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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

## 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 built by Italian governments after each seismic event (L'Aquila, Amatrice, etc.) have been destroyed; their populations have emigrated or live in "temporary houses".

A culture of prevention is becoming a priority in the building field, since modern constructors have learned to build masonry constructions to obtain both a better resistance to seismic actions and an improved protection from cold winters and hot summers.

Studying local seismic cultures is very important to better understand how local resources and local geological features were so well combined by traditional building techniques both for a single building and for a whole city.

Populations must be helped to understand their territory in order to preserve their local culture and their ancient settlement, with the aim of improving their safety and energy performances in order to preserve the anthropic built systems as document of ancient communities. This is a responsibility of politicians in all roles, ranging from local to European-wide.

Direct knowledge of the buildings and the analysis of their state of conservation define the panel of requirements to which the architectural and engineering restoration project must respond. Distributive and functional choices that are consistent with the conservative instances most likely interfere with structural and energy improvement or seismic retrofitting. From the interference of the different needs and consequent choices and design requirements, interesting possibilities could emerge for valorisation of the constructive identity [1].

Methods, approaches, and tools relating to the minimisation of seismic vulnerability and energy consumption are increasingly used and tested in order to ensure both sustainability and seismic safety [2–7] at the same time, with a connection that may improve the performances of both cultural and environmental heritage.

Improving the energy performance of a building, bringing it towards nearly zero consumption, means controlling the project in every aspect of its history. This includes diagnosis in the first phase (anamnesis phase) by analysing the overall performance framework, and choosing the most suitable materials and technologies in the design phase, verifying also the economic advantages of the technical intervention. The diagnosis phase consists of the necessary steps towards the knowledge of the building system in order to assess its vulnerability to seismic safety in particular, and structural security in general, but also to analyse energy in relation to the comfort values that are required by current standards and the needs of direct users. At the same time, for the conservation of cultural heritage in terms of seismic action, it is necessary to access analytical tools in order to assess the vulnerability and risk to cultural heritage as well as the design of seismic improvement interventions.

"The Building Material Survey and Conservation State" (PCM Directive of 12 October 2007) employs knowledge of the mechanical parameters of structures, the physical–chemical parameters of materials, wall quality, nature, and the consistency of fixed and mobile decorative devices, through non-destructive and/or minimally destructive testing, in order to identify those corrective parameters that can be used [8]. A double approach on small ancient hamlets considers both energetic and seismic aspects together. The synthesis of the requirements of these two different approaches, structural and energetic, even if not performed in the present paper, represents a new point of view that architects and engineers need to consider and resolve at the same time.

This research proposes an energetic analysis and resulting retrofitting interventions for buildings in the small hamlet of Baia e Latina (district of Caserta). Moreover, the seismic vulnerability of masonry aggregate structural units is determined on the basis of appropriate quick indexes and a series of damage maps derived from earthquakes with different intensity levels, and locations are developed for the inspected constructions.

Small settlements (less of 5000 inhabitants) constitute the largest part of Italian settlements because of the geography of the country and its mountain systems. This study could provide an example of the contemporary sustainable life required to avoid depopulation for all of the country's small hamlets. This target can also be achieved through an analysis of the seismic vulnerability and risk of the urban built-up, which is intended as a useful tool to valorise all of the investigated territories.

The insertion of technical checks measuring the energy performance of buildings, within the wider monitoring and mapping program of the seismic vulnerability of the historic centre, in order to combine safety and security interventions with energy and environmental redevelopment, would be an interesting strategy in order to optimise both the administration's costs and the time needed for these rehabilitation works.

This is to achieve, as provided by Directive 2010/31/UE, "cost-effective" design solutions.

The proposed methodology [9] includes five phases of action that are propaedeutic to the design phase:

1. Benedetti–Petrini Seismic Vulnerability Assessment of all of the analysed urban sections [10];
2. processing CARTIS sheets for the detection of the prevailing building typologies within sub-communal areas, characterized by the building homogeneity for age and/or construction and structural techniques (Figure 1);
3. energy diagnosis of the points of strength (potentialities) and weakness (problems) of every building of the analysed urban section;
4. identification of architectural and technological solutions that are necessary in order to improve energy performances [11];
5. evaluation of the positive and cumulative benefit of each intervention, after a sensitivity analysis that matches the security needs with the minimum requirements imposed by L.90/2013.

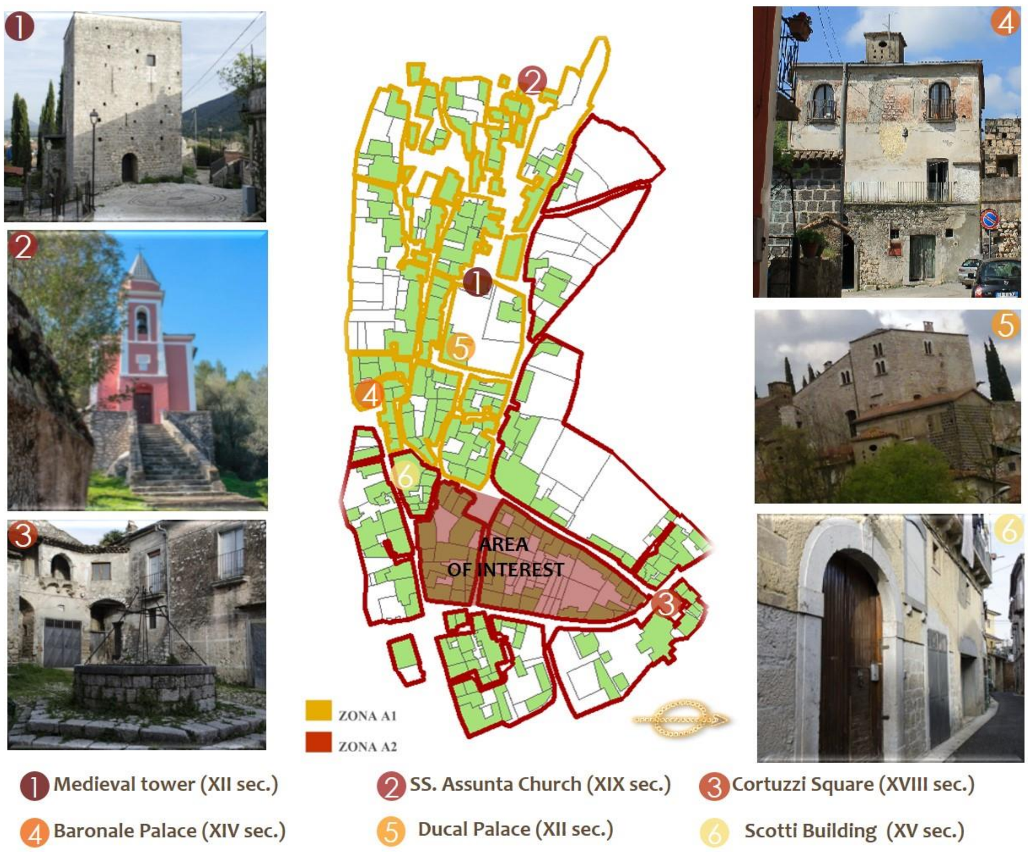



**Figure 1.** The zoning of the municipality of Baia and Latina.

The recommendations are aimed at obtaining an Energy Performance Certificate. However, this is achieved separately from the seismic vulnerability and risk analysis of the inspected built area that is provided in the current study.

