identifies TRM–insulation systems as a multifunctional, lightweight, and high-performance solution capable of simultaneously improving seismic safety, energy efficiency, and fire behaviour of building envelopes. This makes them a promising technology for large-scale interventions in the existing building stock and is fully aligned with ongoing integrated renovation strategies.

4. Redefining terminology and categories for synergic structural and thermal retrofitting

The review of these retrofitting solutions reveals that, despite their technological differences, they can be interpreted as specific instances of broader design logic governing the relationship between structural strengthening and thermal upgrading. This observation motivates the transition from a technology-based classification to a conceptual framework of retrofit approaches, capable of capturing the underlying degrees of interaction between structural and energy layers. Building on this perspective, the current state of knowledge highlights a spectrum of strategies for improving the mechanical and thermal performance of building envelopes through the coordinated—or, in some cases, uncoordinated—use of composite structural layers and insulation materials. The Fig. 3, therefore, proposes a classification of possible configurations for structural and energy interventions on existing façades, illustrating how different systems embody distinct levels of integration between “energy retrofitting layers” (e.g., expanded polystyrene, EPS) and “structural strengthening systems” (e.g. FRPs), namely:

1. “*Separate approach*”. In this configuration, energy and structural interventions are conceived as functionally independent systems, implemented through two distinct modalities represented in Fig. 3 2 a) and b). The first modality, referred to as *Unfair Competition* (Fig. 3 a), consists of energy (yellow) and structural (blue) layers applied irregularly and often at different times (“age 1” and “age 2”), without coordination in their spatial distribution or functional interaction. Although this configuration may offer practical advantages—such as flexibility during phased retrofitting and the possibility to install each system independently—it generally results in poor architectural and functional integration, higher risks of material incompatibility (for example, due to differential thermal expansion or moisture trapping), and potentially reduced overall performance caused by thermal bridges and localized stress concentrations. The second modality (Fig. 3 b) still maintains the independence between the two systems but adopts a more orderly side-by-side arrangement. In this case, the energy and structural layers are placed adjacent to each other while remaining physically and functionally distinct; in some applications, connectors are introduced to prevent detachment or instability at their interface. This configuration offers clearer separation of functions, facilitating inspection, maintenance, and targeted design for thermal and structural performance. However, it requires accurate detailing to avoid moisture accumulation between layers, and the presence of connectors can increase execution complexity and costs while slightly reducing energy efficiency because of interface discontinuities.
2. *Combined approach*. Two or more energy and structural layers are superimposed directly on one another to form a compact but distinct assembly; the structural strengthening system (in blue) supports the energy layer (in yellow). This is a compact configuration that reduces overall thickness; it can also result in improved load transfer between layers and reduced thermal bridging. On the other hand, the difficult maintenance or replacement of individual layers and the potential incompatibility of material behaviour under environmental loads – e.g., FRP resins and insulation adhesives – should be accounted for in the list of disadvantages. Besides that, a more complex installation requires careful sequencing.
3. *Integrated approach*. The energy and structural systems are interconnected through “connectors” or by design so that they act synergistically. Structural and thermal functions coexist and are partially interdependent. It can be appreciated that the enhanced mechanical and thermal performance through functional synergy, improved façade stiffness and integrity, and reduced overall material usage and façade thickness. Unlikely, it asks for high design and execution complexity and interdisciplinary design coordination (structural + energy experts). Lastly, it implies difficult future modification due to interdependence.
4. *Unified approach*. This is the highest level of integration when energy and structural functions are “fully merged” into a single material or system (green). The system behaves as a hybrid multifunctional layer. Advantages include that it maximizes efficiency in terms of space, material, and performance, thanks to a simplified installation (one system for both functions), while an optimal thermal continuity and mechanical response are achieved. On the other hand, this requires advanced materials and manufacturing technologies. It has limited reparability; damage to one function may compromise the other, and it has a potentially higher initial cost with limited market availability.

The classification shows the evolution from additive to synergistic retrofitting strategies:

- *Early systems* (Unfair Competition, Separate) represent additive interventions, where energy and structural measures coexist but do not interact.
- *Modern systems* (Combined, Integrated, Unified): Integrated design, multifunctional materials, and holistic performance optimization are the keys to sustainable and resilient renovation practices.

Fig. 3 clearly reinforces the conceptual progression illustrated in Fig. 2, confirming how the scientific literature is distributed across the four identified retrofit approaches. Most contributions still fall within the separate and integrated categories, reflecting the historical tendency to address structural and energy issues through parallel, yet not fully coordinated, solutions. More recent studies, however, increasingly explore combined and especially unified strategies, signalling a shift toward multifunctional systems capable of merging mechanical and thermal functions within a single envelope layer. This mapping highlights not only the rapid evolution of synergistic retrofitting

