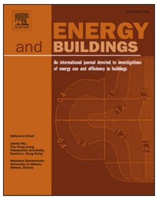
Energy & Buildings 295 (2023) 113299

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb



Post-Insulating traditional massive walls in Southern Europe: A moderate thermal resistance can be more effective than you think

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ARTICLE INFO

Keywords:
Traditional Walls
Historic Buildings
Thermal Mortar
Thermal Render
Thermal Plaster
Validation

ABSTRACT

Post-insulating existing buildings is a promising solution for reducing operational CO_2 emissions from the European built environment. Nonetheless, its efficacy is unclear when traditional and historic massive walls are considered, especially in Southern Europe.

This study employs a validated and calibrated dynamic hygrothermal simulation model to assess indoor comfort and energy demands in a public library with thick stone masonry walls and intermittent occupation, considering three Southern European climates: Porto, Lisbon, and Bologna. Five insulation materials, including three thermal mortars and two conventional materials (Hydrophobic Mineral Wool and Expanded Polystyrene), are compared using internal and external insulation solutions. Thin insulation systems (4 cm) with moderate thermal resistance ($R_t = 0.3–1.0\ m^2K/W$) are studied and found to provide more benefits than drawbacks. One thermal mortar-based system demonstrates comparable performance to conventional insulation materials, indicating that low-conductivity thermal mortars are effective for retrofitting historic and traditional massive walls. Numerical analyses show that optimal reductions of energy demand can be achieved with an insulation R_t of 0.9–1.3 m^2K/W, while further increases yield no additional benefits and even counterproductive outcomes.

Results support adopting moderate R_t insulation in Southern European climates and highlight the need for future research considering the effect of post-insulation on climate change adaptation.

1. Introduction

1.1. Background

To achieve European climate neutrality by 2050, large-scale energy-efficient renovations of the existing building stock are crucial [1]. Historic and traditional buildings, constructed before 1945, constitute approximately 25% of the European building stock [2]. While these buildings can hold significant architectural and cultural value, they account for nearly 40% of total energy consumption and 36% of CO_2 emissions from the European building stock [3]. Thus, retrofitting historic and traditional buildings is essential for reducing European CO_2 emissions, and also for improving indoor comfort, while lowering operational costs [4–6]. These factors are fundamental for ensuring the continued use of these buildings, which is vital for their preservation and durability, as well as for the conservation of historic urban environments as living entities [5,7,8]. Furthermore, heritage buildings and traditional urban environments represent a non-renewable and irreplaceable resource, and their adaptation, reuse, and preservation are key elements for a sustainable development [9–11].

1.2. Technical and scientific literature

In recent years, energy-efficient and thermal retrofits for historic and traditional buildings have gained attention, with thermal insulation of massive masonry walls being a highly debated intervention [12]. Literature presents contradictory indications regarding the best solution for post-insulating massive traditional walls, as the intervention's efficacy depends on various factors like building geometry, materials, usage, and outdoor climate[13,14].

In the context of technical literature, Historic England [15] highlights the complexity of insulating solid walls in historic buildings, emphasizing that it should be considered after other upgrades, such as

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https://doi.org/10.1016/j.enbuild.2023.113299
Received 10 May 2023; Received in revised form 9 June 2023; Accepted 20 June 2023

Nomenclature

ACR	Air Change rate [h^{-1}]
C$_p$	Specific heat capacity [J/(kg.K)]
CV$_{RMSE}$	Cumulative variation of the root mean squared error [%]
EPS	Expanded polystyrene
HVAC	Heating, Ventilation, and Air Conditioning
λ	Thermal conductivity [W/(m.K)]
μ	Water vapour resistance factor [-]
MW	Hydrophobic mineral wool
NMBE	Normalised Mean bias error [%]
R^2	Coefficient of determination [-]
RH	Relative humidity [%]
R$_t$	Thermal resistance [m^{2}K/W]
T	Temperature [°C]
T$_O$	Operative temperature [°C]
TRY	Test Reference Year
U-value	Thermal transmittance [W/(m^2.K)]

Codes used for materials and thermal insulation systems

A1	Thermal mortar 1 (cork aggregates)
A2	Thermal mortar 2 (cork aggregates)
A3	Thermal mortar 3 (EPS aggregates)
B1	Regularization Mortar
B2	Regularization and Finishing Mortar
C1	Lime-based for indoor use
C2	Silicate Paint for Outdoor use
S1	System: A1 + B1 + C1 – Indoor use
S2	System: A1 + B1 + C2 – Outdoor use
S3	System: A2 + B1 + C1 – Indoor use
S4	System: A2 + B1 + C2 – Outdoor use
S5	System: A3 + B2 – Indoor/Outdoor use
S_MW	Theoretical System: MW + B2 – Indoor/Outdoor use
S_EPS	Theoretical System: EPS + B2 – Indoor/Outdoor use

insulating roofs and ground floors, have been carried out. Other guidelines also stress the priority of loft and ground floor insulation over wall insulation due to the difficulty, cost, and risks involved [16,17]. In 2014, the Cornwall Council Historic Environment Service [18] estimated payback costs for insulating solid walls to vary from 13 to 30 years and raises concerns about potential risks such as increased summer overheating and loss of passive cooling capabilities.

In scientific literature, two European projects, Effesus [19] and RIBuild [20], have investigated the use of thermal insulation for retrofitting historic walls. The Effesus project observed that a thin layer (3 cm-thick) of insulating mortar containing EPS resulted in improved thermal transmittance, indoor comfort, and reduced electrical demand for heating in a case study in Benediktbeuern, Germany [21]. The RIBuild project estimated that adopting thermal insulation in 50% of external walls in European historic buildings could save 4.5% to 22% of the energy used for space heating [3]. When it comes to research papers on historic buildings in Southern Europe, it is difficult to find studies that consider wall insulation as a separate measure and not in combination with other solutions e.g., change in heating strategies and technical systems. A study was performed in the monumental complex of Villa Mondragone, in Italy [22], which hosts conference rooms, offices and exhibition areas. Numerical simulations were used to evaluate thermal retrofit options. One of them consisted of substituting existing, damaged, renders with 4–6 cm of thermal mortar (thermal conductivity of 0.045 W/(m.K)), on the exterior of thick masonry walls. This measure was combined with the insulation of floors against unheated spaces. Numerical results showed that insulation can lead to a 60% reduction in heating demands. This study disregards cooling demands and summer comfort. Another investigation [23] focused on a traditional residential building located in southern Italy, having massive stone walls. Dynamic simulations were calibrated and used to evaluate the importance of thermal inertia on indoor and superficial temperatures, during summer. Thermal insulation, namely 2 cm of Expanded Polystyrene, was applied either to the interior or exterior side of the walls. Interior insulation was found to relevantly increase indoor temperature and consequent overheating. Both heating and cooling period were considered in two studies [24,25]. The former adopted simplified dynamic simulation to evaluate energy demands before and after the retrofit of a historical building in Rome. The building hosts offices and has massive brick-masonry walls. Internal insulation was found to reduce heating demands by about 20% and increase cooling needs by almost 10%. Overall, the use of insulation appeared to be more beneficial than detrimental. The latter study focused on a university building in Southern Italy. The authors considered 5 cm of thermal plaster, applied at the interior side of walls (thermal conductivity of 0.058 W/(m.K)) via numerical simulations. Intermittent occupation and use of heating and cooling were considered. The reduction in heating demands was found to be significatively more relevant than the increase in cooling needs, being of almost 10% and$<$0.5%, respectively. A more recent study evaluated post-insulating the walls of the Monastery of Santa Maria de Monfero [26], in Galicia, Spain. Heating and cooling demands were considered, as well as the summer thermal comfort in a free fluctuation scenario. Different types of internal insulations were evaluated, namely 5–6 cm of mineral wool, PUR, and perlite-, cork-, and aerogel-based plasters. Dynamic hygrothermal simulations showed that insulation has a very relevant impact on reducing heating demands and a small effect in terms of increasing cooling needs. Summing up heating and cooling demands, in kW.h/m^2, all solutions were found to reduce total demands by more than 30%. Nonetheless, all insulation solutions were found to increase the daily peak of indoor temperature during summer. Finally, a PhD thesis [27] focused on a historic residential building in Porto, Portugal. The research [27,28] used validated dynamic hygrothermal simulations and showed the relevance of post-insulating the walls for reducing heating demands (considering intermittent heating usage). The research observed that thin insulation, such as a 4 cm thick layer of mineral wool, can lead to relevant benefits, while further increase in insulation thickness can be quite ineffective. Specifically, the research pointed out that passing from 4 to 8 cm of mineral wool provides an additional decrease in heating demands of only 1%. Additionally, external insulation was found to lead to lower overheating risks than interior. The authors underlined that different building typologies and different types of insulation should be further studied to get a more general view of the efficacy of post-insulating walls in different types of historic buildings in Southern Europe [27].