Based on information provided by the energetic analysis, cross-referenced with information obtained analysing the economic and social needs of the small centre sited along the Via Francigena, the main research target is the development of rehabilitation interventions planned to improve the conditions of the usability and liveability of urban spaces, the promotion of local culture, and the implementation of the local economy. Finally, the application of an integrated approach to study the seismic vulnerability and damage of the case study area represents another objective of the study.

## 2. Technological Retrofit Design for the Energy Improvements

### 2.1. The Methodological Approach

Even though in Italy there is no legislative obligation to improve the energy performance of Cultural Heritage (2006/311 Legislative Decree), «where the compliance with prescriptions includes an unacceptable alteration of the historical–architectural and/or artistic and/or landscape characteristics», nowadays it is essential in the design approach to evaluate the best technological and design solutions in order to control the energy–environment balance (reducing energy consumptions and maximising passive contributions and those from renewable sources) that is compatible with preservation strategies. However, cultural heritage represents a strategic sector because it consists generally of public buildings with an exemplary role (see art. 5 of 2012/27/EU Directive) that often have a "widened" use for a significant number of stakeholders. This kind of heritage also enjoys the protection and conservation of historical–architectural features that drastically limit the types of design actions that can be implemented.

Moreover, according to Art. 3 of the 2005/192 Legislative Decree as amended by 2013/90 Law, only buildings are excluded from the application of the decree (falling under the type referred to in Art. 136, paragraph 1, letters b) and c) of the 2004/42 Legislative Decree) for which compliance with the requirements implies a substantial alteration of their historical, artistic, and/or landscape profiles. This means that in these buildings, the law still somehow leans towards the possibility of pursuing energy-efficiency objectives by identifying technological solutions that are compatible with the needs of conservation of the asset. Consequently, the need for energy and environmental sustainability also emerges clearly from integrated contracts in which, pursuant to art. 83 of the 2006/163 Legislative Decree and subsequent amendments and additions, the award criterion for the most economically advantageous offer often rewards the best quality/price ratio and introduces, among the relevant criteria, environmental characteristics and the containment of energy consumption (integration of 2007/113 Legislative Decree). Therefore, retrofitting historical building heritage in order to improve its energy performance requires an integrated approach that is compatible with the objectives of safeguard and valorisation [12].

In accordance with the provisions of the 2010/31/EU Directive and Italian 2013/90 Law and 2015/06/26 Ministry Decrees, integrated conservation is achieved by: rethinking the energy systems integrated into the roofs; re-reading the thermohygrometric characteristics and behaviour of both opaque (roofs, ground floors, and perimeter walls) and transparent (window frames) envelopes in an ecologically appropriate manner; and favouring the use of "cradle to cradle" materials in the utmost respect of local building traditions.

Moreover, the UNI EN 16883:2017 standard "Preservation of the Cultural Heritage–Guidelines to improve the energy performance of the historical buildings" evaluates energy performance improvement interventions according to a procedure based on the investigation, analysis, and documentation of the building. It appraises the impact of interventions according to the preservation of construction elements (assessment of past and present uses and future intended use) through mapping the technical structure of the building, representing the conditional and environmental influences, and evaluating the energy performance and quality of the indoor environment.

The standard follows the assumption that the design of "Energy Renovation", before being a transformation tool, is a knowledge instrument [13,14].

Building renovation for a new performance, or simply for a better performance, requires not only a creative interpretation of architecturally unexpressed spatial potentialities, it also examines control of the material and energy fluxes, either prevented or too generously allowed, for a deep search of a balance between innovation and preservation, as well as comfort and efficiency. The methodological approach of the need–performance type investigates the cause–effect links of the deterioration/alteration found. It finds out the minimum cogent requirements and studies the technological potentiality of the different types of buildings in order to prevent degenerative phenomena that may compromise the historical and physical integrity of the built heritage. Moreover, it proposes feasible and efficient improving solutions for thermal, visual, and acoustic comfort, as well as air quality [15].

The energetically friendly retrofitting design foresees the application of different eco-oriented technological solutions that are harmoniously integrated to realise a linguistic-formal, and functional unit. The evaluation of the energy performance weaknesses of the building system, through a specialised software support, represents a starting point for the elaboration of the retrofit design.

In such a context, the governing bodies (local authorities) play a role that is not only controlling, but also exemplary for the promotion of energy efficiency and the use of renewable energy sources in their territories in order to prevent the degradation and abandonment of the cultural heritage and allow the socio-economic tissue to take the available development opportunities.

### *2.2. The Case Study: Technology Analysis and Energy Optimisation*

The renovation case of the hamlet of Baia and Latina (district of Caserta) fulfils the need of having material and functional efficiency for constructions, consolidating the structures, planning anti-seismic interventions, adjusting the installation systems, giving energy and environmental quality to the built heritage, and integrating innovative technologies [11]. In fact, in this case study, great importance to the improvement of the energy and environmental performances has been given through conscious and suitable choices of technological solutions, which have been configured as a real added value. Knowledge of the best technological solutions for the improvement of a building's energy performance must be coordinated with an evaluation of the best structural solutions for the improvement of the seismic performance of the building in order to plan a retrofit work design that responds simultaneously to the two indicators of efficiency.

From the energetic point of view, the municipality of Baia e Latina is located in climate zone C. The energy improvement was addressed from a methodological point of view that examined the maximisation of free solar gains and the energy performance of existing envelopes [11]. The first evaluation concerns the study of the conditions of exposure to the sun during the two yearly solstices (Figure 2), in order to verify the quantity of the envelope that is directly sunny and consider whether it is advisable to treat the external surfaces with finishes of light (absorption factor 0.3), medium (AF = 0.6), or dark (AF = 0.9) colour.