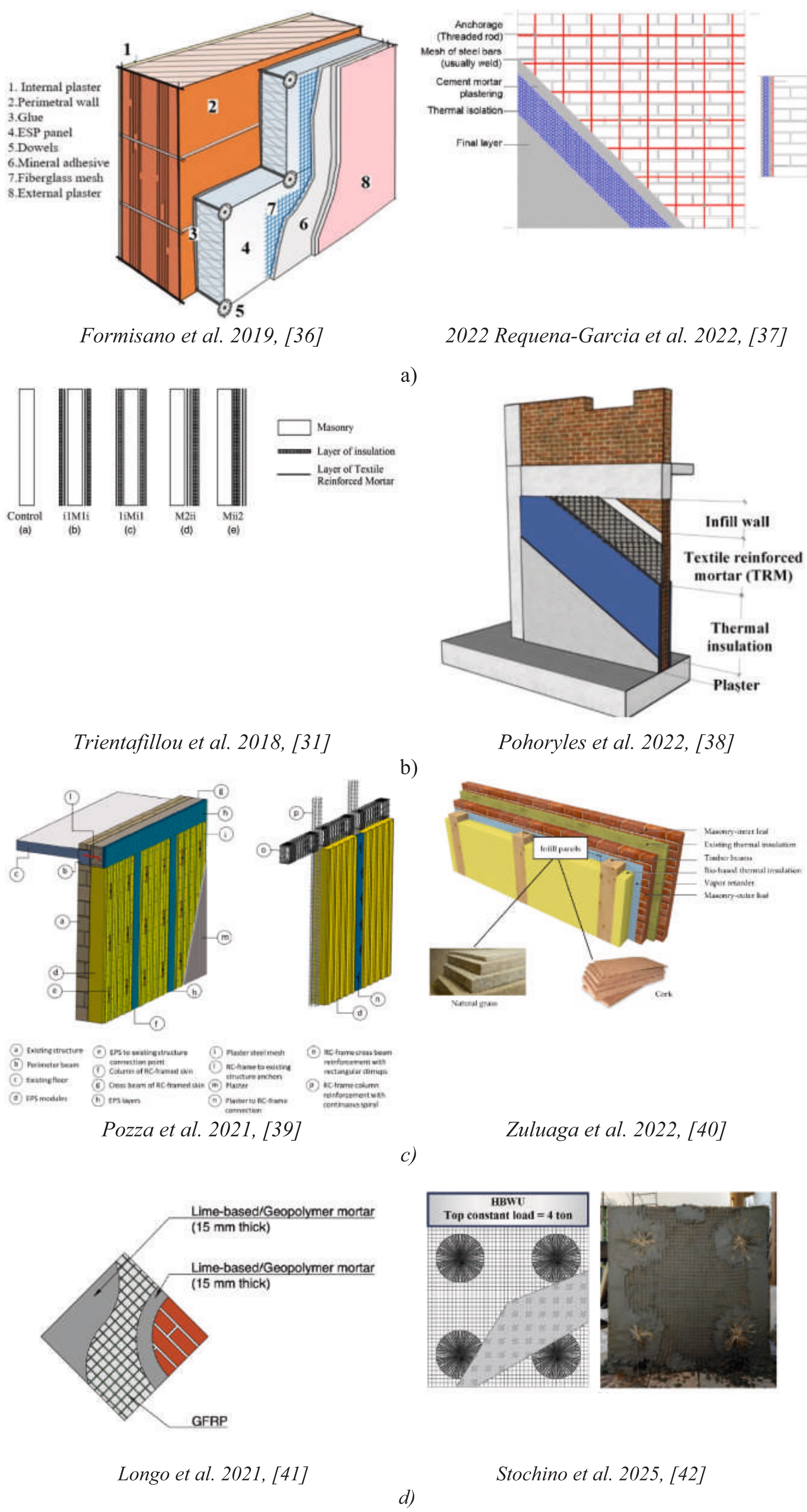

Fig. 4. Examples of approaches: (a) Separate, (b) Combined, (c) Integrated, (d) Unified.

technologies but also the fragmentation of the terminology currently used to describe them. The coexistence of overlapping expressions, such as "integrated," "hybrid," "combined," "multifunctional," "dual-purpose," etc., often leads to ambiguity and makes cross-comparison between studies difficult.

The classification proposed herein and exemplified in Figs. 3 and 4, underscores the urgent need for a common lexicon capable of standardizing how synergic structural–energy retrofit strategies are defined, categorized, and communicated. Establishing such a shared vocabulary would greatly enhance clarity, comparability, and knowledge transfer across research groups, practitioners, and regulatory bodies, ultimately accelerating the adoption of holistic renovation practices. In this perspective, Fig. 4 aims to provide exemplary examples of how existing scientific contributions can be mapped onto the four retrofit categories introduced in Fig. 3. Each study exemplifies a specific level of interaction between structural and energy layers, thereby validating the proposed classification.

- Separate approach Fig. 4a [36,37]. These works address structural and energy improvements as independent interventions, typically applied in different phases or through distinct systems that do not interact mechanically or functionally. The strengthening measures (e.g., local reinforcement, FRP/steel elements) and the thermal upgrades (e.g., ETICS, insulation layers) remain conceptually and physically separated, reflecting the "additive" logic of traditional retrofitting.
- Combined approach Fig. 4b [31,38]. These studies integrate structural and thermal layers into a superimposed yet functionally distinct assembly. TRM/FRCM systems are applied in conjunction with insulation, often in a layered configuration (e.g., TRM over insulation or vice versa). Although the layers remain identifiable, their combined installation reduces thickness and improves load transfer, fitting the definition of a combined—yet not fully synergistic—solution.
- Integrated approach Fig. 4c [39,40]. These contributions exemplify systems where structural and energy functions are interconnected and partially interdependent. Mechanical connectors, hybrid assemblies, or coordinated design strategies ensure that the insulation contributes to the mechanical behaviour (e.g., increased lever arm, improved out-of-plane response), while the structural layer simultaneously protects or stabilizes the thermal component. This mutual interaction is the hallmark of integrated retrofitting.
- Unified approach Fig. 4d [41,42]. These studies investigate multifunctional materials or prefabricated panels in which structural and thermal roles are intrinsically merged into a single system. The envelope behaves as a hybrid layer, simultaneously providing stiffness, strength, and thermal resistance. This represents the highest level of synergy, where the distinction between "structural" and "energy" components becomes technically obsolete.

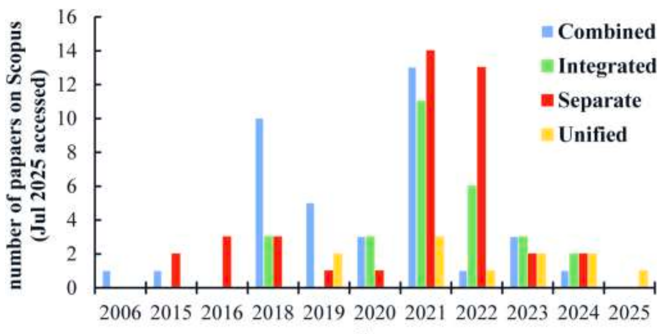

Fig. 5. Number of papers available in the literature on structural and energy renovation by using different approaches (vertical axis is dimensionless).

The trend shown in Fig. 5 directly reflects the classification framework proposed in Fig. 3, confirming its relevance for interpreting the evolution of research on synergistic structural–energy retrofitting. When the available literature is reorganized according to the four conceptual categories—Separate, Combined, Integrated, and Unified—it becomes evident that scientific production has grown rapidly in recent years, with a marked concentration of studies in the Separate and Integrated approaches. This distribution not only validates the usefulness of the proposed taxonomy but also highlights the fragmentation of current terminology and the lack of a shared conceptual structure in the field. The apparent gap between 2007 and 2014 does not reflect a true research hiatus; rather, it results from the scarcity of studies explicitly addressing synergistic structural–energy retrofitting during that period, when most publications focused on structural or energy upgrades as separate topics.

The emerging interest in Unified solutions, although still limited in number, further demonstrates the need for a consistent and common lexicon capable of describing multifunctional retrofit systems with precision and comparability. Establishing such a common language is essential to support cumulative knowledge, facilitate cross-study comparisons, and guide future developments in holistic renovation strategies.

5. Performance assessment

A coherent assessment of seismic–energy retrofit strategies requires performance indicators that are both technically meaningful and comparable across different building types and intervention methods. In this framework, two parameters emerge as the most representative for characterizing the effectiveness of envelope-level upgrades in the energy and structural domains: thermal transmittance (U-value), which quantifies heat-transfer performance and overall envelope efficiency, and the capacity–demand ratio (ζ_E), which expresses the seismic safety margin as the relationship between structural capacity and seismic demand. The present section outlines the regulatory evolution, technical relevance, and interpretative value of these two indicators, which constitute the basis for evaluating envelope retrofitting solutions in both energy and seismic terms. Improving the energy performance of the building envelope is a key requirement in current decarbonization strategies and in the sustainable renovation of the existing building stock. Reducing thermal transmittance (U-value) and ensuring continuity of the insulation layer enable a significant decrease in heating and cooling demand, while enhancing indoor comfort and air quality. Historically, the Italian regulatory framework has evolved from generic limitations on overall energy consumption to performance-based rules explicitly focused on the quality of the envelope and its individual components. This transition culminated in the Minimum Energy Performance Decree issued on 26 June 2015 [43], which introduced mandatory maximum U-values for each envelope element (opaque walls, roofs, floors, windows, and transparent components), differentiated by climatic zone. The decree also requires the assessment and mitigation of thermal bridges, as well as airtightness and moisture-related risks, thereby promoting a holistic and technically robust design of façade assemblies.

