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An energy retrofitting methodology of Mediterranean historical buildings

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Abstract

Purpose – The purpose of this paper is to develop and discuss a methodological approach for energy assessment and retrofitting of envelope systems in Mediterranean historical buildings, in order to ensure the desirable balance between improvement requirements and preservation principles.

Design/methodology/approach – The methodology is based on the assessment of historical districts at the site, building and component scales, the development of energy models of building-types that are highly representative, in terms of materials, construction techniques, typologies and performances, the identification of intervention priorities and the validation of compatible retrofitting solutions.

Findings – The methodology, applied to a representative Adriatic sea town in South Italy, shows the potentialities of innovative materials and technologies (aerogel, PCMs, etc.) as tools to achieve the improvement of the energy performances and the preservation of the original characters. Nevertheless, it shows how the preliminary qualification of the environmental, architectural, constructional and technological characteristics is paramount to support the identification of the current behavior of the building system and the transformation boundaries from the historical values.

Originality/value – The paper proves how assessment and intervention methods and tools, besides effective, compatible, low invasive and durable, should be geocluster oriented and performance based, thus with general reliability for the whole local context and suitable flexibility to be tailored to different specific situations, toward the definition of retrofitting micro-scale measures and macro-scale strategies that are replicable and scalable.

Keywords Energy assessment and retrofitting, Historical buildings, Innovative and compatible solutions

Paper type Research paper

1. Introduction

Due to the increasing energy consumptions in the building sector at international level, the European Community has been moving toward the definition of guidelines – among them the Energy Performance Building Directive 2002/91/EU, recently recast by the Directive 2010/31/EU – in order to establish specific targets and standards toward the 2020 goal of nearly zero energy buildings.

The focus lies on the residential sector, which is responsible for the greatest impact on the global consumption of the community, according to data provided in 2014 by the Energy Efficiency Action Plan of the European Community. Consequently, the development of different platforms has been promoted for energy data gathering and management concerning the residential sector with the aim to provide technicians and professionals with all the useful information for the implementation of new strategies at the macro-scale.

The EC regulations concern not only new constructions but also the existing building stock that covers about 60 percent of the EU territory. However, that stock can be distinguished in reinforced concrete buildings, which can be easily adapted by on-market energy retrofitting products and techniques, as well as the traditional

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building heritage, including historical buildings, which represent the historic, artistic and cultural identity of cities and societies and, thus, are less flexible to transformation (Della Torre *et al.*, 2010).

Such a difficulty has not been overcome by the current practice to waive the energy requirements in order not to alter the cultural values, in accordance with the principles of conservation of the historical-architectural heritage. However, this gap has led all the European research community to define pilot projects, with the purpose of defining best practices for energy retrofits of public and private historic buildings, as well as for training of technicians and public administrations. European projects are GovernEE (Governance in Energy Efficiency), ECO-Culture (Demonstration and dissemination of ECO-concepts for high-performing European cultural buildings), 3ENCULT (Efficient Energy for European Cultural Heritage, 2010-2014) and SECHURBA (Sustainable Energy Communities in Historic Urban Areas) are the evidence of the international effort to deal with such challenging issues.

However, those experiences have been generally referred to North Europe, by focussing on those European countries featured by continental climate and mainly affected by heat loss issues in wintertime. On the contrary, countries in the Mediterranean climate represent an opposite case (Oikonomou and Bougiatioti, 2011; Stazi *et al.*, 2012), where thermal problems are mainly due to very hot summer conditions. Thus, better-established studies in different geo-clusters should not be applied, due to different environmental conditions, as well as different construction traditions and required performances.

In Italy, a few experiences on this topic have been developed. Among them, it is worth mentioning: the research project "Innovative solutions for energy efficiency and micro-production in the existing built heritage," funded by the Italian Ministry of Education, University and Research and carried out by five universities across the country, including the Polytechnic of Bari; ATTESS "Guidelines for energy and environmental improvement of the historical built heritage," promoted in 2010 by the District of Green Building and Cultural Heritage in Veneto Region; and the upcoming publication of the "Guidelines for the efficient use of energy in the cultural heritage" of the Ministry of Heritage and Culture.