The diagnosis method, starting from the energy audit through the building system analysis (above all of the envelope) and the evaluation of the energy imprint of the construction, redesigns the whole system or some of its parts under the energetic point of view.

This method enables the examination of the behaviour of the building installation system, according to different parameters (envelope performances, installation system efficiency, real energy consumptions from direct users, outdoor environment conditions, indoor comfort levels, integration with active and passive solar systems) until the energy requirements of the whole system under standard use conditions are determined.

The assessment of the energy quality of the building heritage on a territorial scale, considering the time of construction, the building density, and the state of conservation, is the precondition for implementing an integrated planning of retrofit interventions on an urban scale (Figure 3).

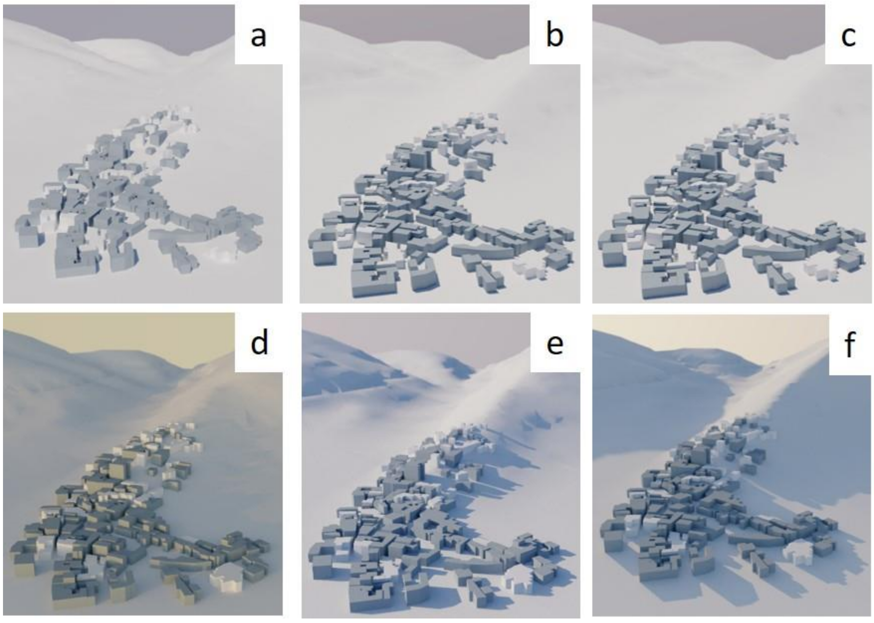



**Figure 2.** Shadow exposure at: (**a**) 21 June at 9:00; (**b**) 21 June at 13:00; (**c**) 21 June at 16:00; (**d**) 21 December at 9:00; (**e**) 21 December at 13:00; (**f**) 21 December at 16:00.

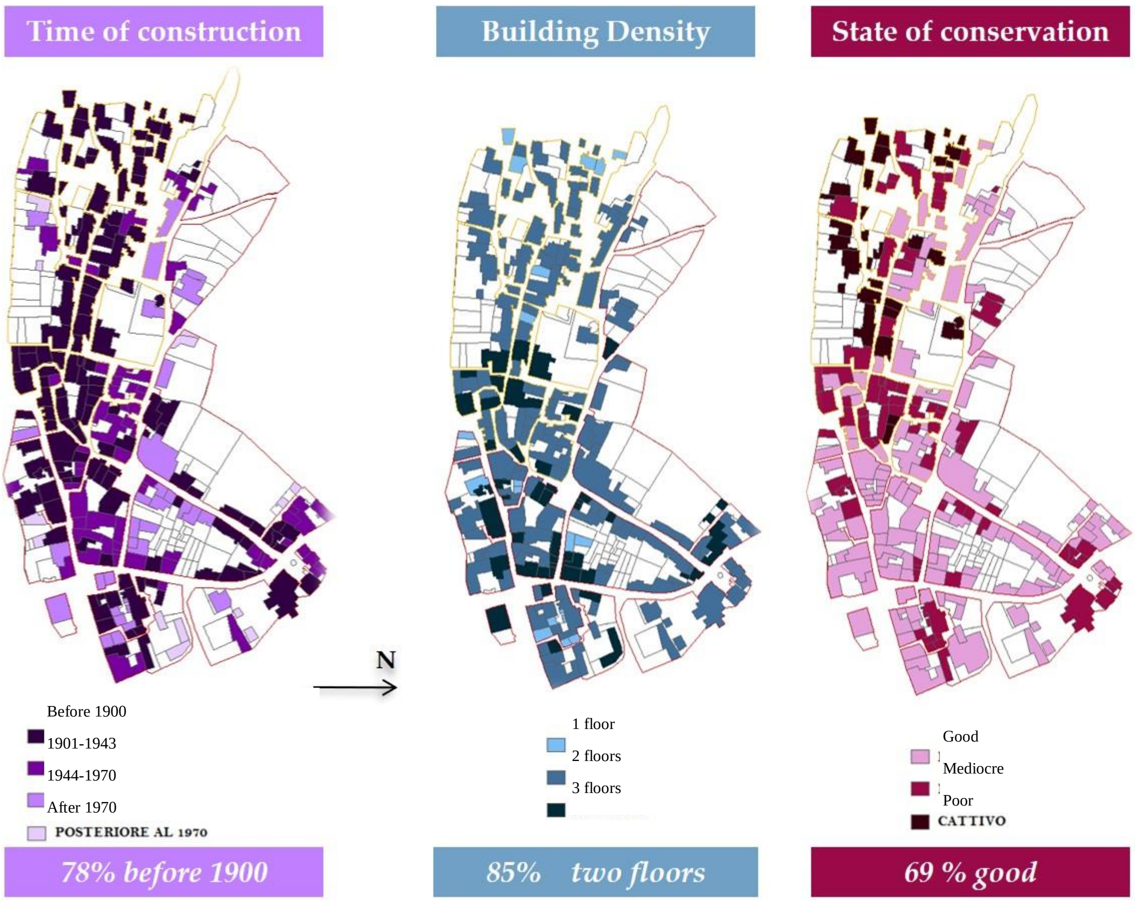



**Figure 3.** Energy quality of the building heritage.

The procedure is supported by simulations of the building energy performance carried out by evaluation methods and computing programs with the aim of evaluating its consumption.