1.3. Problem statement

Post-insulating historic walls is a complex intervention whose efficacy is still not clear, especially in Southern European climates.

On one hand, the feasibility of the intervention is limited by the significance and features of the building. Typically, only thin insulation solutions can be adopted, to avoid altering the characteristic appearance and geometrical proportion of the construction. This restriction leads to a concern for the efficacy of the intervention. How effective is it to apply a thin layer of insulation (moderate thermal resistance) to a thick, massive historic wall? The wonderings that arise in this context are two. First, whether the reduction of heat losses provided by a thin layer of insulation, in winter, is relevant when thick masonry walls are considered. The second concern regards the effect of insulation during hot and warm periods. Historic walls are traditionally thick and massive, built of bricks or stones, and they are largely characterized by a high thermal mass [9]. This feature can provide passive cooling during summer, by absorbing heat during the “hot peak” of the day and releasing it when the temperature falls during night time [29]. Adopting thermal insulation in thermally heavy envelopes can have detrimental effects on their thermal inertia, and thus be counterproductive. This throwback is particularly important when climates with warm and hot summers are considered, which is generally the case of southern European countries. In this context, the introduction of insulation impacts the envelope in different ways according to the side of the application. Internal solutions decouple the thermal capacity of the wall from the indoor air, which is good in terms of heating demands in buildings with intermittent use but counterproductive in terms of passive summer cooling [13]. On the other hand, internal insulation is more effective than exterior for reducing radiant temperature asymmetries [30].

Therefore, when investigating the efficacy of post insulation for massive historic walls, both winter benefits and summer drawbacks should be considered. The outcome strongly depends on the geometry of the building, involved materials, and boundary conditions i.e., indoor comfort requirements, building usage and outdoor climate. It is conceivable to define the efficacy of post-insulation for specific clusters of building usage, construction types, and climate of reference. For this reason, this work focuses on a case study that is considered representative of public buildings with intermittent occupation, relying on intermittent heating and cooling strategy or on free-floating regime, and characterized by thick, massive masonry walls, in the context of temperate climates with hot or warm summer in Southern Europe.

1.4. Objectives

The goal of this investigation is to evaluate the efficacy of adopting 4 cm-thick insulation (equivalent to moderate thermal resistance) on traditional massive walls in Southern Europe. A room located in a public library is taken as a case study. It is subjected to intermittent occupancy patterns typical of buildings with public usage. Three temperate climates with mild winters and hot/warm summers are considered. Efficacy is discussed in terms of thermal comfort and energy demands, including both summer and winter periods. The main questions addressed are:

- Are thermal insulation systems with a relatively low thickness (and moderate thermal resistance) effective for improving indoor comfort and reducing energy demands in the context considered?
- Are thermal mortars competitive in comparison to more conventional insulation materials?
- How significant is the impact of the side of the insulation on thermal comfort and energy demands?

2. Methodology

The methodology adopted in the study is schematically presented in Fig. 1. A historic building located in Porto (Portugal) and currently used as a library is considered. One test reference room is selected within the building and studied in detail. Its intermittent usage makes this space representative of rooms located in historic/traditional buildings that are subjected to public or office usage. The room is modelled by means of dynamic hygrothermal simulations. The simulation model is calibrated and validated against the data measured on-site.

The validated model is then used to evaluate the efficacy of adopting 4 cm-thick (moderate R_t) insulation to retrofit the walls. Simulations are run using typical operational conditions. The temperate climates of three Southern European cities are considered: Porto, Lisbon, and

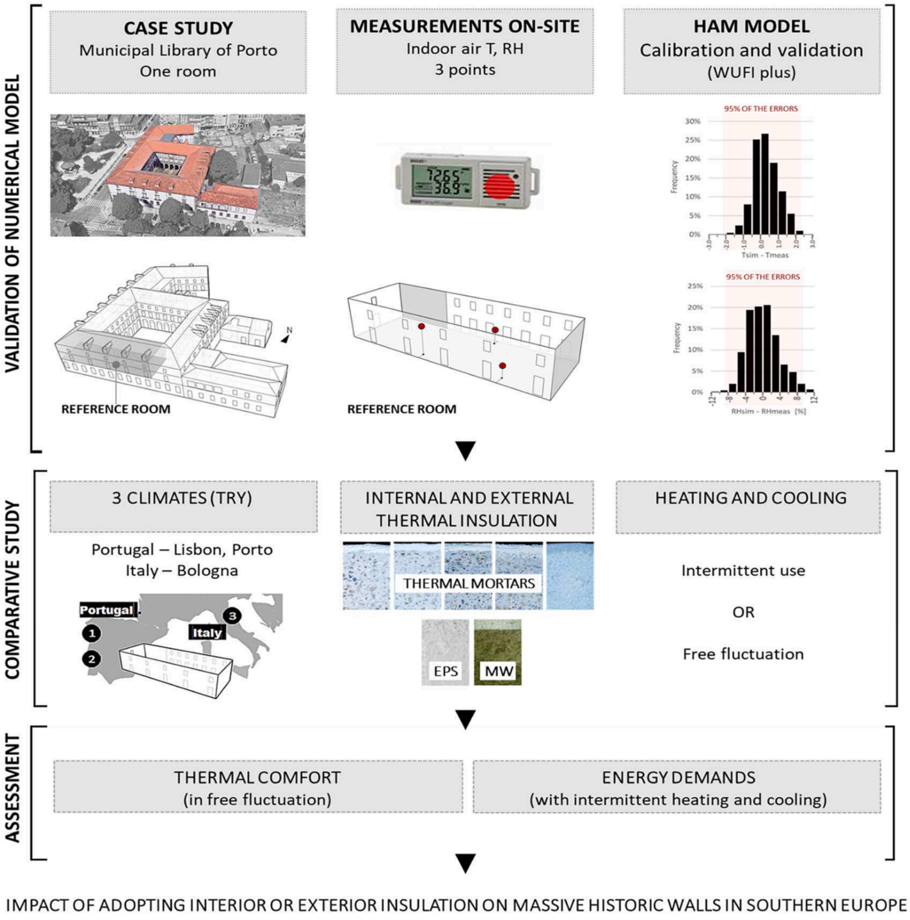


Fig. 1. Methodology of the study. Nomenclature: EPS – Expanded Expanded polystyrene, MW – Hydrophobic mineral wool.

Bologna. Five types of thermal insulations are evaluated, three thermal mortars and two more commonly adopted materials, namely hydrophobic mineral wool and expanded polystyrene. The effect of internal and external insulation systems is compared. The free-floating regime and intermittent use of heating and cooling are alternatively considered, since they are representative of the Southern European context, due to the relatively mild climates and the "lack of motivation to heat" [28]. The former scenario is used for studying thermal comfort and the latter is implemented to investigate energy demands.

3. Case study and measurements on-site

3.1. *Case study*

The case study considered is the Municipal Library of Porto. The building was originally constructed as a Convent, in 1783 [31], and it is located in Porto (Northern Portugal). The building is characterized by massive granite masonry walls, plastered and rendered at their interior and exterior surfaces, respectively. Doors are made of wood, while glass doors and windows are composed of wood frames and single glazing [32]. Insulation was not part of the original design, nor was added to any of the main building components through the years. The building hosts a library and spaces related to this function, such as archives and exposition rooms. This study takes into analysis a reading room in an intermediate floor, which has a double height and relevant dimensions. The main characteristics of the space are shown in Fig. 2a.

3.2. *Measurements on-site*

Indoor air Temperature (T) and Relative Humidity (RH) were measured in three points of the reference room, for one year (April 2019 - March 2020). An additional 2-week-long monitoring was performed during the forced closure due to the COVID-19 emergency in April 2020. Thus, both periods of regular operations and complete closure were considered. The indoor monitoring was performed using one HOBO datalogger UX100-003 (accuracy: ±0.21 °C, and ± 3.5% in the range 25–85% RH, 5% out of this range) and two HOBO dataloggers U12-013 (accuracy: ±0.35 °C, and ± 2.5% in the range 10–90% RH, 5% out of this range). The data were recorded with a sampling interval of 10 min. The positions of the dataloggers are shown in Fig. 2b. They were placed to remain inaccessible to library users while also minimizing the impact of drafts, lighting, and HVAC systems on the measurements.