Such an interest is consistent with the actual scenario in the Italian construction sector. According to CRESME (Rapporto CRESME, 2009) (Center for Economic Research of the Social Market for Building and Land), in 2006-2013, retrofitting activities increased up to 66 percent of the national production. That is due to a considerable existing building stock, mainly composed of residential buildings – about 61 percent – that were built before the first regulations on energy efficiency in 1976 and count for beyond 50 percent of the national energy consumption. As a result, according to data by ENEA (2014) (National Agency for Energy and Environment), only 2 percent of the existing buildings achieve an energy certification equal to or greater than C (total consumption $< 59\,\mathrm{kWh/m^2}$ per year), considering the building envelope the main cause of heat loss.

The described scenario highlights the difficulty of reconciling the reduction of energy consumption, both wintry and summery, through a system of widespread interventions on the envelope, and preserving its historical values. Therefore, the research aims to define a general methodology, in terms of guidelines for the assessment of the actual energy behavior, the selection and validation of suitable interventions and the management of transformation processes for the building heritage in Mediterranean areas. Special attention will be given to the analysis of new materials which, besides high thermal performances, ensure high flexibility and reversibility to the intervention itself, without compromising the conservation of the matter and the image of the building heritage.

2. Method and tools

In the light of the above-mentioned issues, the proposed methodology includes four macro phases, as follows.

(1) Preliminary assessment, concerning climatic-environmental and cultural-social characteristics of the local site as well as historical-typological features of the built settlement, in terms of:

- morphology and typology, namely building types and relative arrangement;
- geometry, concerning shape and size of building components and functional units, also in relation to the surrounding urban background;
- construction techniques, with reference to thermal, acoustic and optical performances and decay patterns;
- materials, in terms of period of construction, defects, anomalies and residual performances.

That phase results from bibliographic and archivist records for the development of historical evolutions maps, as well as from calculation routines and climatic databases for the simulation of solar radiation, wind exposure and outdoor air temperature and humidity.

(2) Taxonomy and definition of energy models, from collection and storage of preliminary assessment data by GIS tools and WEB-GIS platforms for easy and speedy consultation and correlation of geo-referenced and multi-level information flows. It is worth mention that, along with GIS tools, the acquisition of data featuring buildings could be managed by a building information model as an information-geographical system applied to the building. Such structured databases enable the identification of the most representative building-types within the geocluster. Those building-types can be analyzed as performance-based models, featured by pre-set geometry and aspect of building envelope sub-systems and functional units and by parametric configuration of construction materials and techniques in terms of energy-oriented characteristics (thermal transmittance, optical reflection and so on).

(3) Identification of priorities of intervention based on the cross-assessment of transformation boundaries and improvement requirements. Transformation boundaries result from the identification of a "system of constants," namely the system of features of the buildings that cannot be changed due to their historical and architectural value – e.g., original materials and construction techniques, color and finishing of external surfaces, relationship between solids and voids and between the inner and outer volumes. Improvement requirements follow the assessment of actual energy performances – e.g., energy consumptions, indoor temperatures, thermal flows calculated by transient thermal simulation software tools (McKinley and Mitalas, 1983; Mitalas, 1983) – against normative standards. In detail, analyses were performed by Design Builder, using the EnergyPlus dynamic simulation engine. The software is based on the simplified calculation method, defined as transfer function method or ASHRAE procedure. As boundary conditions, according to UNI 11300:2008, input data concerned four categories: the typological characteristics of the building, the thermal and constructional features of the envelope components, the site climatic data and the occupation profiles. Nevertheless, improvement requirements should be based on

the preliminary analysis of how each performance/component weighs on the energy behavior of the global building system. In fact, it might occur that the fulfilment of normative standards for some performances/components would not produce considerable either/or convenient effects. Thus, according to a performance-based approach, only interventions with high incidence on the final energy and environmental quality would be included as priorities.

Selection and validation of suitable solutions, from the analysis of the most influencing performances/components. The selection is based on the critical comparison of available on-market products and systems with the transformation boundaries, as stated in the previous phase. Such a comparison should ensure that energy retrofitting solutions are technologically, chemically and physically suitable, low invasive, highly performing and quite light, in order to avoid structural overloads (De Fino *et al.*, 2013, 2014). Consequently, specific attention should be paid to innovative materials, even used in different sectors, such as Phase Changing Materials (PCMs) (Shilei *et al.*, 2007; Zhang *et al.*, 2007), Nano Insulation Materials, Vacuum Insulated Panels (VIPs) (Baetens *et al.*, 2010) and Transparent Insulation Materials, like aerogel (Jelle, 2011; Soares *et al.*, 2013; Baetens *et al.*, 2011; Stahl *et al.*, 2012), as well as Thin Film Solar cell and Luminescent Solar Concentrator Cell, still under development and validation for the construction field.