In this work, great attention has been given to the study of the envelope as a combination of design, technological and installation approaches, so that at the same time, it may comply with compositional, structural, and technological requirements in addition to energy, enjoyment, and functional ones. From a more strictly energetic point of view, the standard UNI TS 11300—part I highlights the different factors that are meaningful for the envelope analysis:

(1) dispersions (both horizontal and vertical) from external walls towards unheated rooms, rooms with different temperatures, and the outdoor environment;
(2) dispersions from the transparent components (windows) towards the outdoor environment;
(3) free heating provisions: solar provisions and from indoor emissions.

Control of the thermal energy quantity exchanged by the envelope with the outdoor environment is monitored through the calculation of both the stationary parameters of transmittance ($U < 0.40$ W/m$^2$K in climatic zone C) and surface mass ($M > 230$ kg/m$^2$), and the dynamic parameters of attenuation ($A < 0.10$) and shift ($S \geq 12$ h). Nevertheless, the risk of creating superficial mould and interstitial condensation are tested on the opaque envelope (Figure 4).

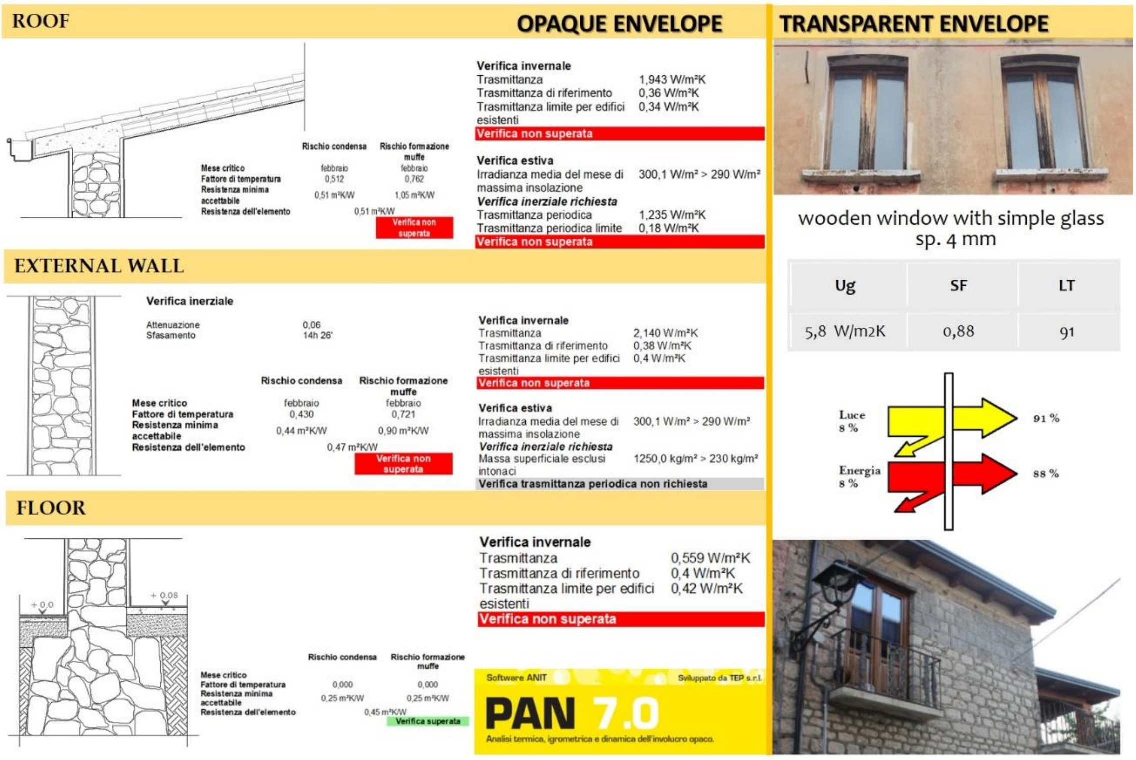



**Figure 4.** Energy performance of existing buildings.

The trend towards an ever-increasing reduction in energy requirements leads to the identification of high-performance materials and components which, in order to be used in historical contexts [16], must be suitable to a resilient level of technological integration, in full compliance with the requirements of the conservation project.

In the retrofit project of a historic building, the assessment of stratigraphy must:

- comply with the limits imposed by the Implementing Decrees of Law 90/2013 (of 26 June 2015), Appendix B, regarding the thermal transmittance requirements for opaque and transparent components;
- comply with the limits imposed by Presidential Decree 59/2009 for periodic thermal transmittance, and limit energy requirements for cooling, in order to ensure summer comfort;

- verify the equivalent solar area (solar radiation control on transparent envelope);
- verify and, where possible, encourage natural ventilation.

In many cases, the requirement of thermal transmittance is not satisfied because it is impossible to install outside the thermal insulation. Even internal insulation with counter walls is incompatible with the presence of vaulted rooms.

The massive walls of historical buildings generally guarantee a good level of attenuation and shift, but not always of transmittance, which must be reduced with the integration of a breathable insulating layer. The natural fibre material, both organic (such as cork, cellulose, sheep wool, etc.) and inorganic (such as expanded vermiculite or perlite used for thermoinsulating plaster) are open-cell structured and extremely compatible with the thermohygrometric behaviour of the traditional brickwork [15].

The technological innovation proposes thermoreflecting and vacuum insulators that are advantageous for their reduced thickness with respect to other materials with the same performances.

Notwithstanding the advantages above, they are limited by a poor facility to equip walls, if set internally, and their minimum breathability, which has the effect of a barrier to steam.

The roof is the part of the envelope that is mostly subjected to physical and mechanical stresses due to atmospheric agents, solar radiation, rain, and wind. Within the evaluation of the energy performances in summertime, they are the technological element that is mostly involved in the direct solar radiation, and therefore responsible for the thermal accumulation. Therefore, for such systems, the proposal is oriented towards the creation of insulated and windy roofs, as they limit accumulated heat transmission towards the indoor space with a preventative approach, without substantial change to the building features.

The choice of insulating materials is determined by the requirements of lower conductivity to minimise the necessary thickness. Technological research offers high-performance materials, such as nanotechnologies that combine the Aerogel™ of amorphous silica with reinforced fibres to provide a product with extremely high energy performance, breathability, and thermal conductivity $\lambda = 0.013$ W/mK at 10 °C. However, in many cases, the only compatible intervention is the application of thermal insulating plaster, which guarantees adequate performance, even with a few centimetres of thickness, if applied on both sides of the wall (exterior and interior).

The simplest interventions concern the roofs and the floors on the ground, for which high performances are generally possible.