A crucial step in this regulatory evolution is the tightening of U-value thresholds between 2015 and 2021. While the 2015 decree already enforced a marked improvement compared to previous standards, subsequent updates—driven by EU nearly-zero-energy building (nZEB) objectives—led to further reductions, especially for major renovations. In typical climatic regions, the admissible U-value for external walls has decreased from approximately 0.34–0.32 W/m^{2}K to 0.26–0.24 W/m^{2}K, whereas roof elements have shifted from 0.28–0.26 W/m^{2}K to around 0.22–0.20 W/m^{2}K, making the adoption of high-performance insulation systems a mandatory requirement. The resulting increase in performance levels has accelerated the industrial development of continuous external insulation systems, high-efficiency windows, and more advanced façade technologies. Compliance with progressively stricter U-values has shifted envelope retrofitting from the simple addition of insulation toward integrated design approaches that ensure material compatibility, continuity of the thermal barrier, and durability. This convergence between stringent energy requirements and seismic safety needs creates favourable conditions for integrated seismic-energy retrofit strategies. Composite systems applied externally—combining thermal insulation with structural reinforcement—can simultaneously satisfy updated U-value limits and enhance façade stiffness, connectivity and energy dissipation capacity, thereby reducing out-of-plane vulnerabilities and improving global seismic response without invasive interventions inside the building.

Improving the seismic performance of existing buildings—particularly those constructed before the introduction of modern seismic codes—is a fundamental requirement within current resilience and risk-mitigation strategies. Enhancing the lateral resistance, ductility, and out-of-plane stability of the building envelope significantly reduces the probability of damage or collapse under seismic loading, while also limiting functional disruptions and economic losses. Historically, the Italian regulatory framework has transitioned from prescriptive rules focused on material strength to performance-based criteria centred on global structural behaviour and acceptable damage states. This evolution culminated in the *Norme Tecniche per le Costruzioni* (NTC 2008, i.e. updated in 2018) [44], which introduced explicit requirements for the assessment of seismic safety through the evaluation of capacity–demand ratios, limit states and deformation-based criteria for both structural and non-structural components. The regulations also mandate the verification of local collapse mechanisms, such as out-of-plane failure of masonry walls and detachment of infill panels, recognising the building envelope as a key seismic-sensitive subsystem whose behaviour must be explicitly characterised and, when necessary, strengthened. A significant step in this regulatory evolution is the progressive tightening of seismic safety thresholds between 2008 and 2018. While the earlier code already formalised the need for nonlinear capacity assessment, the 2018 update emphasises more detailed modelling of infill–structure interaction, the consideration of façade elements as potential global instability triggers, and the quantification of seismic improvement through indices such as ζ_E, the seismic safety coefficient defined as the ratio between structural capacity and seismic demand.

These increasingly stringent requirements have accelerated the development and adoption of integrated envelope retrofit strategies in which structural enhancement is achieved through composite systems placed externally—such as TRM layers, FRP laminates, anchored ventilated façades, or prefabricated CLT-based panels—that simultaneously improve shear resistance, out-of-plane stability, and energy dissipation capacity. Because these systems contribute to the global stiffness and connectivity of the façade while remaining external to the occupied space, they effectively address regulatory demands on local and global seismic performance without intrusive work inside the building. In many applications, the resulting improvement is expressed in terms of increased peak shear capacity, reduced inter-storey drift, enhanced stability of non-structural components, and significant gains in the capacity–demand ratio, often enabling compliance with the safety targets defined by NTC 2018 [44], even in highly vulnerable building typologies.

Furthermore, a cross-analysis of the reviewed studies highlights that the long-term performance of integrated seismic–energy retrofitting systems depends not only on structural and thermal efficiency but also on fire resistance, moisture management, and material durability. Research consistently shows that organic-matrix systems such as FRP suffer significant degradation at elevated temperatures, losing stiffness and bond capacity, and thus require protective layers when applied externally [32,45]. Conversely, inorganic composite systems (TRM-based solutions) exhibit superior thermal stability, fire resistance, and vapor permeability, making them more suitable for façade-scale applications where exposure and ageing effects are critical [46,47]. Studies on ventilated façades with mechanical anchorage show that the use of non-combustible and vapor-permeable insulation materials, combined with ventilated cavities and carefully designed fixing systems, can enhance façade safety and functional durability while effectively preventing cladding detachment under service and seismic actions, as demonstrated in integrated seismic–energy retrofit applications [30]. The adoption of ventilated envelope solutions also supports improved hygrothermal behaviour and energy performance of the façade, contributing to the overall robustness and long-term effectiveness of the retrofitting intervention. Although [48] do not perform dedicated hygrothermal analyses or experimental investigations on moisture-related phenomena, their life cycle and energy-based assessment framework highlights the critical role of envelope continuity, thermal bridge mitigation, and appropriate detailing in achieving durable retrofit solutions. The study shows that inadequate envelope performance results in increased operational energy demand, higher maintenance requirements, and greater life-cycle environmental impacts. Within this framework, moisture-related degradation mechanisms—such as material ageing, loss of integrity, and reduced service life—are implicitly recognized as factors that can undermine the long-term reliability and cost-effectiveness of seismic–energy retrofit interventions. The study therefore reinforces the view that effective moisture management is a core component of durable seismic–energy retrofitting strategies, as envelope performance influences not only operational energy demand but also long-term reliability, maintenance needs, and the overall sustainability of the intervention.

The assessment of seismic–energy retrofitting strategies is currently also based on a life-cycle perspective, in which both economic feasibility and environmental performance are evaluated over the entire service life of the building, rather than being limited to initial construction costs. Within this framework, *Life-Cycle Cost* (LCC) and *Life-Cycle Assessment* (LCA) approaches are widely used to capture the balance between initial investment, energy savings during operation, maintenance, and replacement needs, reduction of seismic losses, and impacts associated with end-of-life phases. As a result, cost estimation for integrated seismic–energy retrofits move beyond conventional budgeting practices and incorporates long-term economic and environmental performance indicators. Recent literature shows that integrated retrofit strategies generally perform better over the life cycle than sequential or single-purpose interventions. By combining structural strengthening and energy upgrading within a single design and construction process, these solutions reduce material overlaps, streamline installation phases, and limit disruption to building use, leading to lower overall costs and more efficient use of resources [29,39,49]. Although the initial investment may be slightly higher, life-cycle analyses consistently demonstrate that these costs are compensated by substantial reductions in energy consumption during operation and by lower seismic-related repair and downtime costs, resulting in improved cost-effectiveness and shorter payback periods [50,51]. From an environmental standpoint, LCA-based studies confirm that operational energy use is often the dominant contributor to total life-cycle impacts, especially in existing buildings with low initial energy performance. This highlights the central role of envelope retrofitting in achieving long-term reductions in greenhouse gas emissions [52–54]. At the same time, several studies stress the importance of accounting for embodied impacts, as solutions that rely on large quantities of materials or energy-intensive processes may reduce the overall sustainability benefits of retrofitting [48,55]. When LCA is combined with probabilistic seismic loss and risk-based assessment methods, the benefits of integrated seismic–energy retrofits become even clearer, showing significant reductions in expected annual losses, repair-related emissions, and long-term resource consumption at both the building and portfolio levels [35,56,57]. Overall, the literature consistently points to integrated seismic–energy retrofitting as a cost-effective and environmentally sound strategy for upgrading the existing building stock. By simultaneously lowering energy demand, reducing environmental impacts, and mitigating seismic risk over the life cycle, these approaches contribute to climate mitigation goals, improve building resilience, and support the long-term sustainability of the built environment.