(4) The validation of those systems and technologies should concern, not only technical reliability and durability, but also cost/benefit analysis and life cycle assessment.

3. Case study and results

The proposed methodology has been applied to a representative case study in Mediterranean climate as described below.

3.1 Preliminary assessment

The case study is located in the town of Molfetta, 40 km north from Bari, Apulia Region, South Italy. The Mediterranean climate is featured by hot and dry summer and by cool and rainy winter (Table I).

The historical town was founded in the middle ages and it was developed until the nineteenth century. It is composed of traditional buildings, which did not undergo significant changes throughout modern times. The buildings are made out of local stone masonries and wooden ceilings and they are arranged in NNW-SSE oriented blocks, from 35 up to 50 m, along quite narrow streets. Windows are wide, without balconies (Plate 1) and generally placed on the only external front, shaded by the surroundings. The facades are generally unplastered at the ground floor and plastered at the upper floors (Plate 2).

Two recurring typologies can be found: "tower-houses" with narrow façade on the street – from 3 to 5 m wide – and predominant development toward the inside and "palace-houses," on a single floor, with large façade on the street and openings in all the rooms. Both the typologies are included in buildings with up to five floors, where the ground floor is typically used as small shop with independent entrance. The small shops generally show stone barrel vaults, while the dwellings mostly have wooden ceilings (Plates 3 and 4).

3.2 Taxonomy and definition of energy models

From GIS-based data collection and management, several thematic maps have been developed, in order to analyze and compare the information flows according to a

Table I.
Climate data

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Average max. temperature (°C)	13.6	14.3	16.6	17.9	23.6	27.0	28.9	30.5	25.2	22	20.5	15.1
Average min. temperature (°C)	3.8	2.6	4.2	8.5	11.4	17.6	17.7	20.4	18.9	10.9	8.3	6.2
Average monthly temperature (°C)	8.1	8.7	10.5	13.7	17.6	21.9	24.3	24.3	21.5	16.8	13.5	10.1
Mean direct solar radiation (kW/mq)	0.930	1.728	2.224	3.316	4.803	5.238	5.621	5.182	3.407	2.465	1.338	0.724
Mean diffuse solar radiation (kW/mq)	0.898	1.149	1.767	2.258	1.993	2.281	2.048	1.707	1.729	1.099	0.873	0.900

Source: Author's own

Plate 1.
Window without balcony

Source: Author's own

Plate 2.
Surface treatment of the masonry walls

Plate 3. Wooden ceiling at the upper floor

Source: Author's own

Plate 4. Barrel vault at the ground floor

Source: Author's own

multidisciplinary approach. In detail, the thematic maps concern period of construction, height, typology, envelope thermal transmittance, incident solar radiation. For instance, Figures 1 and 2 represent the building height and the period of construction of the entire historical town.

The development of models based on representative building-types is herein presented for the "tower-house," featured by four floors – with a small store at the ground floor and one dwelling at the upper floors, plan of 4×8 m square per floor,

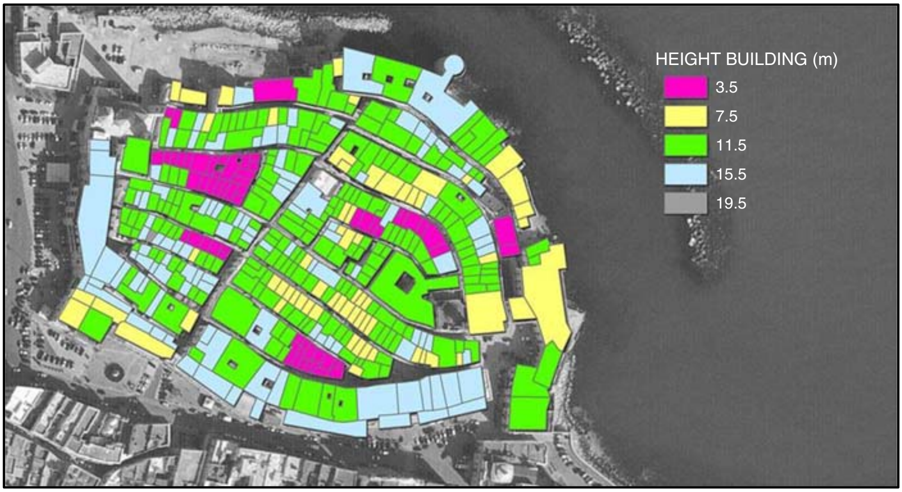

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Figure 1.
GIS elaboration of data on building height