The current roof conditions of copper roof tiles develop transmittance values higher than 1.5 W/m$^2$K. All of the significant energy parameters have performances that do not comply with the normative standards (periodic thermal transmittance, attenuation, and thermal phase shift).

In order to comply with the regulatory requirements established for the two-year period 2019–2021 for existing buildings, and remain consistent with the rules dictated by the local Master Plan, the use of insulated and ventilated roofs is suggested, which are optimal technological solutions to ensure an appropriate performance in both winter (insulation) and summer (ventilation) conditions. In addition, an insulated and ventilated roof is recommended in the presence of condensation.

Comparing insulated and ventilated roofs with copper tiled roofs, positive results include the stationary transmittance value of 0.299 W/m$^2$K, the periodic thermal value of 0.08 W/m$^2$K, an attenuation of 0.19, and a phase shift of 12 h 40′. If there is no interstitial condensation, an insulated, non-ventilated covering is recommended. In this case, the stationary transmittance value is 0.28 W/m$^2$K, periodic thermal transmittance 0.02 W/m$^2$K, attenuation is 0.06, and phase shift is 19 h 20′.

In order to improve the winter energy performance, the most commonly used strategy is the integration of one or more layers of thermal insulation to the envelope in a way that is compatible with its construction characteristics and especially with the type of finishes (moulding, pilaster, frame, etc.).

Research has shown that the integration of 10 cm of thermal insulation with a stone wall structure of about 60 cm reduces the value of stationary thermal transmittance from 2009 W/m$^2$K to 0.276 W/m$^2$K, increasing the thermal phase shift to over 18 h and maintaining almost unchanged values of attenuation and periodic thermal transmittance (Table 1). For the historical village of Baia e Latina (CE), it is possible to hypothesise a significant energy renewal of the urban building heritage as a whole, improving the performance of roofs and vertical perimeter walls with very basic and cost-effective technological solutions [17,18]. In reality, the most difficult parameter to improve is the share of renewable energy produced by increasingly efficient technical plants, which are designed and built so as to ensure compliance with the coverage of 50% of expected consumption for domestic hot water, heating, and cooling through the use of systems from renewable sources.

**Table 1.** Energy performance of different types of thermal insulation with a stone masonry of 60 cm.

| Thermal Insulation | Transmittance | Periodic Transmittance | Attenuation | Thermal Phase Shift |
|---|---|---|---|---|
| **Thickness: 10 cm** | **[W/m$^2$K]** | **[W/m$^2$K]** | **[n]** | **[h]** |
| Without insulation | 2009 | 0.088 | 0.044 | 16 h 21′ |
| Stone wool panel (density 40 kg/m$^3$) | 0.298 | 0.004 | 0.012 | 18 h 26′ |
| Wool glass panel (40 kg/m$^3$) | 0.276 | 0.003 | 0.012 | 18 h 30′ |
| EPS S sintered expanded polystyrene panel (40 kg/m$^3$) | 0.334 | 0.004 | 0.012 | 18 h 45′ |
| EPS S sintered expanded polystyrene panel with improved thermal conductivity through reduction of heat radiation transmission (30 kg/m$^3$) | 0.283 | 0.003 | 0.012 | 18 h 30′ |
| PSE in slabs made from blocks (30 kg/m$^3$) | 0.334 | 0.004 | 0.012 | 18 h 19′ |

## 3. Analysis Criteria for Seismic Vulnerability and Damage Assessment of Historical Centres

The problem of the seismic assessment of historical centres [19–26], which are the testimony of building art and culture over the centuries, has always been a concern for the scientific communities in the structural engineering and cultural heritage conservation and protection fields. Historical centres are usually composed of building aggregates made of different structural units placed in continuity with each other and sharing common walls. The possible interactions resulting from their structural contiguity, together with the presence of both staggered floors and discontinuities in elevation among buildings, should be taken into account.

Nevertheless, several previous studies [10,27,28] examined the behaviour of isolated structural units, rather than that of entire aggregates, without considering the interactions among buildings under earthquakes. Therefore, it is of a fundamental importance to identify preliminarily the Structural Units (S.U.) of the aggregate in order to properly assess the actions deriving from staggered floors and adjacent walls of near constructions, as well as those generated by vaults, arches, or tie rods belonging to neighbouring buildings.

During seismic events, masonry buildings, according to their characteristics, can undergo local or global collapses. Two different types of failure mechanisms, namely first-order mechanisms (overturning, vertical arch effect, horizontal arch effect, and corner overturning as the main failures) and second-order ones (diagonal shear, sliding shear, and compression–bending) can be identified. Generally, the first mechanisms occur when connections among structural parts are not effective, whereas the latter ones are detected when the building has a box-like behaviour and shows global failures. Therefore, large-scale seismic vulnerability assessment methods of masonry buildings within historical centres should consider both these failure mechanism types.

With reference to the global behaviour of building aggregates, the basic methodology for isolated masonry buildings developed in Benedetti and Petrini [10] has represented the starting tool for the elaboration of a novel quick evaluation form that has been appropriately considered for the structural units of historical centres. This new form is the result of adding five new parameters to the basic 10 of the original survey form [10], taking into account seismic interaction effects among structural units [29,30]. The new additional parameters appear with italic characters in Table 2.

Four scores $s_i$ (from A, minor, to D, major) are used to describe the vulnerability classes of each parameter, whereas the weight $w_i$ (ranging from 0.25 to 1.50) represents the importance of the parameter in quantifying the building's vulnerability.

The different classes defined for each of the five parameters added to the original vulnerability form correspond to the conditions illustrated in Figure 5.

In order to achieve a form that is totally homogeneous with the original one, scores and weights assigned to these five additional parameters have been numerically calibrated on the basis of the results of specific numerical parametric analyses on several masonry aggregates.

Such analyses were performed by the 3MURI non-linear numerical software (S.T.A. DATA: Torino, Italia), which uses the Frame by Macro Elements (FME) computational method [31]. For each new parameter, several numerical pushover analyses have been performed in order to reproduce different boundary conditions among adjacent structural units contemplated in the survey form.