6. Database and case studies

A database was constructed through a structured screening process applied to peer-reviewed scientific literature and technical reports published between 2000 and 2024. The initial search yielded more than 300 publications, which were filtered according to explicit inclusion and exclusion criteria. Only studies that (**i**) addressed retrofitting solutions applied to the building envelope, (**ii**) explicitly combined or compared structural and thermal performance, and (**iii**) provided quantitative mechanical and/or energy data were included. Works focusing exclusively on structural strengthening or solely on energy retrofitting, without any interaction between the two domains, were excluded. Additional exclusion criteria involved insufficient experimental or numerical detail, lack of applicability to masonry or RC buildings, or purely theoretical contributions without validation. After applying these criteria, 93 publications were retained, corresponding to 154 individual retrofit cases (more case studies may refer to a single publication) that met the requirements for comparative analysis. The database records, for each contribution, its bibliographic profile, including year of publication, authorship, and type of source (journal article, conference paper, open-access report, or European research project), together with the methodological and technical characteristics of the proposed intervention. Each study is classified according to the design approach adopted (Separate, Combined, Integrated, or Unified) and whether additional coupled interventions are considered, such as window replacement or the installation of photovoltaic systems, which complement the primary seismic–energy retrofit. When a case study is presented, the database documents its main features, including whether it concerns cultural heritage, the climatic zones A–F (Italian D.Lgs. 192/2005), seismic areas 1–4 (Italian NTC08), structural typology (masonry, reinforced concrete, timber, or mixed systems), pre-intervention energy class, and the *compactness index* (S/V). The dataset also captures relevant information on the building envelope, such as infill wall typology, façade transmittance values, window systems, and heating or cooling technologies. From a methodological perspective, the database identifies whether the study relies on numerical, analytical, or experimental analyses and provides a concise description of the proposed seismic–energy intervention, including aspects such as the increase in envelope thickness, the treatment of thermal bridges, and the reported performance outcomes. These outcomes include both energy indicators—such as the reduction in annual primary energy demand expressed in tonnes of oil equivalent (TEP%)—and seismic indicators, such as the percentage improvement of the capacity-to-demand ratio. In addition, the database records whether a cost assessment is provided and summarises the main advantages and limitations of each solution in terms of constructability, economic feasibility, sustainability, reversibility, recyclability, and overall versatility. For the sake of conciseness, Table A1 reports a selection of key information for each publication, namely the methodological approach, the presence or absence of a case study, the structural typology of the case study (RC, masonry, timber, or mixed structure), and the main advantages and limitations associated with the technique under investigation.

This database structure enables an objective comparison of heterogeneous studies and provides the analytical foundation for defining a conceptual framework for integrated seismic and energy retrofitting strategies. The set of graphs in Fig. 6 represents the outcomes of a comprehensive database analysis carried out on 93 scientific papers concerning seismic and energy retrofit interventions on existing buildings.The elaboration aimed to assess, for each approach identified in the

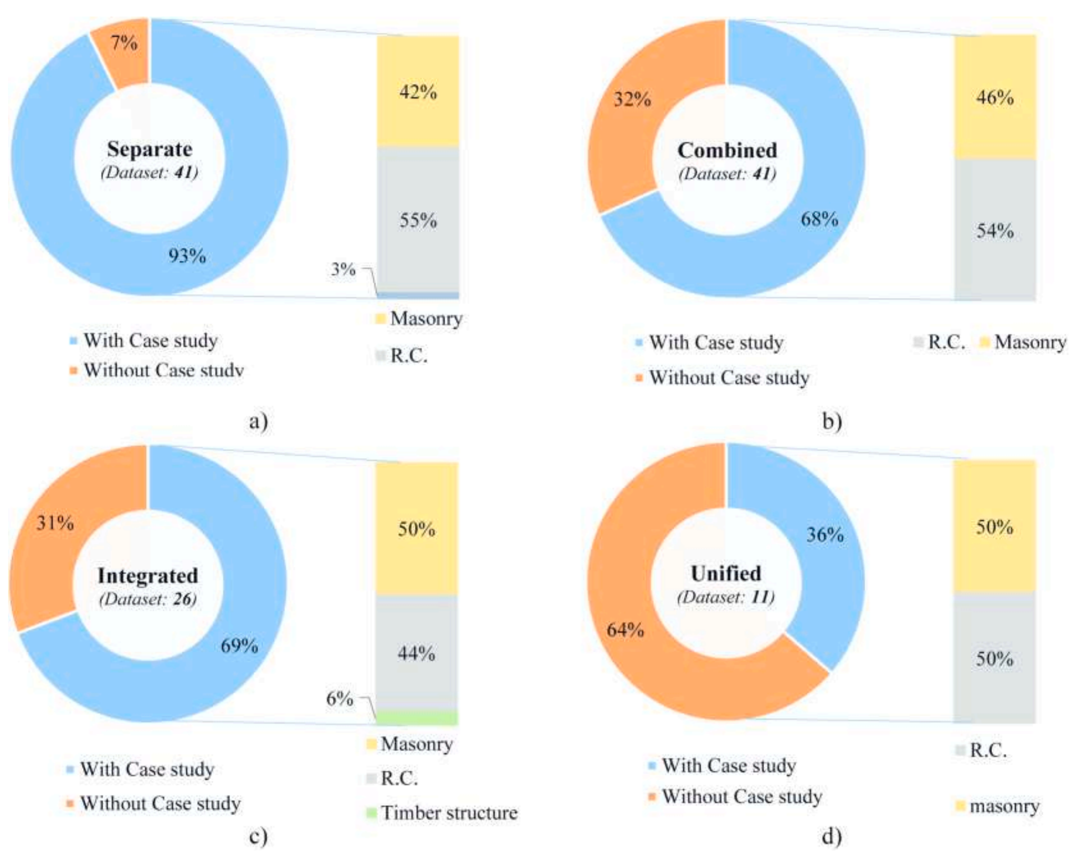

Fig. 6. Classification of the seismic–energy retrofit cases according to the four main approaches identified in the literature: (a) Separated, (b) Combined, (c) Integrated, and (d) Unified. For each approach, the graphs indicate the total number of analysed cases, the share of studies with case studies, and the distribution of building typologies (masonry, reinforced concrete, timber, or mixed).

literature, the presence or absence of real case studies and, when such applications were reported, the type of structural system involved (e.g., masonry, reinforced concrete, timber, or mixed structures). It is important to note that the numbers shown in each figure do not refer to the number of papers but rather to the number of individual cases extracted from the literature. In fact, several publications presented more than one retrofit approach, leading to a total dataset larger than the number of reviewed articles. Each graph also reports the dataset size (i.e., the total number of cases analysed for each approach) and the distribution between documented case studies and theoretical or numerical works, together with the typology of the buildings involved.

The *Separated* approach, see Fig. 6a, includes 41 cases, in which energy and structural upgrades are designed and installed independently. This configuration reflects conventional practice and remains the most widely applied in literature. Most entries (93%) correspond to real or experimental applications, confirming their maturity and frequent adoption in both masonry (42%) and RC (55%) buildings.