4. Numerical model: Calibration and validation

4.1. *Numerical model*

WUFI Plus [33] whole-building simulation software is used in this study. It relies on a holistic hygrothermal model [34] that combines thermal building simulations and hygrothermal envelope calculations [35].

4.1.1. *Input*

The test reference room considered in this study was modelled as one zone with homogeneous indoor hygrothermal conditions. The main characteristics of building components, as well as other input parameters, are reported in Table 1. Interior components, namely partitional walls, floor and ceiling, were modelled as adiabatic. Employees' and users' presence was determined by visual observation and simplified with a range of 2–20 people. The heat and moisture gain due to occupation were approximated considering the indications of WUFI database for a seated person, working in the office (which are based on ASHRAE 55 [36], IEA ANNEX 41), i.e. about 99 W and 35 g/h for each individual. Casual heat gains due to lighting and computers in the rooms were approximated at 15 W/m^2 [37]. The heating system located in the room relies on manual regulation and it is subjected to periodical adjustments, with a setpoint in the range of 18 °C – 23 °C. Heating was mainly adopted continuously in the period January-February, with reduced capacity during closing hours. It was used intermittently in November, December and March. The infiltration rate was approximated with the value 0.1 h^{-1}, based on literature. Specifically, Ref. [38] reports measured infiltration rates ranging from 0.1 to 1.0 h^{-1} in various historic churches, while Ferreira, de Freitas, and Delgado [39] adopted 0.1 ACH for the hygrothermal modelling of a Portuguese historic building hosting a museum. An infiltration rate of 0.1 ACH is commonly used in numerical simulations and, although it falls towards the lower end of the range typically observed in historic buildings, it is considered a reasonable choice due to the low volume-to-outdoor-exposed-walls ratio. The outdoor climate was modelled according to the climatic data obtained from local meteorological stations. Namely, a complete dataset of hourly values for meteorological data was provided by the Portuguese Institute of Sea and Atmosphere (IPMA), from a meteorological station located about 11.5 km away from the case study. To better represent the outdoor climate, the dataset was integrated with the outdoor air temperature and relative humidity hourly recorded by the faculty of Engineering of the University of Porto, located about 4 km away from the case study.

4.2. *Calibration and validation*

4.2.1. *Methods for calibration and validation*

A generally shared method for calibrating and validating hygrothermal simulations of historic buildings does not exist. A largely adopted approach is to compare indoor climate data measured on-site to those obtained via numerical simulations [40]. The difference between simulated and measured hourly data is referred to as "error". When the quantification of errors complies with specific requirements, the model can be defined as "calibrated", "validated" or both.

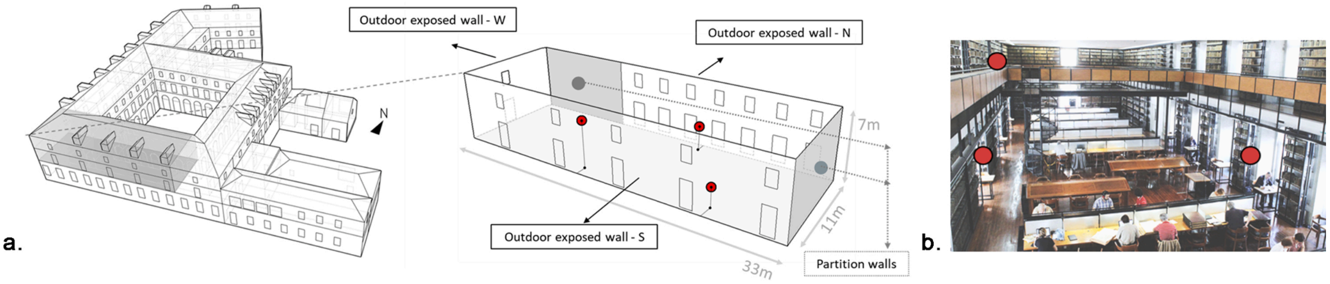


Fig. 2. Case study: (a) on the left, the case study is displayed and the reference room is highlighted in grey (intermediate floor, below the attic, which is used as a storage space); on the right, the reference room is presented, with its dimensions, the exposure of exterior walls, and red points are used to indicate the position of the three sensors adopted for indoor T and RH monitoring; (b) view of the room and position of the sensors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Main input data adopted in the simulation model.

Walls			
	Lime plaster – 3 cm μ=12,λ = 0.7 W/(m.K), C_p = 850 J/(kg.K)	Granite – 90 cm μ=70, λ = 2.3 W/(m.K), C_p = 850 J/(kg.K)	Lime render –3cm μ=12,λ = 0.7 W/(m.K), C_p = 850 J/(kg.K)
Windows			
	U-value = 2.87 W/m^2k	Frame factor = 0.7	
Opening time			
	Monday	Tuesday-Friday	Saturday
15th July – 15th Sept	10AM-18PM	10AM-18PMPM	10AM-18PM
16th Sept – 14th July	10AM-18PM	9:30AM-7:30PM	10AM-18PM
Internal loads			
People seated, reading/working	2–20 people	Heat: 99 W/person	Moisture: 35 g/h/person
Lighting and electrical appliances		Heat: 15 W/m^2	
Heating			
Maximum capacity	12 kW		
Setpoint	18–23 °C		
Use	11th Nov – 1st Jan: During opening hours	1st Jan – 1st March: During opening hours and often during closing time, with reduced capacity.	1st Mar-15th March: During opening hours
Natural ventilation			
Infiltration ACH	0.1 h^{-1}	all year	
Windows	0.5 ACR	all year: 9–9:30 h	
	0–0.8 ACR	Variable during opening hours	

Calibration is the process of adjusting physical parameters in the computational model to improve the agreement with experimental data [41]. A standard for calibrations based on indoor climate parameters does not exist, but the indications of ASHRAE Guideline 14 [42] are often considered. A model is defined as “calibrated” when it complies with the thresholds defined for the statistical indexes of the errors [43]. The statistical indexes considered in ASHRAE Guideline 14 are the cumulative variation of the root mean squared error (CV_{RMSE}), the normalized mean bias error (NMBE) and the coefficient of determination (R^2) [44]. According to the Guideline, the three parameters should respectively fall below ± 10%, 30%, and above 0.75 for models calibrated against hourly measurements. Nonetheless, when it comes to historic construction, it is common practice to consider the model as calibrated once it complies with the restrictions on the first two parameters only [45–48]. In this study, the model was considered calibrated when the quantification of errors complied with ASHRAE limits $CV_{RMSE} < 5\%$ and NMBE < 20%.

Validation is the process of assessing the physical accuracy of the model by comparing simulation and experimental results [41]. An extensive review of validated hygrothermal models for historic buildings is provided by Huerto-Cardenas et al. [40]. The authors outline that in most research a model is considered validated when the quantification of error has a high share of residuals (90%–95%) in the ranges 1–2 °C for temperature, 5–10% for relative humidity and 1–2 g/kg for specific humidity. For instance, in a study on a historical archive [48], the model is validated with most simulated data having errors within ± 1 °C, ±4% and ± 0.5 g/kg. Kramer, Schijndel and Schellen [49] validated the model of a historic museum with ± 2 °C, and ± 4% maximum errors for 90% of hourly data. In other studies, the validation is based on air temperature (T) and relative humidity (RH) only. For instance, two studies on historic buildings located in Porto [28,50], consider the models validated when all errors are below ± 1 °C and ± 4.5%, for temperature and relative humidity respectively. Given the lack of a general reference, a new method was recently proposed in the context of preventive conservation [51]. This methodology proposes three levels of accuracy: excellent, acceptable, and low. Excellent results are observed when errors are within ± 1 °C (T) and ± 5% (RH), while they are acceptable if the errors are within the ranges ± 3 °C (T) and ± 10% (RH). All considered, validation is hereby defined based on the cumulative errors at residual 95%. More in detail, residuals ± 1 °C (T), and ± 5% (RH) are evaluated as indicators of excellent accuracy of the simulations. Residual errors in the range ± 3 °C (T), and ± 10% (RH) are considered to indicate acceptable accuracy. The calibration and validation criteria defined for this study are summarized in Table 2.