**Table 2.** The new vulnerability form for masonry building aggregates.

| Parameter | Class Score (s) | | | | Weight (w) |
|---|---|---|---|---|---|
| | A | B | C | D | |
| 1. Organization of vertical structures | 0 | 5 | 20 | 45 | 1 |
| 2. Nature of vertical structures | 0 | 5 | 25 | 45 | 0.25 |
| 3. Location of the building and type of foundation | 0 | 5 | 25 | 45 | 0.75 |
| 4. Distribution of plan resisting elements | 0 | 5 | 25 | 45 | 1.5 |
| 5. In-plane regularity | 0 | 5 | 25 | 45 | 0.5 |
| 6. Vertical regularity | 0 | 5 | 25 | 45 | 1 |
| 7. Type of floor | 0 | 5 | 15 | 45 | 1 |
| 8. Roofing | 0 | 15 | 25 | 45 | 0.75 |
| 9. Details | 0 | 0 | 25 | 45 | 0.25 |
| 10. Physical conditions | 0 | 5 | 25 | 45 | 1 |
| *11. Presence of adjacent buildings with different heights* | *−20* | *0* | *15* | *45* | *1* |
| *12. Position of the building in the aggregate* | *−45* | *−25* | *−15* | *0* | *1.5* |
| *13. Number of staggered floors* | *0* | *15* | *25* | *45* | *0.5* |
| *14. Structural or typological heterogeneity among adjacent structural units* | *−15* | *−10* | *0* | *45* | *1.2* |
| *15. Percentage difference of opening areas among adjacent facades* | *−20* | *0* | *25* | *45* | *1* |

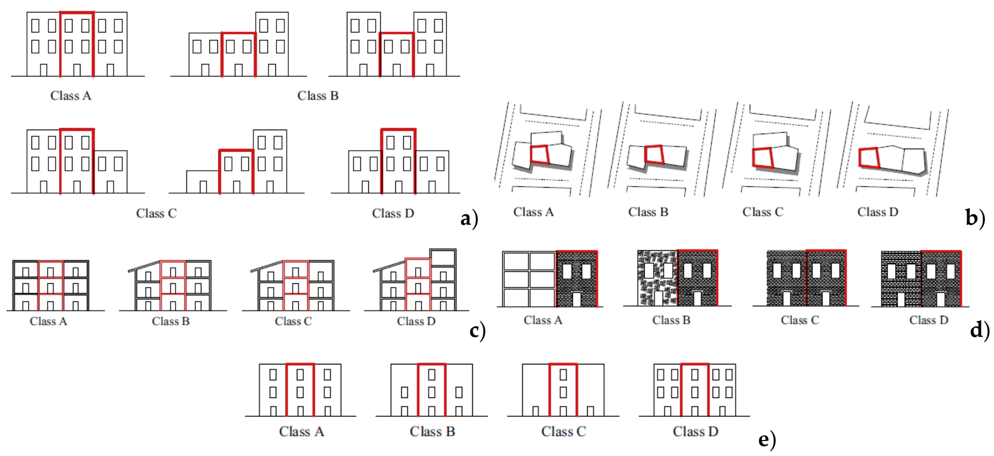



**Figure 5.** Vulnerability classes associated to the parameters of in-elevation interaction (**a**), plan interaction (**b**), staggered floors (**c**), structural heterogeneity (**d**), and opening areas (**e**).

Scores have been therefore determined so that the difference among the indexes associated with the different classes of each parameter is proportional to the difference among the corresponding mechanical vulnerability index values obtained in the analyses performed in the most severe direction. In particular, negative scores have been introduced in the new form in order to take into account the positive effects deriving from the aggregate condition.

For weight assignment, as a first step, the absolute value maximum differences among vulnerability indexes related to the several classes of each parameter have been considered. Subsequently, weights have been assigned to each new parameter proportionally to these differences, and finally, they have been homogenised with the original forms.

After assigning a class to each parameter, the vulnerability index $I_{V,I}$ is calculated as follows:

$$I_{V,I} = \sum_{i=1}^{10} s_i \cdot w_i, \quad (1)$$

The vulnerability index $I_{V,I}$ assumes values within the range $[-125.5 \div 526.5]$.

Later on, since the vulnerability index does not give information about the damage level caused by earthquakes, a deterministic correlation based on previous studies [32] can be used to evaluate the mean damage grade ($\mu_D$) of aggregated S.U. on the basis of the following exponential expression:

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{S + 6.25 \cdot V_I - 13.1}{Q}\right)\right] \quad (2)$$

where:

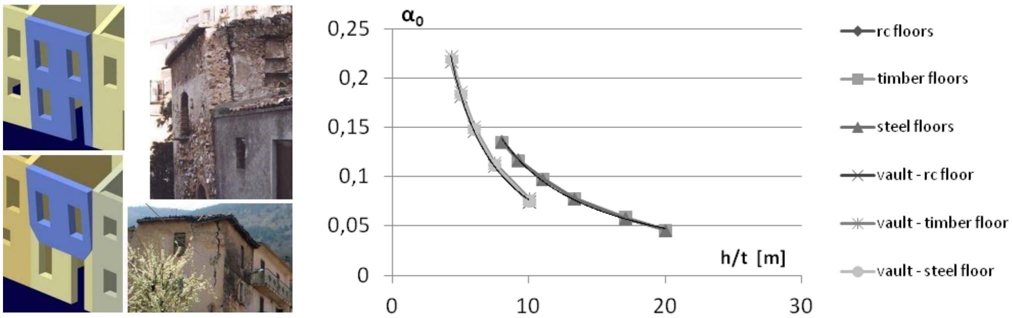
- $\mu_D$ is the mean damage grade;
- $Q$ is the ductility factor, equal to 2.3;
- $S$ is the macroseismic intensity, calculated on the basis of both the earthquake magnitude and the epicentre distance according to a given attenuation law [33];
- $V_I$ is the normalized vulnerability index, framed within the range [0–1], that can be achieved from the $I_{V,I}$ one through the procedure specified in Formisano et al. [30].

Therefore, the variation of both the seismic intensity and the distance of the seismic source from the town centre allows plotting different damage maps, which are useful forecasting tools for predicting the damages suffered by buildings so as to easily manage post-earthquake emergency and address the financial resources that are necessary for priority retrofitting interventions.

On the other hand, with respect to the local behaviour of building aggregates, the most significant failure mechanisms of masonry walls are identified. These mechanisms are primarily connected to disconnections among walls, which are usually caused by seismic actions, and identify macro elements that are susceptible to collapse from instability.

The most recurrent out-of-plane failure mechanism, namely the wall overturning, can be evaluated for masonry S.U. of historical centres on the basis of the principle of virtual work, which provides the collapse load multiplier $\alpha_0$ activating that mechanism. Based on the previous research activity illustrated in Formisano et al. [34], these multiplier factors were determined for several masonry walls, belonging to buildings with one to three storeys, by considering the variability of input data (mechanical properties of the masonry, wall thickness, number of floors, storey height, geometry of openings, and type of floors). As an example, these multipliers related to the building with two storeys have been plotted as a function of the wall slenderness (h/t) in Figure 6.