These results underline how traditional retrofits continue to dominate, with distinct measures addressing thermal and structural needs separately. Fig. 6b refers to the *Combined* approach, which also comprises 41 cases. In this configuration, the energy and structural interventions are designed separately but installed dependently, usually following a two-layer arrangement, in which the thermal insulation and the mechanical strengthening are physically connected. Approximately 68% of these cases report experimental or numerical validation, while the remaining 32% correspond to theoretical approaches. From the structural point of view, reinforced concrete buildings (54%) are slightly more represented than masonry ones (46%). This configuration represents an intermediate step toward integration, allowing partial synergy between the two systems while maintaining distinct functional layers. The *Integrated* approach (Fig. 6c) comprises 26 cases, where seismic and energy functions are jointly conceived and implemented as two-phase materials within a single-layer system. About 69% of the studies include real or experimental case studies, demonstrating the growing maturity and practical applicability of this approach. The cases are nearly equally divided between masonry (50%) and RC (44%), with a small share of timber structures (6%). These solutions often employ composite systems such as TRMs coupled with insulation, enabling direct interaction between thermal and mechanical behaviour. Lastly, the *Unified* approach, Fig. 6d—11 cases—represents the highest level of integration, where both functions are realized through a single multifunctional material providing thermal and mechanical performance simultaneously. Only 36% of these studies involve experimental validation, while 64% remain theoretical. Applications are equally distributed between masonry and RC buildings (50% each), showing the potential versatility of such solutions. Despite its limited diffusion, this approach points toward next-generation thermo-structural materials for sustainable retrofitting.

In addition to the classification by retrofit typology, the database was further analysed to investigate the type of buildings addressed in the case studies. Attention was paid to distinguishing whether the interventions were applied to cultural heritage assets or to ordinary existing buildings. Fig. 7 presents this elaboration, showing the distribution of the 145 cases included in the database, distinguishing between studies with or without real applications, and identifying those involving heritage buildings. The results indicate that 77% of the cases include a real application, while 23% correspond to theoretical work. Among the applied cases, 86% are concerned with non-heritage buildings, only 7% refer explicitly to cultural heritage assets, and another 7% do not specify the building type. This distribution highlights the scarcity of seismic–energy retrofit applications on heritage buildings, where the integration of structural and energy improvements remains particularly complex due to conservation constraints, material heterogeneity, and architectural preservation requirements. Consequently, most studies in literature focus on modern masonry or reinforced-concrete structures, which allow easier experimental validation and practical implementation. The analysis of the 145-case dataset thus reveals a significant research gap in the development of heritage-compatible seismic–energy retrofit solutions, calling for reversible, low-intrusive, and compatible techniques capable of improving both seismic safety and energy efficiency without compromising the historical and architectural integrity of protected buildings.

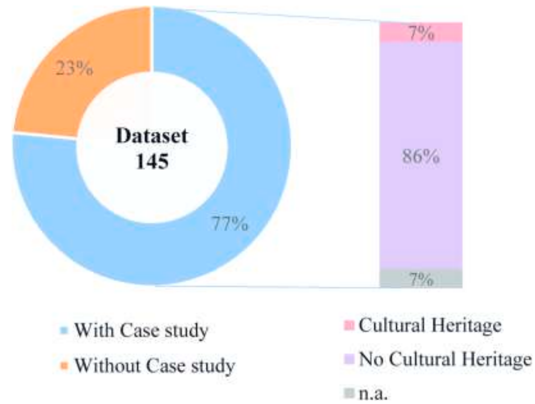

Fig. 7. Distribution of the 145-case dataset by the presence of case study and cultural heritage relevance.

In addition to the classification by building typology and heritage relevance, the database was further analysed to investigate the geographical distribution of the identified case studies with respect to the Italian seismic and climatic zoning systems.

Fig. 8 reports the location of the analysed cases according to the seismic areas defined by the *Italian Building Code* (NTC 2018, D.M. 17/01/2018) [44] and the climatic zones defined by D.P.R. 412/1993 [58], which jointly influence both the design of retrofit interventions and their expected performance outcomes. According to the Italian seismic classification, Area 1 represents areas with the highest seismic hazard, where the reference peak ground acceleration (ag) exceeds 0.25 g, while Areas 2, 3, and 4 correspond to decreasing hazard levels. Similarly, the Italian climatic zoning divides the national territory into six climatic zones (A–F) based on the degree days (DD), ranging from mild coastal areas (Zone A, DD $<$ 600) to cold alpine regions (Zone F, DD $>$ 3000). These two parameters jointly determine the energy demand and the structural safety requirements of buildings, making them essential for evaluating the applicability and performance of combined retrofit solutions. The results in Fig. 8 clearly show that most interventions are in medium to high seismic hazard areas (Areas 2 and 3) and in cold or temperate climatic zones (D and E). This distribution indicates that seismic–energy retrofit strategies are predominantly applied where both seismic vulnerability and heating energy demand are high. Specifically, Zone E – representing a large portion of central and northern Italy- hosts the greatest number of case studies, confirming that colder climates with

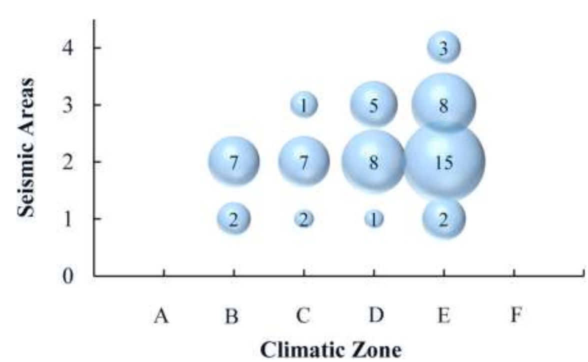

Fig. 8. Distribution of the case studies by seismic areas and climatic zones according to Italian standards (NTC 2018 [44] and D.P.R. 412/1993 [58]).

long heating seasons tend to justify the implementation of energy retrofits together with seismic strengthening. Conversely, very few cases are observed in low seismic Areas (Area 4) or in milder climatic regions (Zones A–C), where the incentive for integrated interventions is less pronounced. Overall, the analysis highlights a strong correlation between seismic hazard and climatic severity, underlining the importance of integrated design approaches that can simultaneously enhance both the structural resilience and the energy performance of existing buildings.

To further characterize the building envelope configurations considered in the collected case studies, Fig. 9 illustrates the distribution of external wall typologies across the analysed dataset, which includes 154 identified cases. The classification reflects the most common wall systems used in the Italian building stock, distinguishing between masonry typologies (solid and hollow bricks), RC- walls, and multi-layer or composite systems such as sandwich or mixed walls. The results show that the most represented category corresponds to single-leaf hollow brick walls (24%), which are typical of post-war residential buildings and widely found in southern and central Europe. They are followed by single-leaf solid brick walls (20%) and double-leaf solid brick configurations (19%), often characteristic of traditional masonry buildings and older construction techniques. The proportion of double-leaf hollow brick walls (8%) and mixed systems combining hollow and solid bricks (4%) is comparatively lower but still significant, reflecting more recent construction practices with cavity walls or composite infills. A small share of sandwich walls (1%) and reinforced-concrete walls (8%) is also observed, the latter being representative of frame or wall-type RC structures.

Finally, 16% of the cases are labelled as *n.a.* (not available), indicating that the wall typology was not explicitly specified in the source publication. Overall, the distribution confirms that masonry walls – both solid and hollow brick typologies – dominate the database, accounting for more than two-thirds of the total sample. This finding is consistent with the characteristics of the existing building stock, where unreinforced masonry envelopes are predominant and represent a key target for integrated seismic and energy retrofit interventions. The relatively smaller share of reinforced-concrete walls and sandwich systems reflects their limited presence in older constructions but also points to emerging research interest in addressing these wall types within combined retrofit strategies.