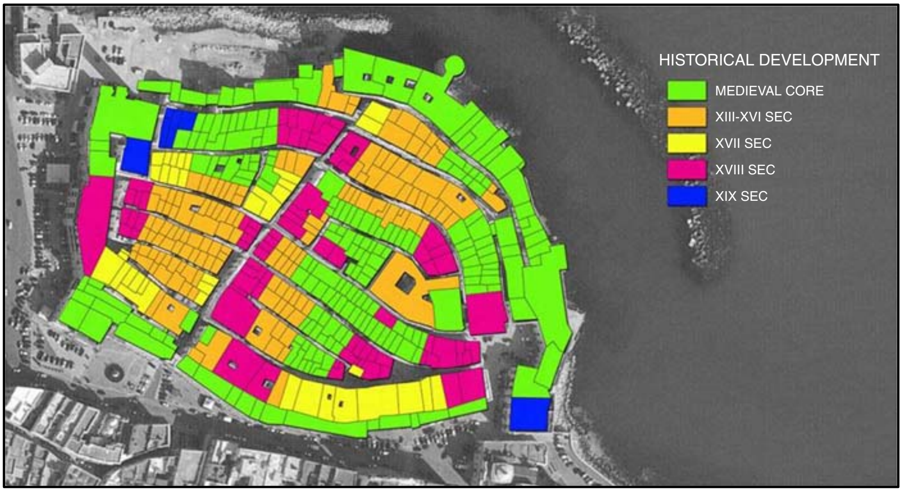

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Figure 2.
GIS elaboration of data on period of construction

SSW-NNE orientation and one façade facing south. As far as the construction characteristics are concerned, the following data was assumed:

(1) The roof is quite thin – about 18 cm – with historical-architectural structure of wooden beams and slab and original stone floor tiles, which require specific attention for treatment, conservation and maintenance.

(2) The walls are typically thick – ranging from 65 up to 100 cm – with two outer leaves with squared blocks and an inner cavity filled by mortar mixtures and natural aggregates. They are unplastered at the ground floor, so that their formal character is quite restraining in terms of transformation (Figure 3).

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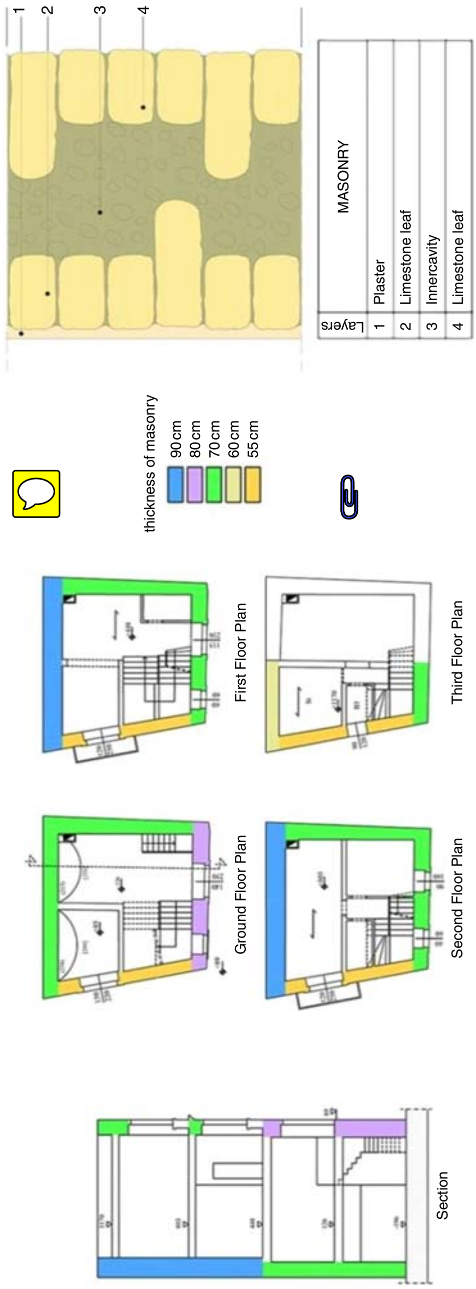

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Figure 3.
Construction characteristics of wall masonries

(3) The windows are narrow compared to the opaque envelope. They are generally not original, with wooden frame and double-glazing. Solar parameters of glass were selected according to data from technical sheets based on the most recurring solutions.