With reference to the overturning mechanism of structural unit masonry walls, the collapse load multipliers, representing their capacity accelerations, are determined first. Later on, the demand accelerations due to the earthquake expected in the historical centre site are computed for those walls. Finally, by comparing capacity accelerations with demand ones, the safety checks of masonry walls towards the investigated collapse mechanism can be done and, therefore, the most dangerous situations can be determined.




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

**Figure 6.** Multipliers related to the building with two storeys: (**a**) overturning mechanisms, (**b**) design chart for collapse load multipliers assessment of two-storey buildings.

## 4. The Case Study of Baia e Latina: Guidelines for a Sustainable Plan Action

### *4.1. Historical and Geographic News*

The analysis of seismic and energy renovation has been applied on the historical centre of Baia, which is part of the town of Baia e Latina. Baia e Latina is a small Campania town with less than 2200 inhabitants in the Alto-Medio Volturno plane. It is a small community that retains the typical cultural and historical features of its own rural tradition. The origins of Baia e Latina are very ancient and uncertain. Among the most accredited theories about the origin of two cities, it is believed that Baia was an Etruscan settlement, and in Latina it was a Latin legion's camp. The origin of the unified hamlet of Baia e Latina dates back to French domination (1806–14). The historic centre of Baia is one kilometre long and encompasses more than 150 buildings. It lies on the boundary of the hills of the Monte Maggiore chain.

The settlement mostly retains its 15th century structure. The building settlement of the historical centre is located along the west–east direction towards the shrine of Maria S.S. Assunta (Figure 7). The three main longitudinal roads (Via Biondi, Via PortaFerrata—Via Sopportico, Via Marconi—Via Vicinato) are connected by stairs, paved areas, porticos, and arches. The northernmost part of the historical centre is connected to the remaining part through Via Cortuzzi and Corso Italia. This consisted originally of a pattern of linear streets following the same parallel direction, which were broken by orthogonal roads. During the centuries, the original road apparatus was enriched with new directions of development and new streets. Among the architectures of greater interest in the historic centre, there are: the Norman tower, the S.S. Assunta shrine, the baronial palace with the dovecote tower, and piazza Cortuzzi with its respective baronial palace. The study area covers urban areas A1 and A2 of the 2008 PRG Variation. For these areas, the interventions allowed are those provided for in the Recovery Plan approved by C.C. n. 119 of 30/12/1988, and no. 26, dated 28/06/1991, and drawn up in accordance with art. 28, Law 457/78 and art. 29 Law 219/81.

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

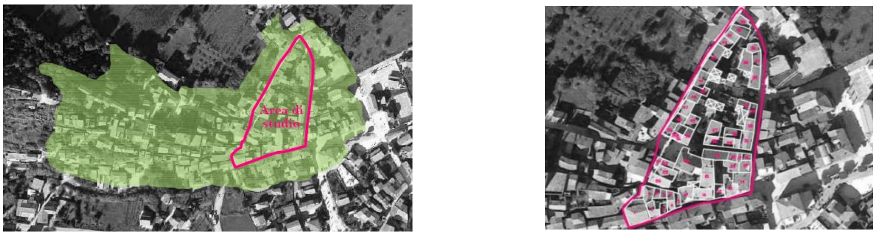
**Figure 7.** Panoramic view of Baia: (**a**) historical centre, (**b**) satellite view with recognition of streets.

## *4.2. Vulnerability, Damage Analysis, and Seismic Retrofitting*

An area of the historic centre has been identified, featuring 53 structural units (Figure 8). They have almost homogeneous features from a structural and typological point of view.

Load-bearing vertical structures and foundations are made of local calcareous stones, while steel–hollow tile floors and timber floors make the horizontal structures.

The new vulnerability form for masonry building aggregates has been utilised to evaluate the seismic behaviour of inspected structural units [29,30]. For each parameter, after its class has been identified, the related score is multiplied by its weight. Therefore, by computing the sum of scores thus obtained, the vulnerability index of each of all the 53 structural units is defined (Figure 9).




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

**Figure 8.** Baia: (**a**) recognition of study area, (**b**) recognition of structural units.

Magnitude (4, 5, and 6) and epicentre distances (5 km, 10 km, 15 km, 20 km, 25 km, and 30 km) have been chosen as a range of analysis for damage mapping. Starting from the knowledge of the earthquake magnitude, the macroseismic intensity is calculated by applying the formula provided in Sabetta and Pugliese [33]. Subsequently, the average degree of damage in each structural unit investigated is referenced to the damage ranges given in the EMS-98 scale [35]. By combining the different epicentre distances with the different magnitude values, 18 scenarios of damage are identified.

Damage ranges have been defined with an individual colour in order to map the study area. Colours used are:

- green for D1 damage condition (no damage) with $0 < \mu_D \leq 0.2$;
- blue for D2 damage condition (moderate damage) with $0.2 < \mu_D \leq 0.4$;
- yellow for D3 damage condition (intense damage) with $0.4 < \mu_D \leq 0.6$;
- magenta for D4 damage condition (extended damage) with $0.6 < \mu_D \leq 0.8$; and
- red for D5 damage condition (collapse) with $0.8 < \mu_D \leq 1$.

| S.U. | $I_v$ |
|---|---|
| 1 | 70.5 |
| 2 | 124.25 |
| 3 | 88 |
| 4 | 101.75 |
| 5 | 100.75 |
| 6 | 68.25 |
| 7 | 67 |
| 8 | 67 |
| 9 | 80.5 |
| 10 | 119.5 |
| 11 | 150.75 |
| 12 | 69.5 |
| 13 | 102 |
| 14 | 119.25 |
| 15 | 108.25 |
| 16 | 130.75 |
| 17 | 103.25 |
| 18 | 104.5 |
| 19 | 102 |
| 20 | 137.5 |
| 21 | 102 |
| 22 | 125.75 |
| 23 | 118 |
| 24 | 208 |
| 25 | 127 |
| 26 | 144.5 |


| S.U. | $I_v$ |
|---|---|
| 27 | 87 |
| 28 | 64.5 |
| 29 | 80.75 |
| 30 | 105.75 |
| 31 | 89.25 |
| 32 | 129.25 |
| 33 | 69.25 |
| 34 | 99.25 |
| 35 | 83 |
| 36 | 79.25 |
| 37 | 65.75 |
| 38 | 73.25 |
| 39 | 164.5 |
| 40 | 162 |
| 41 | 78 |
| 42 | 58 |
| 43 | 54.25 |
| 44 | 51.75 |
| 45 | 110.5 |
| 46 | 106.75 |
| 47 | 94.25 |
| 48 | 114.25 |
| 49 | 126.75 |
| 50 | 114.25 |
| 51 | 213.25 |
| 51b | 153 |
| 52 | 79.25 |