To complement the statistical analysis, three representative cases were selected from the database to illustrate the practical implementation and performance of different synergistic retrofit strategies. These cases were chosen based on (i) completeness of mechanical and thermal data, (ii) clarity of the retrofit configuration, and (iii) relevance to the main categories identified in this review. These representative cases highlight the diversity of synergistic retrofit strategies and demonstrate how structural and thermal benefits can be simultaneously achieved through integrated design. The first case [28] considers a prefabricated CLT panel system, which was externally applied to a 1960 s RC building, integrating bio-based insulation. The intervention reduced wall transmittance from 1.15 to 0.27–0.29 W/m^{2}K and decreased heating demand by 65–70%. Structurally, the CLT panels increased lateral stiffness and reduced inter-storey drift, confirming their suitability for dual seismic–energy retrofitting. In the second case [31], a TRM/insulation/TRM configuration using mineral wool was tested under in-plane and out-of-plane loading. Results showed significant increases in shear strength and out-of-plane capacity, with the insulation layer contributing to a larger lever arm. Thermal simulations indicated energy savings up to 60–70% depending on the climate zone. In the third case [29], a combined intervention using mineral-wool ETICS and localized CFRP strengthening at openings was identified as the optimal cost/benefit solution. Although not experimentally implemented, the modelling demonstrated that coordinated structural and thermal actions can outperform separate interventions in terms of life-cycle performance.

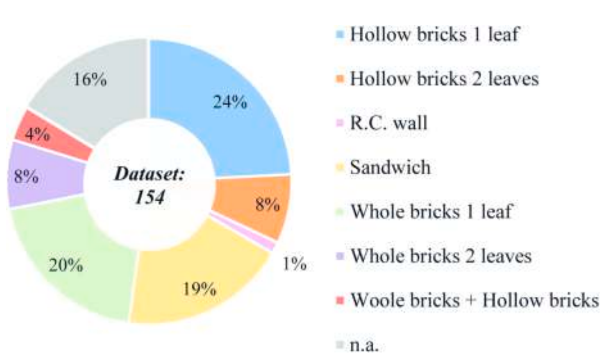

Fig. 9. External wall typologies analysed in the case studies (154 total cases).

7. Unified renovation index: a future challenge

In light of the considerations outlined above, it is necessary to define a renovation index that provides a comprehensive measure of building improvements in terms of both energy efficiency and structural performance, as achieved through different retrofit approaches. One effective method is the equivalent economic performance assessment, conceived as a unifying framework that translates seismic, energy, and environmental performance outcomes into a common monetary metric over the building's life cycle. The primary objective of this assessment is to enable an immediate, transparent comparison of alternative retrofit solutions by expressing diverse benefits and impacts in economic terms. Within the [59] The framework evaluates initial investment costs, expected seismic losses, energy-related operational expenses, and environmental externalities across multiple life-cycle stages: the initial condition, the extended service life following retrofit, and the end-of-life phase. Seismic performance is captured through the reduction of expected economic losses due to earthquake damage, whereas energy performance is reflected in the variation of operational costs associated with energy consumption. Environmental impacts are monetized by assigning economic values to factors such as CO_2 emissions and resource use. The equivalent total initial cost (Total IC_{eq}, expressed in €/m^2) at time t_0 is defined as the sum of the initial costs of seismic retrofit interventions (IC_S), energy retrofit interventions (IC_E), and the environmental impact costs (IC_{EI}) associated with the manufacturing of materials used in the retrofit, as formalized in the following Eq. (1).

$$\text{Total}\,IC_{eq}(t_0) = IC_S + IC_E + IC_{EI} \tag{1}$$

The seismic, energy, and environmental performance, evaluated annually and expressed in economic terms, are integrated into a single global indicator, namely the Integrated Retrofitting Performance Parameter (IRPP, expressed in €/m^2·year). The IRPP is defined as the sum of the Expected Annual seismic Losses (EAL_S), the Expected Annual Costs of energy consumption (EAC_E), and the expected equivalent costs associated with CO_2-equivalent emissions resulting from both seismic damage and energy use (EAC_{EI}). This parameter is calculated for both the pre- and post-retrofit conditions to enable a direct comparison of performance improvements.

Within the evaluation of seismic and energy retrofitting strategies for existing buildings, the Net Present Value (VAN, *Valore Attuale Netto* in Italian as proposed by [60] and previously by [61]) method represents an alternative economic-based approach aimed at assessing the long-term convenience of alternative interventions. The VAN method is grounded in classical investment analysis and is particularly suitable for retrofit problems because it explicitly accounts for the time distribution of costs and benefits associated with seismic risk reduction and energy efficiency improvements. By discounting future cash flows to a common reference time, the method allows different retrofit options to be compared on a consistent economic basis over a predefined analysis period. In the context of integrated seismic and energy retrofitting, the VAN is defined as the algebraic sum of all discounted costs and benefits

Table 1
Table of terms.

Term	Definition	Clarifying notes
Structural layer	Any material or system applied to the building envelope whose primary function is to improve mechanical performance (strength, stiffness, ductility, out-of-plane stability).	Includes FRP, FRCM/TRM, CLT panels, steel frames, and RC jackets.
Energy (thermal) layer	Any material or system applied to the envelope to reduce heat transfer, improve U-value, or enhance hygrothermal comfort.	Includes EPS/XPS, mineral wool, aerogel, polyurethane, and ventilated façade insulation.
Synergistic retrofit	A retrofit strategy in which structural and thermal improvements are conceived together to achieve combined benefits in a single intervention.	Central theme of the manuscript.
Separate approach	Structural and energy interventions are designed and installed independently, often at different times and without functional interaction.	Because structural and energy interventions are usually designed and executed in isolation—often at different times—they rarely function as a coordinated system.
Unfair competition (separate – type a)	A subtype of the Separate approach where structural and thermal layers are applied irregularly, at different ages, and without spatial coordination.	Leads to incompatibilities, thermal bridges, and poor façade continuity.
Side-by-side configuration (separate – type b)	A subtype where structural and thermal layers are adjacent but remain functionally independent; connectors may be added only to prevent detachment.	Easier maintenance but requires careful detailing to avoid moisture issues.
Combined approach	Structural and thermal layers are superimposed in a compact assembly; they remain functionally distinct but physically dependent.	Structural and thermal layers are combined into a compact assembly; they perform distinct functions but rely on each other for physical integrity.
Integrated approach	Structural and thermal layers are interconnected so that they interact mechanically and thermally; functions are partially interdependent.	TRM + insulation systems with mechanical connectors are typical examples.
Unified approach	The highest level of synergy: structural and thermal functions are merged into a single multifunctional material or prefabricated system.	Optimal integration occurs when structural and thermal functions are fully merged into a unified double-scope material.
Multifunctional system	Any retrofit solution capable of simultaneously providing structural strengthening and thermal insulation within one assembly.	Umbrella term; includes Combined, Integrated, and Unified systems.
Hybrid system	A retrofit system combining different materials (e.g., FRP + insulation, CLT + insulation) but not necessarily achieving full functional synergy.	Often used ambiguously in literature, the glossary clarifies its meaning.
Composite envelope panel	Prefabricated panel integrating structural and thermal layers, typically installed externally to minimize disruption.	Includes CLT-based retrofit panels.
TRM/FRCM–insulation system	A composite system where textile-reinforced mortar is combined with insulation in layered or sandwich configurations.	Demonstrated to improve both in-plane and out-of-plane capacity.
Ventilated reinforced façade	A ventilated façade system where the cladding and insulation are supported by a structural frame that also prevents façade detachment.	Provides local structural improvement + thermal upgrade.
Capacity–demand ratio (ζ_E)	The seismic safety index is defined as the ratio between structural capacity and seismic demand.	Used to quantify seismic improvement after retrofit.
Thermal transmittance (U-value)	Heat transfer coefficient of the envelope; lower values indicate better insulation performance.	Central energy metric in the manuscript.
Life-cycle cost (LCC)	Economic evaluation method considering initial, operational, maintenance, and end-of-life costs over the building's service life.	Used to compare retrofit strategies.
Life-cycle assessment (LCA)	An environmental evaluation method assessing embodied and operational impacts over the building's life cycle.	Relevant for sustainability-oriented retrofits.
Integrated retrofitting performance parameter (IRPP)	A unified indicator expressing seismic, energy, and environmental performance in €/m^2·year.	Introduced in Section 7.
Net present value (NPV/VAN)	Economic metric evaluating the long-term convenience of a retrofit by discounting future benefits and costs.	Used to assess payback and economic viability.
Two-phase material/ system	A façade system where structural and thermal components coexist within a single layer but remain distinguishable.	Typical of Integrated approaches.
Multilayer envelope system	A façade assembly composed of multiple layers (structural + insulation + finishing), each with distinct functions.	Common in Combined approaches.
Envelope-level retrofit	Any intervention applied externally to the building envelope to improve both seismic and energy performance.	Minimizes disruption to occupants.