Finally, literature indicates that it is good practice to calibrate and/or validate the simulations while considering both operative periods and periods of free fluctuation [48]. The first assessment helps to observe if

Table 2
Criteria for calibration and validation of the model.

Calibration	Validation
Statistical analysis of the errors: - $CV_{RMSE} < 5\%$ (T and RH) - NMBE < 20% (T and RH)	Residual 95% (cumulative errors): - Range ± 1 °C (T), ±5% (RH) *Excellent* - Range ± 3 °C (T), ±10% (RH) *Acceptable*

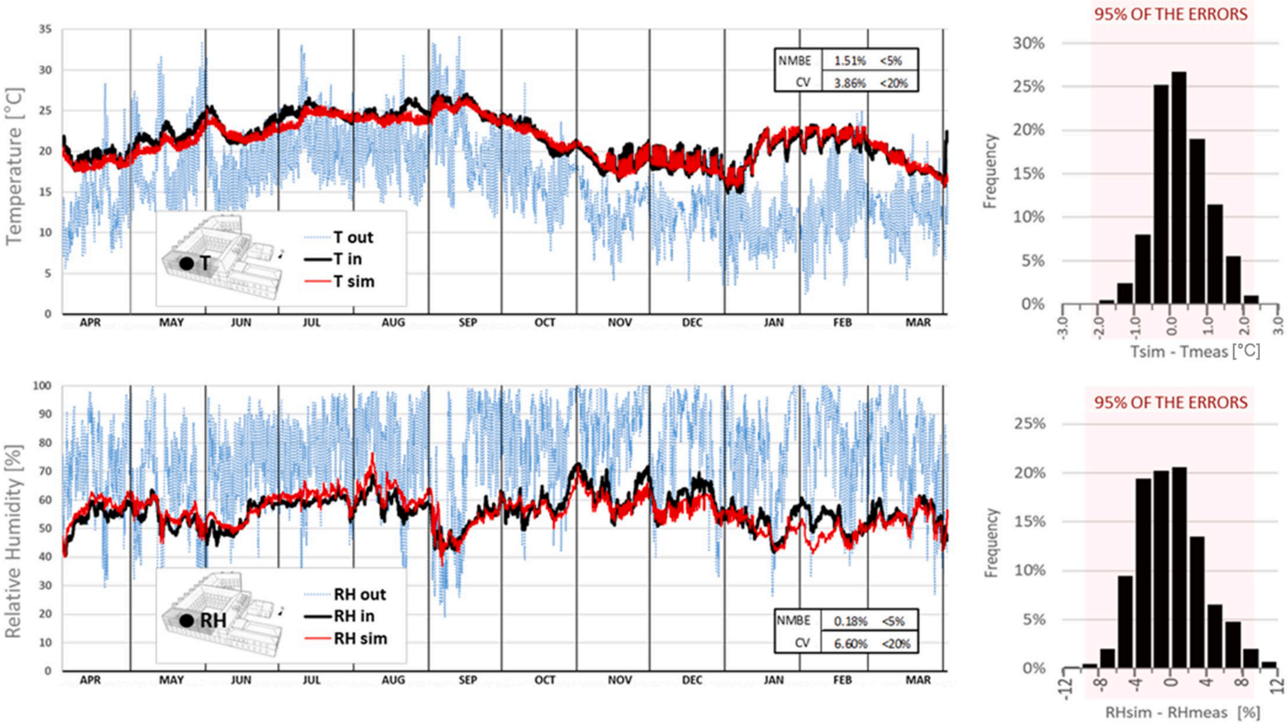


Fig. 3. Results of the calibrated and validated numerical simulations. On the left, the hourly data of indoor air temperature and relative humidity measured on-site are compared to those obtained via numerical simulation. On the right, a representation of the frequency of errors. Nomenclature: NMBE - Normalised Mean bias error [%], CV - Cumulative variation of the root mean squared error [%].

the model well represents regular conditions (accounting for the occupancy and the use of HVAC systems), whereas the second provides information about the correct representation of the building envelope and boundary conditions. In this study the calibration was performed considering a period of free fluctuation, to calibrate envelope-related parameters (namely, the U-value of windows and the infiltration rate). Other parameters were calibrated considering one year of operational conditions. The validation was based on one year of operational use, which also includes short periods of free fluctuations, namely during holidays and weekends.

4.2.2. Results of calibration and validation

The indoor climate was simplified with the average hourly data of the three dataloggers used in the monitoring campaign and compared to the hourly results of simulations. First the U-value of windows and the infiltration rate were calibrated considering 2 weeks of free fluctuation (forced closure due to the COVID-19 emergency). For this period the errors observed are in the range ± 1 °C and ± 7.5% for temperature and relative humidity, respectively. NMBE and CV comply with the limits defined in ASHRAE Guidelines: NMBE = 0.7%, CV = 2% for air temperature, and NMBE = -1%, CV = 4% for relative humidity.

The results obtained during one year of simulations under operational conditions are reported in Fig. 3. Simulations appear to well estimate the overall shape of indoor air temperature and relative humidity, with more relevant discrepancies on the latter parameter. The statistical evaluation of the error (NMBE and CV), which is reported in the same image, complies with the criteria defined for the calibration. The relative frequency of the simulation errors is displayed in the histograms on the side of Fig. 3. The 95th percentile of the errors remain within ± 2 °C and ± 8% for temperature and relative humidity, respectively. Hence the accuracy of the model appears acceptable. Overall, the model defined is considered calibrated and validated. Further information, such as detailed weekly results can be found in Ref. [52].

5. Comparative study

5.1. Materials and methods

5.1.1. Thermal insulation systems

Three thermal mortars and two more common materials are considered, namely hydrophobic mineral wool and Expanded Polystyrene (EPS) [12]. The characteristics of the complete insulation systems are fully described in a previous experimental study [53] on thermal insulation solutions suitable for application on historic walls.

Following the nomenclature adopted in [53,54], the materials and systems hereby considered are the following. Two lime-based mortars containing cork aggregates, and one mortar based on mineral binders

Table 3
Thermal insulation systems [53].

Nomenclature	Thermal resistance Rt [m^{2}K/W]	Layers – inner to outer (from the wall surface to the interior/exterior environment)
S1	0.41	Th. m. A1 (4 cm) + reg. m. B1 (2 mm) + paint C1 (0.5 mm)
S2	0.41	Th. m. A1 (4 cm) + reg. m. B1 (2 mm) + paint C2 (0.5 mm)
S3	0.31	Th. m. A2 (4 cm) + reg. m. B1 (2 mm) + paint C1 (0.5 mm)
S4	0.31	Th. m. A2 (4 cm) + reg. m. B1 (2 mm) + paint C2 (0.5 mm)
S5	0.61	Th. m. A3 (4 cm) + reg./fin. m. B2 (2 mm)
S_EPS	1.00	Hydrophobic mineral wool – MW (4 cm) + reg./fin. m. B2 (2 mm)
S_MW	1.00	Expanded Polystyrene - EPS(4 cm) + reg./fin. m. B2 (2 mm)

Notation: Th. m. - Thermal mortar, Reg.m. - Regularization mortar.
Nomenclature [53]: A1 and A2 – thermal mortars with cork aggregates, A3 – thermal mortar with EPS aggregates, B1 and B2 – regularization mortars based on mineral binders, C1 – Potassium silicate paint, C2 – Lime-based paint.