(4) The basement slab is made out of concrete and it is placed above a layer of stone blocks and gravel as barrier against the dampness.

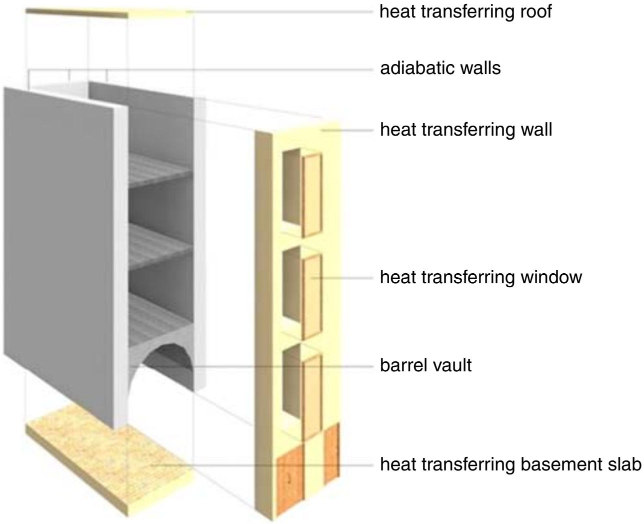
Based on that information, the model has been developed, describing each sub-system undergoing heat transfer toward the outside – roof, walls, windows, basement slab – as a single-material component featured by the equivalent thermal transmittance (Tables II, III and Figure 4).

Sub-system	Thermal conductance (W/mq K)
Wall	2.00
Floor	2.83
Ceiling	1.83
Windows	2.55

Table II. Thermal conductance of each sub-system in the model

Heat transferring sub-system	Extension (mq)	Extension (%)
Floor	32	29
Windows (SSW)	8.22	7
Wall (SSW)	37.78	34
Roof	32	29
Total envelope	110	-

Table III. Geometrical input data of each sub-system in the model



Source: Author's own

Figure 4. Sub-systems undergoing heat transfer toward the outside

U-values for windows, basement slabs and internal slabs were assumed from the literature, whereas U-values for walls and roofs were onsite measured (Plate 5). Installations were nor changed before and after the intervention, as the analyses mainly focussed on the envelope components. Heating system provided a natural gas boiler and radiators (COP = 0.85), while cooling system by electricity fan-coils (COP = 1.67).

3.3 Identification of priorities of intervention

Based on the model, the transient heat analysis has been performed to calculate heating and cooling loads. Thus, the thermal transmittance of each sub-system has been iteratively changed, through several values from the actual to the desired configuration – as required by current normative standards – in order to evaluate the incidence of each performance/components on the global behavior of the building system.

The results in Table IV clearly show that the highest impacts on energy saving – e.g., about 20 percent for heating loads come from the performance improvement of the roof and the walls. Nevertheless, the cooling loads would not go under about 11 percent saving, even when the retrofitting process involves the roof, which is obviously the most exposed sub-system to high summer temperature and radiation of the Mediterranean climate and, thus, it requires higher thermal inertia rather than thermal resistance.

Consequently, for both the components, a cross-comparison between possible retrofitting solutions and transformation/conservation boundaries has been developed. Specifically, for the roof, the conservation of the wooden structure and the terrace

Source: Author's own

Plate 5. Experimental set-up of onsite measurements on the roof

Table IV. Thermal transmittance decrease vs energy consumption saving

Sub-system	Thermal transmittance decrease (%)	Heating consumption saving (%)	Cooling consumption saving (%)
Wall	+83.5	+19.76	+6.26
Windows	+35	+3.56	+4.3
Ceiling	+81.9	+18.23	+11.79
Basement slab	+87	−1.28	−26.17

height was required, whereas for the walls, a limited alteration of internal volumes at the ground floor with unplastered surfaces and of internal and external volumes at the upper floor with plastered surfaces was considered acceptable.