generated by the intervention during the service life of the building (Δ_{EAL}). These include the initial investment cost for the retrofit, the expected reduction in seismic losses due to improved structural performance, the savings in operational energy costs resulting from enhanced energy efficiency, and, where relevant, residual values or end-of-life costs. A positive VAN indicates that the retrofit strategy is economically advantageous when compared to the reference scenario, typically represented by the as-built condition ($EAL_{as\ built}$) or by a less invasive intervention ($EAL_{retrofitted}$). The general expression of the Net Present

Value for a retrofit option can be written as in Eq. (2):

$$\Delta EAL[€] = \left(EAL_{asbuild} - EAL_{retrofitted}\right)Buildingvalue \tag{2}$$

The effectiveness of the investment is evaluated through the *PayBack Period* (PBP), which represents the number of years required for the benefits generated by the intervention to equal the initial cost incurred. If the PBP is shorter than the remaining service life of the building, the intervention can be considered economically advantageous.

8. Conclusions

This review set out to examine the current state of synergistic structural–energy retrofitting solutions applied to the building envelope, with a dual objective to systematize the wide and heterogeneous body of literature on combined seismic and energy renovation strategies, and to propose a common, valid conceptual classification capable of describing, comparing, and interpreting the different levels of interaction between structural strengthening systems and thermal insulation layers. Through the analysis of 93 scientific contributions and 154 case-specific applications, the study reconstructed the technological evolution of façade retrofit systems—from traditional, functionally independent interventions to advanced multifunctional solutions—and highlighted the need for a shared lexicon to support cross-disciplinary communication and design practice. The following remarks can be addressed accordingly.

- The literature reveals a proliferation of terms such as integrated, hybrid, combined, multifunctional, and dual-purpose, often used inconsistently. This terminological ambiguity hampers comparison between studies and slows down the transfer of knowledge to practitioners and policymakers. The proposed four-level classification—*Separate*, *Combined*, *Integrated*, *Unified*—provides a clear conceptual structure to interpret existing and emerging solutions.
- Early retrofit strategies treat structural and energy upgrades as independent actions, typically executed in different phases and with limited mutual interaction. Modern systems increasingly aim to merge mechanical and thermal functions, reducing façade thickness, improving performance continuity, and optimizing installation processes. Unified systems, although still limited in number, represent the frontier of multifunctional materials and prefabricated panels.
- The limited representation of Cultural Heritage buildings in the collected case studies (only 7%) highlights the need for further research on synergistic retrofit solutions specifically tailored to heritage assets, where stricter preservation constraints significantly influence the feasibility and design of envelope-level interventions.
- Experimental and numerical studies consistently demonstrate that combined TRM–insulation systems, CLT-based panels, and mechanically anchored ventilated façades are capable of simultaneously enhancing both in-plane and out-of-plane structural capacity, while also reducing inter-story drift and the risk of local collapse mechanisms. At the same time, they contribute to a significant reduction in U-values and annual energy demand. When properly designed, these systems offer improvements in durability, fire resistance, and moisture control.
- The progressive tightening of energy performance requirements (U-value limits, thermal bridge mitigation, airtightness) and the evolution of seismic safety criteria (capacity–demand ratios, local mechanism verification) create a favourable context for envelope-level multifunctional retrofits. External composite systems are particularly effective in meeting both regulatory domains without invasive interior works.
- The review highlights the absence of a single metric capable of capturing seismic, energy, and environmental performance simultaneously. Emerging approaches—such as the Integrated Retrofitting Performance Parameter (IRPP) and Net Present Value (NPV)-based methods—represent promising steps toward a unified renovation index, essential for decision-making and policy development.

Addressing these gaps will be essential to accelerate the adoption of multifunctional retrofitting technologies and to support the development of future regulatory frameworks and design guidelines. The proposed classification, common vocabulary, and comprehensive mapping of existing studies aim to contribute to this process, offering a structured foundation for future research and practical implementation.

9. Glossary

To consolidate the conceptual framework introduced in this work, the following glossary in Table 1 defines the principal terms used to describe the different levels of interaction between structural and thermal retrofit layers.

CRediT authorship contribution statement

Silvia Calò: Writing – original draft, Investigation, Formal analysis, Data curation. **Alessio Cascardi:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marielisa Di Leto:** Writing – original draft, Investigation, Formal analysis, Data curation. **Lidia La Mendola:** Writing – review & editing, Visualization, Validation, Supervision. **Maria Antonietta Aiello:** Writing – review & editing, Validation, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

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Table A1
Database.