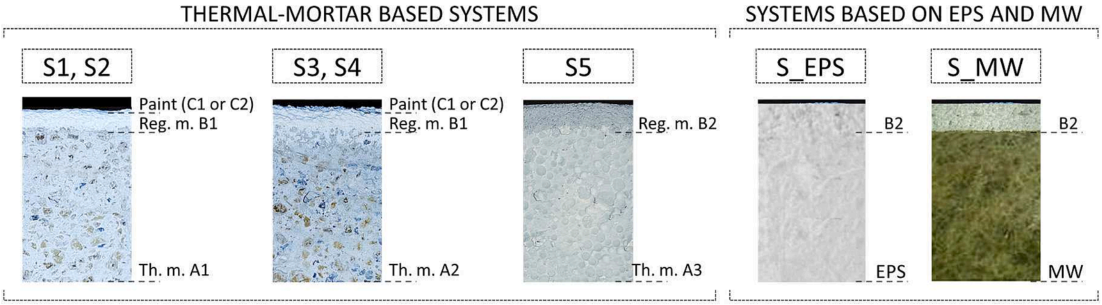


Fig. 4. Graphical representation of the thermal insulation systems [adapted from Ref. 54]. Nomenclature: Reg. m. - Regularization mortar, Th. m. - Thermal mortar.

and EPS aggregates. The three thermal mortars (A1, A2, and A3) have dry thermal conductivities of 0.098 W/(m.K), 0.128 W/(m.K), and 0.065 W/(m.K). The mortars are completed with a regularization layer and/or a finishing to implement complete insulation systems. Hydrophobic mineral wool and EPS have dry thermal conductivities of 0.04 W/(m.K), and the complete insulation system is composed of an insulation layer and a covering mortar. Overall, 7 systems are considered, based on three thermal mortars, hydrophobic mineral wool and EPS. Systems S1 and S2 are based on mortar A1, systems S3 and S4 on mortar A2, and system S5 on mortar A3. Systems S1 and S3 are designed for interior application, S2 and S3 for the exterior. System S5, S_MW, and S_EPS are designed for both interior and exterior use. The choice of interior or exterior application depends on the presence of a regularization and/or finishing layer, which, in the case of exterior systems, are specifically designed by the manufacturer to be relatively resistant to liquid water intake. S_MW and S_EPS are theoretical systems constructed based on the EPS and MW data provided in the WUFI database, along with the application of the same finishing layer as in S3. Their inclusion in this study aims to provide a comparison between thermal-mortar-based systems and more conventional solutions.

All systems have a 4 cm thick insulation layer and thermal resistances in the range $R_t = 0.3–1.0\ m^2K/W$. The main characteristics of thermal insulation systems and a graphical representation are respectively provided in Table 3 and Fig. 4.

5.1.2. Simulated scenarios

The comparative study aims to evaluate if a relatively thin layer of insulation, characterized by moderate R_t, is effective for reducing thermal discomfort and energy demands in the test reference room, in three temperate climates.

Thermal insulation systems are applied on the interior or exterior side of walls, to evaluate the different impact on the thermal behaviour of the room. The simulated scenarios are summarized in Table 4.

The room is first considered under free fluctuation, and the results are evaluated in terms of indoor comfort. Then it is simulated with intermittent heating and cooling, and the results are analysed in terms of energy demands. Three outdoor climates are considered, namely those of Porto, Lisbon, and Bologna. To account for typical usage conditions, some parameters are assumed as fixed. Namely, occupation is set at 7 users and morning ventilation is provided with open windows (ACR = 0.5) from 9 to 9:30 AM throughout the entire year. Simulations performed under free fluctuation consider additional ventilation in summer: 0.5 ACR (10 AM – 2 PM), in the period 15th May – 1st July, and 0.8 ACR (10 AM – 6 PM) in the period 1st July-15th September. Scenarios accounting for the use of technical systems consider an intermittent use (10 AM – 6 PM, Monday to Saturday) of heating and cooling devices with setpoints of 20 °C and 25 °C, respectively. In total, 66 scenarios are simulated. All simulations are run for two years. The results analysed in the study are those obtained in the second year, since the first year is used only to provide realistic initial conditions for the second one.

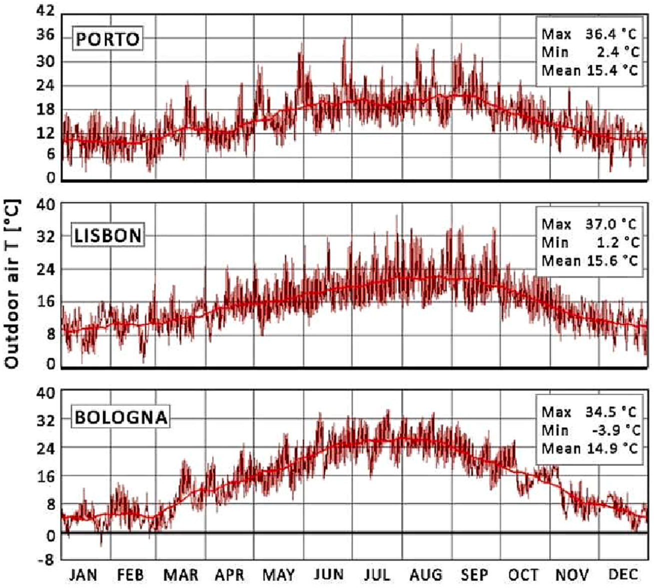


Fig. 5. Outdoor air temperature in the TRY of Porto, Lisbon and Bologna (darker red) and 30-day moving averages (lighter red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Simulated scenarios for the comparative study and type of results analysed.

Climate (x3)	Insulation (x11)	Use of HVAC (x2)	Results analysed(66 scenarios)
- Porto - Lisbon - Bologna	- No insulation - 4 cm of Internal insulation (S1, S3, S5, S_MW, S_EPS) - 4 cm of External insulation (S2, S4, S5, S_MW, S_EPS)	a) Free fluctuation b) Intermittent heating and cooling (only during opening hours, static setpoint, 20–25 °C)	a) Thermal comfort (in 33 scenarios) b) Energy demands (in 33 scenarios)

Notation: S1, S2, S3, S4, S5 - thermal mortar-based insulation systems; S_MW, S_EPS – Thermal insulation systems based on hydrophobic mineral wool and Expanded Polystyrene, respectively.

5.1.3. Outdoor climate

As introduced in the previous section, three outdoor climates are considered in this study: Porto, Lisbon, and Bologna. This choice allows considering temperate climates with noticeable differences in average winter and summer temperatures. To consider typical meteorological conditions, the Test Reference Years (TRY) are used. For Porto the TRY adopted is the one defined in Ref. [55], while for Lisbon and Bologna the files are those provided in WUFI database. For Bologna, due to the limited availability of data, the file considered refers to the climate at a 35 km-distance from Bologna. The courses of temperature in the three TRYs considered are presented in Fig. 5.

In terms of outdoor temperature, Bologna experiences lower winter temperatures compared to Porto and Lisbon, with the 30-day moving average dropping below 8 °C for a significant portion of the winter season. Furthermore, Bologna records the lowest temperature point in the hourly temperature data, specifically reaching −3.9 °C. Lisbon records the highest temperature peak, reaching a maximum of 37 °C, while Bologna has higher average summer temperatures. Namely, the 30-day moving average exceeds 24 °C throughout July and August in Bologna, while staying below this threshold in Porto and Lisbon during the entire summer.

5.1.4. Assessment of thermal comfort and energy demands

Thermal comfort can be investigated considering operative temperature (T_O) [56], which is a parameter that combines air temperature and mean radiant temperature in the room. Literature provides several models for the analysis of thermal comfort, and the main distinction is between classic and adaptive ones. Classic methods rely on the analytical approach, as explained by Fanger's model. This method is explained in the international standard for comfort assessment EN ISO 7730:2005 [57]. The model allows evaluating the comfort level for a specific static context, where the environmental (e.g., air velocity, air temperature, relative humidity and mean radiant temperature in the room) and personal factors (e.g., metabolic rate and clothing) are known. Since the end of the 1990 s, a new approach has gained popularity [58], i.e. the adaptive comfort model, which takes into consideration that thermal comfort also depends on the ability of users to adapt to environmental conditions. The classic approach gives a strict criterion and an operative temperature to aim to, thus promoting a high use of HVAC systems for reaching a static target environment. This type of approach is not aligned with the current global focus on energy efficiency and reduction of CO_2 emissions. On the contrary, adaptive models are more suitable for reducing energy demands in buildings. These models are indeed more tolerant as they consider that users can adapt to indoor climate variations. Adaptive models are considered to well represent thermal comfort in real, dynamic environments and they are introduced in the European standard EN 16798–1:2019 [59]. In the standard, the indoor operative temperature of comfort is defined in correlation with the running mean outdoor temperature. The standard outlines that for buildings in free-running conditions, temperatures that fall within ± 3 °C from the daily operative temperature of comfort are acceptable (Category II - rehabilitated buildings). Further limits are introduced in this study i.e., a minimum temperature of 18 °C and a maximum of 32 °C, as indicated in the standard for rooms with a "sedentary use" with cooling appliances. A schematic representation of the adaptive model used in the study is provided in Fig. 6.