3.4 Selection and validation of suitable solutions

The available on-market products for energy retrofitting of building components often prevent from ensuring good compatibility and conservation of the original architectural and construction features in historical structures. For the case study, the requalification strategies have concerned the thermal insulation on the internal surfaces of the unplastered walls, the thermal insulation on the external surfaces of the plastered walls and the thermal insulation under the floor tiles of the roof. However, the above-mentioned restraints, in terms of changes of volumes and heights, has required the selection of high-performing insulation materials, in order to reduce as much as possible the added thickness to each component. Thus, some innovative products have been considered, such as VIPs consisting of a nearly gas-tight enclosure surrounding a rigid core, from which the air has been evacuated and aerogel panels – a synthetic porous ultralight material derived from a gel, in which the liquid component of the gel has been replaced with a gas. Considering their thermal conductivity, Table V shows the required thickness for achieving the wall thermal transmittance, according to the Italian standards.

The most suitable solution has been considered the aerogel board, since VIPs are less flexible to be cut and adapted to irregular and shapes and dimensions. The board has been selected for both walls and roof, with 15 and 30 mm thickness, respectively.

In order to improve the thermal inertia, along with the thermal resistance, PCMs have been assessed, as they are able to store large amounts of heat in order to melt above a certain temperature – in this case 27°C – and, thus, to mitigate the summer temperature peaks and to reduce the cooling loads. PCMs are manufactured as powders and water-based solutions, besides flexible and rigid boards. Consequently, they are quite attractive for applications in restoration and refurbishment of historical buildings, because they could be potentially included in mortars, slabs and fillings, as well as in artificial blocks and tiles (Figure 5).

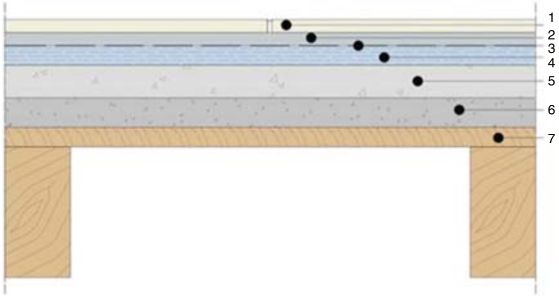
Table VI shows the energy saving of internal and external PCM solution for the roof, when combined with the above-mentioned aerogel panel.

Finally, it should be underlined that cost/benefit analysis for those innovative products is still challenging.

However, the predictable technological maturity and on-market diffusion will potentially make them competitive in the near future. Nevertheless, their capability to ensure both performance improvement and architectural-historical conservation of the buildings should be supported by incentives and breaks.

Type of insulation	Thermal conductivity (W/mK)	Thickness (mm)
EPS	0.036	90
Cork	0.044	110
Wood fiberboard	0.04	100
VIP	0.004	10
Aerogel	0.015	40

Table V. Required thicknesses of the thermal insulating panels



Livelli	ROOF SOLUTION
1	Stone floor tiles with PCM water-based solution
2	Mortar
3	Water proofing membrane
4	Insulation board (Aerogel)
5	Concrete slab (low density)
4	Concrete slab (high density)
5	Wooden slab

Source: Author's own

Figure 5. Integration of PCMs on the external surface of the roof

Table VI. PCMs solutions vs energy saving

Solutions	heating consumption saving (%)	cooling consumption saving (%)
(a) External PCM	+16.1	+25.5
(b) Internal PCM	+17.8	+19.1

4. Conclusions

The paper has meant to show the potentialities of innovative materials and technologies as tools to achieve the energy retrofitting of the historical built heritage, by ensuring the desirable balance between improvement requirements and preservation principles. Nevertheless, it has showed how that balance might only come from a rigorous methodological approach, involving the preliminary qualification of the environmental, architectural, constructional and technological characteristics, in order to define the current behavior of the building system and address suitable strategies that are consistent with the transformation boundaries of the original configuration.

Further studies will follow, with specific focus on cost/benefit analysis and life cycle assessment of the retrofitting solutions, as decision-making support for the implementation of geocluster-based strategies of requalification of historical urban sites by public bodies and administrators.

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