Ref.	Approach	Case study	Type of structure	Benefits	Drawbacks
[62]	Combined	yes	RC	Removability	Maintainability
[63]	n.a.	yes	masonry	Cost-effectiveness	Continuous occupation of tenants
[49]	Separate	yes	RC	Cost-effectiveness	Removability
[64]	Separate	yes	masonry	n.a.	n.a.
[65]	Combined	no	masonry	Ease of realization, Versatility, Removability, Sustainability, Maintainability, Speed of realization	Interference with commercial premises or piloty floor, Interference with facilities that run on facades, Cost-effectiveness
[61]	Separate	no	n.a.	n.a.	n.a.
[66]	Separate	no	n.a.	Recyclability	Versatility
[50]	Separate	yes	RC, masonty	Cost-effectiveness, Versatility	Removability, Continuous occupation of tenants
[67]	Separate	yes	RC	Cost-effectiveness, Sustainability, Removability	Ease of realization
[68]	n.a.	yes	RC	Sustainability, Versatility	Removability, Interference with facilities that run on facades
[69]	Separate	yes	masonry	Maintainability, Sustainability	Removability, Recyclability
[70]	Separate	no	n.a.	Sustainability,	
[71]	Separate	yes	RC	Cost-effectiveness, Continuous occupation of tenants	
[29]	Combined	no	masonry	Cost-effectiveness	Continuous occupation of tenants
[52]	Combined	yes	masonry	Cost-effectiveness	n.a.
[72]	Combined	yes	RC	Maintainability	Ease of realization, Speed of realization, Continuous occupation of tenants
	Integrated	yes	RC	Maintainability, Continuous occupation of tenants	Interference with facilities that run on facades
[51]	Combined	yes	RC	Speed of realization, Cost-effectiveness	n.a.
[73]	Integrated	no	RC	Recyclability	Interference with facilities that run on facades
[74]	Integrated	yes	masonry	Removability, Continuous occupation of tenants	Interference with facilities that run on facades
[31]	Combined	no	n.a.	Maintainability, Sustainability, Ease of realization	Removability, Recyclability
[32]	n.a.	n.a.			
[75]	Combined	yes	RC	Cost-effectiveness	n.a.
[76]	Unified	yes	RC	Sustainability	Cost-effectiveness,
[77]	n.a.	yes	masonry RC	n.a.	n.a.
[36]	Separate	yes	masonry	Sustainability	Ease of realization
[78]	Combined	no	RC	n.a.	n.a.
[79]	Combined	yes	masonry	Cost-effectiveness	n.a.
[26]	Combined	no	RC	Sustainability, Ease of realization	Maintainability
[80]	Combined	yes	RC	Ease of realization, Continuous occupation of tenants	Interference with commercial premises or piloty floor, Interference with facilities that run on facades
[46]	Combined	yes	RC	Cost-effectiveness	n.a.
[81]	n.a.	no	masonry	n.a.	n.a.
[82]	n.a.	yes	RC	Cost-effectiveness	n.a.
[33]	Combined	no	RC	n.a.	n.a.
[53]	Separate	yes	masonry	Sustainability, Cost-effectiveness	Interference with facilities that run on facades, Continuous occupation of tenants
[83]	Combined	no	masonry	Speed of realization, Sustainability	Interference with facilities that run on facades, Removability, Continuous occupation of tenants
[28]	Integrated	yes	RC	Speed of realization, Ease of realization, Removability, Continuous occupation of tenants, Maintainability, Recyclability	Interference with facilities that run on facades, Use of unskilled labor
[84]	n.a.	no	n.a.	n.a.	n.a.
[35]	Combined	yes	RC, masonry	n.a.	n.a.
[85]	Integrated	yes	RC	Speed of realization, Ease of realization, Removability, Continuous occupation of tenants, Maintainability, Recyclability	Interference with commercial premises or piloty floor, Use of unskilled labor
[86]	Integrated	yes	RC	Speed of realization, Ease of realization, Removability, Continuous occupation of tenants, Maintainability, Recyclability	Interference with commercial premises or piloty floor, Use of unskilled labor
[87]	Integrated	no	n.a.	Ease of realization, Sustainability	Versatility, Maintainability
[88]	Combined	yes	RC	Ease of realization	Versatility, Sustainability
[30]	Separate	yes	RC	Continuous occupation of tenants	Use of unskilled labor, Interference with facilities that run on facades
[89]	Separate	yes	RC	Sustainability, Cost-effectiveness	Removability, Use of unskilled labor
[90]	Separate	yes	mixed structure	Continuous occupation of tenants, Sustainability	Ease of realization, Removability
[47]	Combined	yes	masonry	Ease of realization, Continuous occupation of tenants	n.a.
[91]	Combined	yes	masonry	Speed of realization, Sustainability, Removability, Cost-effectiveness	n.a.
[41]	Unified	no	RC	Sustainability, Speed of realization, Removability	n.a.
[92]	Integrated	no	n.a.	Sustainability	n.a.
[93]	Integrated	yes	RC	Sustainability	n.a.
[94]	Integrated	yes	masonry, RC	Ease of realization, Speed of realization, Versatility, Continuous occupation of tenants	Removability, Maintainability, Interference with facilities that run on facades
[94]	Unified	no	masonry	Speed of realization	n.a.
[34]	Combined	yes	masonry, RC	Ease of realization, Cost-effectiveness, Continuous occupation of tenants	Recyclability, Removability
[39]	Integrated	yes	RC	Ease of realization, Versatility, Continuous occupation of tenants	Removability
[95]	Separate	yes	RC	Continuous occupation of tenants	n.a.

(*continued on next page*)

Table A1 (*continued*)

Ref.	Approach	Case study	Type of structure	Benefits	Drawbacks
[96]	Combined	no	RC	Continuous occupation of tenants, Speed of realization	Interference with facilities that run on facades
[97]	Integrated	yes	masonry	Continuous occupation of tenants	n.a.
[98]	Integrated	yes	masonry	Recyclability	Ease of realization
[55]	Separate	yes	masonry	n.a.	n.a.
[99]	Separate	yes	masonry	n.a.	n.a.
[100]	Separate	yes	RC	Continuous occupation of tenants	n.a.
[101]	Unified	no	masonry	Ease of realization	n.a.
[102]	Integrated	no	RC	Ease of realization	n.a.
[56]	Separate	yes	RC	Continuous occupation of tenants	n.a.
[103]	Separate	yes	RC	n.a.	n.a.
[104]	Integrated	no	RC	Ease of realization	n.a.
[105]	Separate	yes	RC	n.a.	n.a.
[57]	Integrated	yes	masonry, RC	Cost-effectiveness, Sustainability, Versatility	n.a.
[106]	Separate	yes	masonry	Speed of realization	n.a.
[107]	Separate	yes	masonry, RC	Cost-effectiveness, Versatility	n.a.
[37]	Separate	yes	RC	n.a.	n.a.
[54]	Separate	yes	masonry	n.a.	n.a.
[108]	Integrated	yes	timber structure	Cost-effectiveness	n.a.
[40]	Integrated	yes	masonry	Recyclability	n.a.
[38]	Combined	yes	masonry, RC	Cost-effectiveness	n.a.
[59]	n.a.	yes	masonry, RC	Cost-effectiveness, Versatility	n.a.
[109]	n.a.	no	n.a.	n.a.	n.a.
[110]	n.a.	yes	RC	Cost-effectiveness	n.a.
[111]	Integrated	yes	masonry	Ease of realization, Speed of realization	n.a.
[112]	n.a.	yes	RC	Sustainability	n.a.
[113]	Unified	no	RC	Speed of realization, Ease of realization, Sustainability	Continuous occupation of tenants
[114]	Unified	yes	masonry	Speed of realization, Ease of realization, Sustainability	Continuous occupation of tenants
[115]	Combined	no	RC	Cost-effectiveness, Continuous occupation of tenants	n.a.
[116]	Integrated, Unified	no	RC	Ease of realization, Continuous occupation of tenants, Speed of realization	n.a.
[48]	Combined	yes	RC	Sustainability	n.a.
[117]	Combined	yes	RC	n.a.	n.a.
[118]	Integrated	yes	masonry	Speed of realization	Versatility
[119]	Integrated	yes	masonry, RC	Cost-effectiveness, Sustainability	Versatility
[120]	n.a.	yes	n.a.	n.a.	n.a.
[121]	Combined	yes	masonry	Ease of realization, Sustainability	Versatility
[122]	Unified	no	masonry	Sustainability	n.a.
[123]	Unified	yes	masonry	Sustainability, Speed of realization	n.a.
[42]	Unified	no	masonry	Sustainability, Speed of realization	n.a.

Data availability

The original contributions of this study are included in the article; further inquiries can be directed to the corresponding author.

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