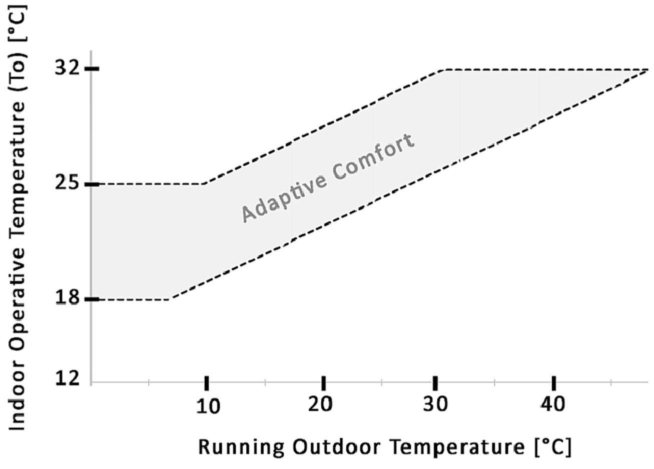


Fig. 6. Model used for adaptive comfort evaluation.

In this investigation, thermal comfort is evaluated by comparing the hourly output of T_O of the simulations to the operative temperature of comfort defined with the adaptive model. Only occupation hours are considered. Two types of indexes are defined, based on Ref. [60]:

- Hours of discomfort [h], in terms of overheating and undercooling. They respectively represent the time during which operative temperature is found to be above or under the range defined with the comfort model, thus representing the temporal extension of discomfort;
- Index of discomfort [°C.h], obtained as the sum of the hours of discomfort multiplied by the corresponding thermal distance from the limit of comfort T_O, thus representing the intensity of discomfort. For overheating and undercooling indexes, the thermal distance represent respectively how much higher or lower the indoor T_O is, in comparison to the threshold value for thermal comfort.

The annual amount of total discomfort is calculated in terms of hours and index by summing up the absolute values of undercooling and overheating hours and indexes, respectively. Energy demands are evaluated by accounting for the hourly energy demands for heating and cooling in numerical simulations. Based on the hourly results, the cumulative annual energy demands for heating and cooling are evaluated. Finally, the total energy use due to the combination of heating and cooling systems is considered.

5.2. Comparative study – Results and discussion

5.2.1. Thermal comfort

Results obtained in terms of discomfort hours and indexes are shown in Fig. 7. Some general patterns emerge, such as:

- In all case studies the increase of thermal resistance of the insulation is effective for reducing the total index of discomfort, meaning that the higher the R_t the smaller index of annual discomfort. On the other hand, increasing the R_t of insulation has different effects on the discomfort hours, depending on the climate. In Porto and Bologna increasing the R_t of insulation leads to reduce the annual hours of discomfort. On the contrary, in Lisbon increasing the thermal resistance of the insulation from 0.4 m^2K/W to 0.6–1 m^2K/W does not lead to any additional benefit but rather to a reduced effectiveness.
- A strong parabolic correlation ($R^2 \geq 0.97$) is found between undercooling and overheating discomfort and thermal resistance of the insulation systems, when internal and external insulation are considered separately. The correlations indicate the higher the thermal resistance of the insulation, the lower the undercooling and the higher the overheating discomfort, in terms of both hours and index.
- In terms of total annual discomfort hours and indexes, all the parabolic correlations observed have a positive coefficient for the quadratic variable, thus indicating a parabola that opens upwards. This type of correlation suggests that the higher the thermal resistance of the insulation, the smaller the proportional benefit. Furthermore, this last correlation indicates that with a high R_t of insulation, the effect of the retrofit might even become counterproductive.

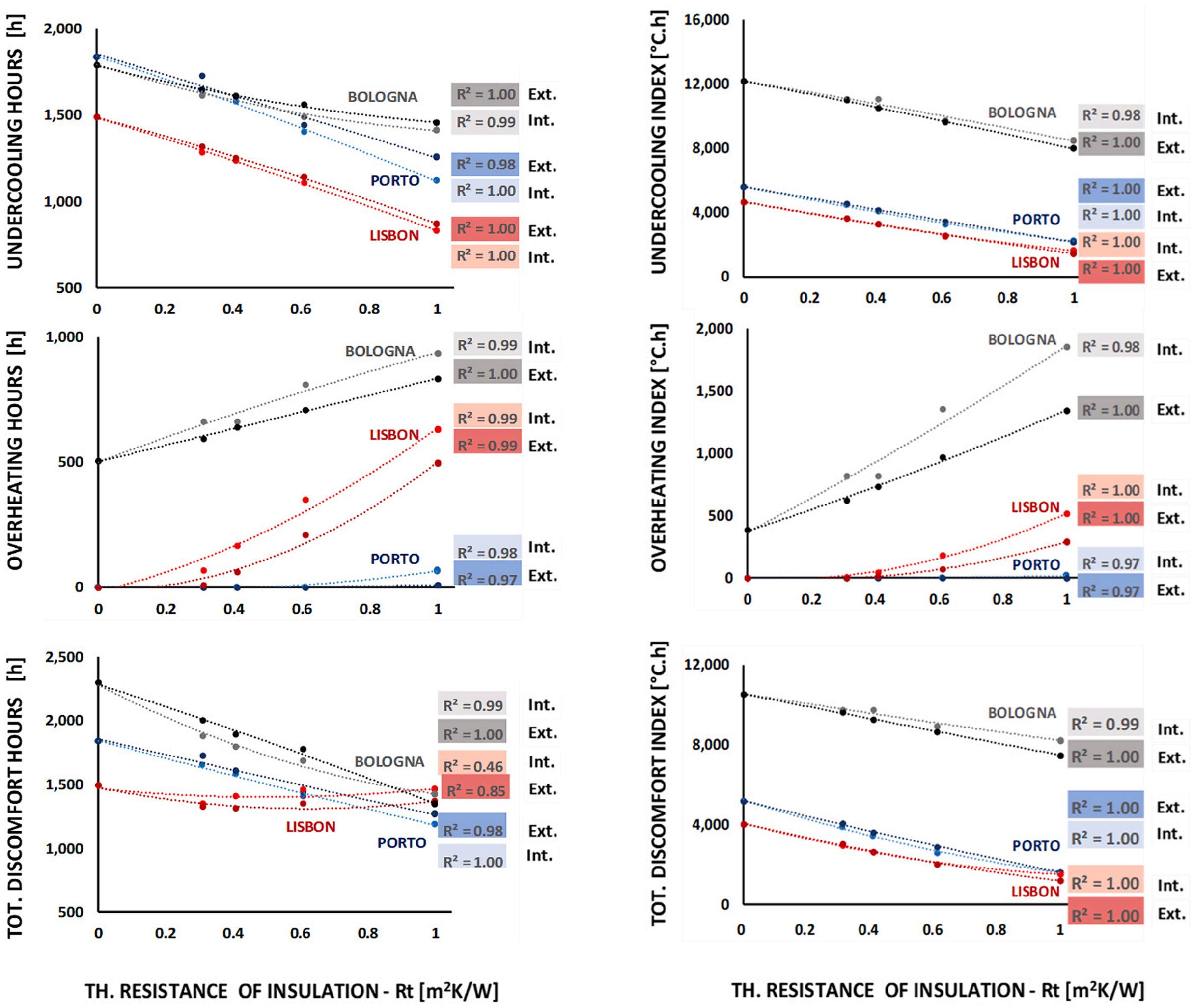


Fig. 7. Correlation between discomfort (hours and indexes) and the thermal resistance of thermal insulation systems, for the test room, in the climate of Porto, Lisbon and Bologna.

- In terms of total discomfort hours, in Lisbon a R_t of 0.4 m^2K/W is already enough to reach minimal discomfort hours. Thus, higher thermal resistances should be used cautiously because they give lower benefits and might even lead to counterproductive results for R_t above 1 m^2K/W. In the climate of Porto and Bologna, the correlations indicate that the hours of discomfort can be further decreased with the use of an increased R_t of insulation. The different effect of insulation in the 3 climates seems a result of the different winter conditions, indeed Lisbon has milder winter temperatures than Porto and Bologna, which leads to lower benefits of insulation.
- The range of R_t considered has a positive effect on decreasing discomfort hours and index in the three climates. Nonetheless, the parabolic correlations suggest that the use of higher R_t could lead to counterproductive effect. For instance, an internal thermal insulation system with R_t above 2.5 and 3.5 m^2K/W (corresponding to 10–15 cm of Mineral Wool) would lead to a higher discomfort index than in the un-insulated scenario, in Lisbon and Porto, respectively.

The different effect of internal and external insulation doesn't seem significant in terms of undercooling. On the contrary, it is relevant for overheating discomfort, where internal insulation is found to have a more detrimental effect than external. More moderate results are observed in Porto, due to the milder summer temperatures. Considering the total hours and index of discomfort, external insulation appears preferable to the interior in the climates of Lisbon and Bologna, especially when higher R_t are considered. The contrary applies to Porto. This difference seems related to the different summer conditions of the two climates.