**Figure 9.** Summary table of vulnerability indexes and photos of some investigated structural units.

Figures 10–13 show some of the 18 damage maps. It is highlighted that increasing magnitude, at the same epicentre distance, corresponds to an increase in buildings that suffer serious damage, just as the increase in epicentre distance reduces the number of extremely damaged buildings. The buildings that develop the most damage are especially those that have a poorer planimetric interaction and a more irregular distribution of in-plan resistant elements. From the maps, it is apparent that the most damaged buildings, which are located in the lower part of the study area, are the most ancient ones, and have not been subjected to retrofitting interventions to improve their seismic behaviour.


**Figure 10.** Damage maps: (**a**) E.D. = 5 km and M = 4; (**b**) E.D. = 5 km and M = 5; (**c**) E.D. = 5 km and M = 6.


**Figure 11.** Damage maps: (**a**) E.D. = 10 km and M = 4; (**b**) E.D. = 10 km and M = 5; (**c**) E.D. = 10 km and M = 6.

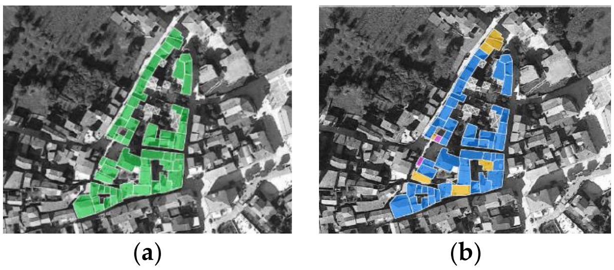



**Figure 12.** Damage maps: (**a**) E.D. = 20 km and M = 4 and 5; (**b**) E.D. = 20 km and M = 6.


**Figure 13.** Damage maps: (**a**) E.D. = 30 km and M = 4 and 5; (**b**) E.D. = 30 km and M = 6.

Further analysis conducted is related to the activation of the overturning mechanism related to walls in buildings belonging to the study area. These analyses, together with those related to the kinematics of the main complex of masonry walls, should be taken into account when thrust effects due to roofing are not reduced or eliminated.

Calculations of both the demand accelerations (PGA) and the collapse load multiplier ($\alpha_0$) of the inspected masonry walls are plotted in Table 3.

**Table 3.** Walls overturning checks for E.D. = 5 km and variable earthquake magnitudes.

Overturning mechanism INACTIVE (green)
Overturning mechanism ACTIVE (red)

| S.U. | $\alpha_o$ | PGA M = 4 | | PGA M = 5 | | PGA M = 6 | |
|---|---|---|---|---|---|---|---|
| **1** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **2** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **3** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **4** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **5** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **6** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **7** | 0.339 | | INACTIVE | | INACTIVE | | ACTIVE |
| **8** | 0.339 | | INACTIVE | | INACTIVE | | ACTIVE |
| **9** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **10** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **11** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **12** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **13** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **14** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **15** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **16** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **17** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **18** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **19** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **20** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **21** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **22** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **23** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **24** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **25** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **26** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **27** | 0.339 | **0.209** | INACTIVE | **0.284** | INACTIVE | **0.386** | ACTIVE |
| **28** | 0.339 | | INACTIVE | | INACTIVE | | ACTIVE |
| **29** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **30** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **31** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **32** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **33** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **34** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **35** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **36** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **37** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **38** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **39** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **40** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **41** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **42** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **43** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **44** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **45** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **46** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **47** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **48** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **49** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |
| **50** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **51** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **51b** | 0.261 | | INACTIVE | | ACTIVE | | ACTIVE |
| **52** | 0.301 | | INACTIVE | | INACTIVE | | ACTIVE |

The evaluation of the activation of the simple overturning mechanism is carried out for the six different epicentre distances (5 km, 10 km, 15 km, 20 km, 25 km, and 30 km) and the three earthquake magnitudes (4, 5, and 6). Table 3 presents the results of the evaluation for the 5-km epicentre distance and earthquake magnitude variables from 4 to 6. In this table, green represents satisfied checks, while red represents unsatisfied ones.

The results obtained from the study of the collapse mechanism can be compared with the results of the damage maps. The overturning mechanism is especially active for taller buildings, which in most cases correspond to those more vulnerable and more likely to develop damage. The realisation of damage maps and the study of failure mechanisms allow the identification of areas of building heritage where a seismic event can develop major damages [36,37]. This can guide the municipality administration towards the implementation of retrofitting interventions performed before or after the seismic events [38].

This result can be considered as a useful tool for civil protection, as well as for the local administrative authorities, as a support for:

- planning and management of emergency response in the municipal area;
- definition of municipal-wide thematic charts where, depending on the magnitude and the epicentre distance, it is possible to program certain interventions according to the damages scenarios;
- location of interventions in the drafting of urban planning tools for the improvement of the quality of the existing building stock;
- enhancement of infrastructure and services on the ground, depending on their vulnerability;
- development of an integrated energy–seismic retrofit programme for urban habitats [39].

## 5. Conclusions

"Knowing to Retrieve" is the guiding principle of this study, targeting the application of a multifaceted analysis for the recovery of a small hamlet. Versatility, i.e., the ability to serve a number of purposes (example: private information on improving the quality of the building park, addresses for public administration on localisation of areas where interventions can be foreseen, etc.) is the result of conducting investigations that begin from the territorial scale to the single building, but above all by the combination of different fields of research: territorial, building park stock, seismic, and energy. In the current paper, energy analysis on the urban hamlet of Baia e Latina has first been performed and, based on the achieved results, effective retrofitting interventions have been foreseen. Subsequently, a seismic vulnerability and damage analysis based on an integrated quick evaluation method has been carried out by executing local and global-scale analyses. The analysis results have demonstrated the high vulnerability towards seismic actions of the investigated urban habitat.

The acquired results can be considered as useful tools for the civic protection department, as well as for the local administrative authorities, to support planning and managing emergency responses in the municipal area, as well as organising interventions according to the damage scenarios, in order to improve the quality of the existing building stock and enhance infrastructures and services.

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