5.2.2. *Energy demands*

In Fig. 8, the annual energy use for intermittent heating, cooling, and entire operations (heating and cooling) is displayed.

The case study has the highest energy use for heating and cooling in the climate of Bologna, which is consistent with the more extreme outdoor temperatures of this climate during both summer and winter. In the two Portuguese climates, the annual energy use is similar i.e., around 12 MW.h in the un-retrofitted scenario.

Results obtained in Porto show higher heating demands than in Lisbon, while the latter has higher cooling needs. Results indicate that insulation strongly reduces heating demands. At the same time, it increases cooling needs, but to a less significant extent. Overall, the adoption of insulation systems with a moderate thermal resistance (R_t = 0.3–1.0 m^2K/W) appears effective for reducing total energy demands in the test room analysed, especially in Porto. The reduction of annual energy use is in the order of 30–50% in Porto. In Lisbon and Bologna, the reduction is of about 20–35% and 20–40%, respectively. These outcomes suggest that post-insulation is beneficial in heating-dominated climates and it loses relevance when cooling demands get more significant. Furthermore, thermal mortar-based solutions appear promising, especially S5, which provides reductions of 30–40% in the three

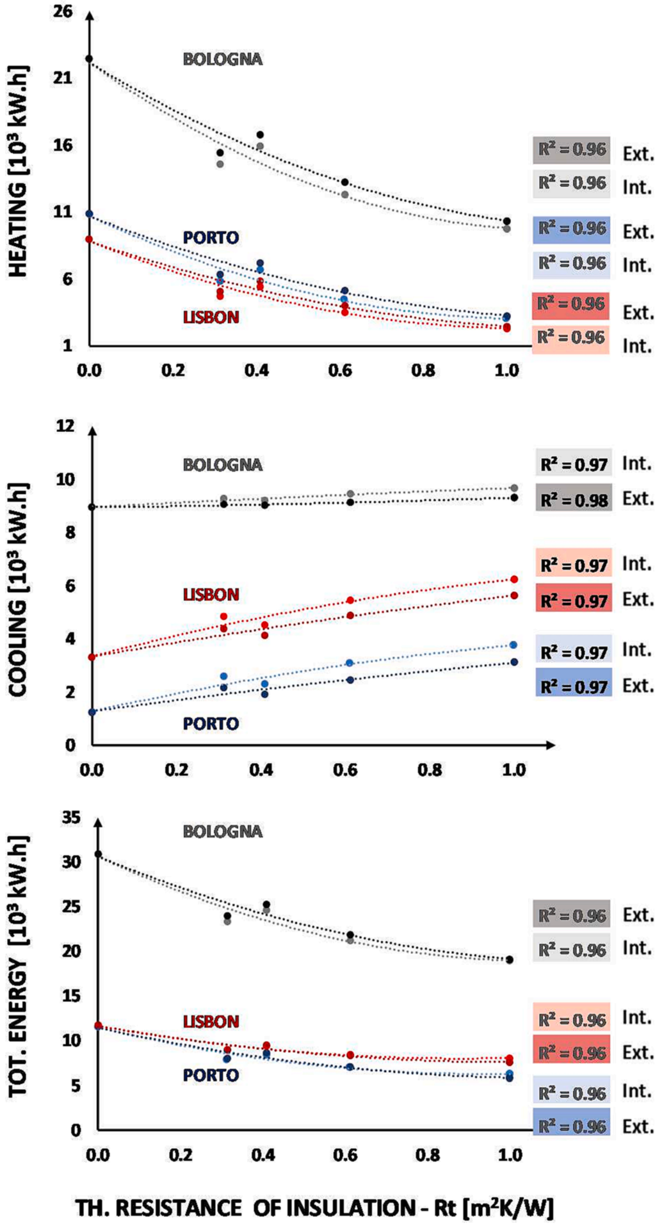


Fig. 8. Correlation between annual energy (heating, cooling, and total operations) and the thermal resistance of thermal insulation systems, for the test room, in the climate of Porto, Lisbon and Bologna.

climates analysed. This outcome suggests that if more advanced thermal mortars are used, such as those containing aerogel, reductions in the order of 30–50% could be achieved. Indeed, literature indicates that aerogel mortars can reach thermal conductivities as low as MW and EPS, and even lower [61,62]. For the same 4 cm-thick insulation layer, a thermal resistance of 1–1.3 can be expected when using aerogel mortars (thermal conductivity around 0.03 W/(m.K)).

Considering the total energy for heating and cooling, the maximum differences due to the side of the insulation are in the order of 5%, thus not very relevant. Systems S_MW and S_EPS ($R_t = 1.0$ m^{2}K/W) appear similarly or more effective when used on the exterior side of the wall. This result is consistent with the fact that these solutions give similar results for heating demands when adopted at the interior and exterior side of walls, while they are preferable at the exterior side for cooling needs. Thermal mortar-based insulation systems S1 and S2 give better or comparable performance when adopted as interior insulation. Comparable results are obtained when thermal mortar S5 is adopted at the exterior or interior side of the walls. Overall, it seems that the preference for internal or external insulation depends on both the climate and the type of insulation system adopted.

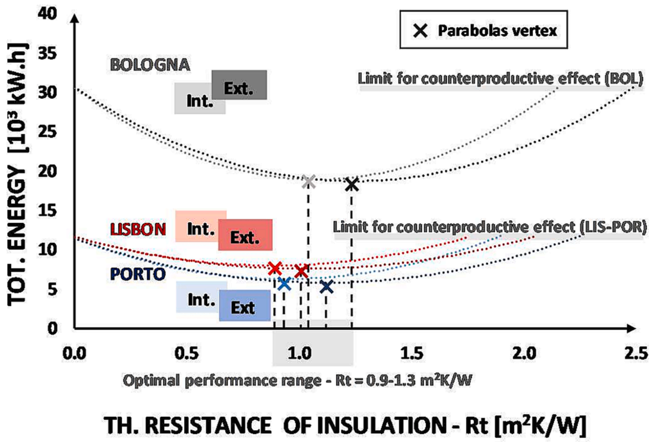
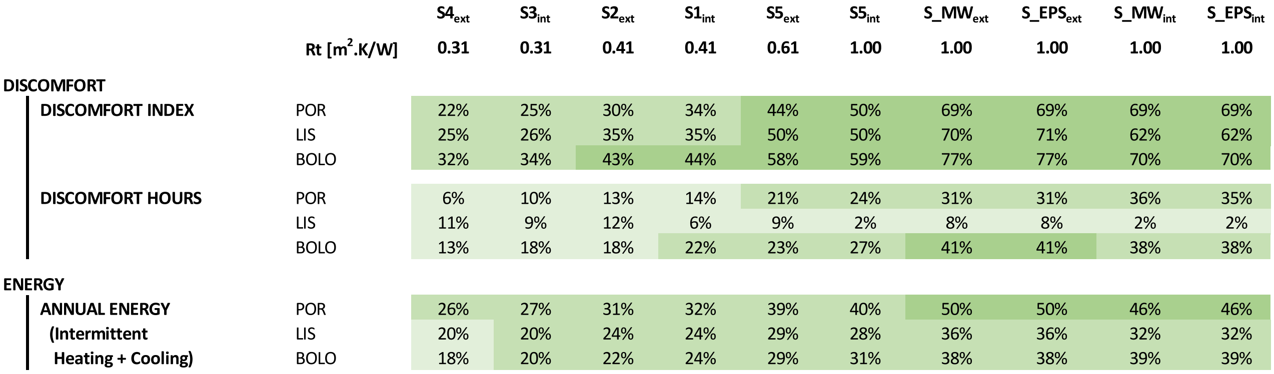


Fig. 9. Extension of the parabolic correlations (total energy demands - R_t of insulation), until reaching counterproductive effects. Identification of the minimum of each parabola (vertex).

A strong parabolic correlation ($R^2 \geq 0.96$) is found between energy demands and R_t, when internal and external insulation are considered separately. The correlations observed allow to extrapolate the following observations:

- The higher the R_t the lower the heating demands and the higher the cooling needs.
- Internal and external insulation have a different impact on heating and cooling. Internal insulation appears to be better for reducing heating demands and worse for moderating cooling needs. This result is expected since internal insulation decouples the thermal mass of indoor air from that of the wall. This effect is positive for reducing the heat absorbed by the walls during the heating season, but it is counterproductive in terms of thermal inertia, thus counterproductive in summer. With increasing R_t, the total annual energy demands decrease in all climates. The highest reductions are observed in Bologna and Porto, probably because of their higher heating demands.
- The correlations observed between total energy demands and R_t of insulation suggest that external insulation is preferable in Portuguese climates, whereas interior performs better in Bologna. Nonetheless, for the range of R_t considered, the difference between the use of internal and external insulation seems neglectable.
- Although a positive reduction of total energy demands is observed in the three climates, the positive coefficient of the parabolic correlations indicates that a counterproductive effect might be reached if insulation systems with a higher thermal resistance are adopted.

Fig. 9 shows an extension of the parabolic correlations. According to these correlations, an R_t of 1.7–2.3 m2K/W can lead to counterproductive effects in Lisbon and Porto, whereas in Bologna counterproductive effects are reached with higher R_t (2.1–2.5 m^{2}K/W). In all climates the minimum of total energy demands is reached with a moderate R_t of the insulation, namely in the range $R_t = 0.9$–1.3 m^{2}K/W. This range of R_t means reaching U-values in the range 0.7–0.5 W/m^{2}K, considering the thick granite walls of the case study. Currently, Portuguese and Italian standards indicate a maximum U-value in the range of 0.5–0.35 W/m^{2}K, for renovation interventions on walls, in the climates considered [63,64]. The standards do not apply to buildings with Heritage values but to existing constructions that are not listed, such as most traditional constructions with thick, massive envelopes. The case study considered shows that standard restrictions would lead to less beneficial



			$S4_{ext}$	$S3_{int}$	$S2_{ext}$	$S1_{int}$	$S5_{ext}$	$S5_{int}$	S_MW_{ext}	S_EPS_{ext}	S_MW_{int}	S_EPS_{int}
		Rt [m^2.K/W]	0.31	0.31	0.41	0.41	0.61	1.00	1.00	1.00	1.00	1.00
DISCOMFORT												
	DISCOMFORT INDEX	POR	22%	25%	30%	34%	44%	50%	69%	69%	69%	69%
		LIS	25%	26%	35%	35%	50%	50%	70%	71%	62%	62%
		BOLO	32%	34%	43%	44%	58%	59%	77%	77%	70%	70%
	DISCOMFORT HOURS	POR	6%	10%	13%	14%	21%	24%	31%	31%	36%	35%
		LIS	11%	9%	12%	6%	9%	2%	8%	8%	2%	2%
		BOLO	13%	18%	18%	22%	23%	27%	41%	41%	38%	38%
ENERGY												
	ANNUAL ENERGY (Intermittent Heating + Cooling)	POR	26%	27%	31%	32%	39%	40%	50%	50%	46%	46%
		LIS	20%	20%	24%	24%	29%	28%	36%	36%	32%	32%
		BOLO	18%	20%	22%	24%	29%	31%	38%	38%	39%	39%

Fig. 10. Matrix of performance: percentual reduction in thermal discomfort and energy demandswith different insulation systems.

outcomes than possibly achievable with less stringent U-values.

5.3. Comparative study – Summary of results

The results obtained in terms of thermal discomfort and energy demands in the retrofitted scenarios are synthesized in the matrix of performance reported in Fig. 10. Each column represents the results observed with one thermal insulation solution. Thermal insulation systems are ordered from left to right according to their thermal resistance, lowest to highest. For solutions having the same thermal resistance, external insulation is put before the interior. The performance observed with the different insulation solutions is expressed as a percentage of those in the un-retrofitted scenario.

Results indicate that in the three climates considered, thermal insulation systems with a moderate thermal resistance (R_t = 0.3–1.0 m^2K/W) lead to higher benefits than throwbacks. They are effective for reducing energy demands for intermittent use of heating and cooling systems with static setpoints, and improve indoor thermal comfort under free fluctuation. Specifically, in terms of annual discomfort index and duration, reductions are in the range of 22%-77% and 6%-41%, respectively. The higher the thermal resistance of the solution, the lower the index of annual discomfort. Additionally, for the reduction of annual discomfort, results show that S_MW and S_EPS (R_t = 1.0 m^2K/W) perform better if applied at the exterior side of walls, with a difference up to 15% in the percentual reduction of discomfort index, depending on the side of the application. In terms of hours, the best results are obtained with the same thermal insulation systems, used at the interior side in Porto climate, and at the exterior in Bologna. This difference is likely to be related to the moderate summer temperatures in Porto, which lead to reduced drawbacks with interior insulation during summer.

For thermal mortars, interior solutions are mostly preferable, in terms of energy demands and thermal comfort. The better performance at the interior side can be related to the fact that thermal mortars are sensible to liquid water infiltrations, thus they can partly lose their thermal performance if relevant rainwater intake occurs. However, very small differences due to the side of application are observed, up to 7%.

5.4. Limitations

Before outlining the overall conclusions of the study, it seems important to underline some limitations.

The simulations hereby presented disregard thermal bridges. Additionally, in the input values for numerical simulations, the air infiltration rate is set at 0.1 h^{-1}. Experimental measurement of air infiltration in large-volume, historic spaces is challenging and sometimes not even feasible. Therefore, a relatively standard value, commonly adopted in practice, is chosen for this study. This step was necessary to standardize the modeled scenarios by neutralizing this parameter as a determinant of the results in the comparative analyses, in accordance with the research objectives.

The results obtained refer to Granite walls with a thickness of 90 cm, having a U-value of about 1.7 W/(m^2.K). Since the benefits of thermal insulation are related to the reduction of heat losses through the walls, lower benefits can be expected when massive walls with lower U-value are considered, and better ones when walls with worse thermal performance are evaluated.

This study considers a public building and its typical usage. Namely, intermittent heating and cooling and free-floating conditions are considered. The results of the study are not extendable to buildings that rely on continuous use of technical systems. For similar buildings with analogue use, overheating problems might be less relevant if prolonged summer closure, e.g. 2–3 weeks in the middle of the hot season, is forecasted.

Finally, this study accounts for typical reference climatic conditions and neglects the impact of climate change, which is recognized to be relevant when considering passive strategies for improving comfort and energy performance in historic constructions [65,66]. Since it was observed that thermal insulation can be counterproductive during warm and hot periods, future studies should analyse the effect of insulation under future climatic scenarios, accounting for the potential increase in temperatures.

6. Conclusions

In this work, a room with monumental dimensions, thick stone masonry walls, and intermittent occupation is used as a case study. A comparative analysis is performed to evaluate the effect of different insulation solutions with moderate thermal resistance on thermal comfort and energy demands when free fluctuation and intermittent conditioning are considered, respectively. Five types of insulation materials are adopted, namely three types of thermal mortars and two more conventional materials, such as hydrophobic mineral wool and expanded polystyrene. Internal and external insulation solutions are compared. Three climates are considered, namely those of Porto, Lisbon and Bologna, i.e. cities located in southern European countries and characterized by temperate climates with mild winters and hot or warm summers. This study leads to the following conclusions:

- When thick, massive traditional walls are considered, a relatively thin layer of insulation, such as 4 cm thick, can lead to a relevant decrease in thermal discomfort and operational energy demands. Increasing the thickness of insulation might be not beneficial and even counter-productive, both in terms of thermal comfort and energy demands
- In terms of total energy for intermittent heating and cooling, results indicate that optimal decrease is achieved with a moderate thermal resistance of the insulation (R_t = 0.9–1.3 m^2K/W), which

corresponds to 4–6 cm of mineral wool and EPS (System S_MW and S_EPS) and 5–8 cm of thermal mortar A3 (System S5). Further increase in insulation thickness do not lead to any additional benefits.

- These thermal resistances correspond to achieving U-values between 0.7–0.5 W/m^{2}K, which are higher than the maximum allowed in the local standards for renovations. This outcome indicates that standard requirements may lead to suboptimal outcomes compared to using less stringent U-values in traditional buildings with massive, thick walls and intermittent use of heating and cooling.
- Numerical correlations indicate that adopting insulation with an R_t above 1.7 m^{2}K/W (equivalent to 7 cm of MW), and 2.1 m^{2}K/W (equivalent to 8 cm MW) can lead to higher energy needs than in the un-insulated scenario, respectively in the Portuguese and Italian climates. Thus, not only increasing the insulation thickness and R_t can produce no benefits, but it might even lead to relevant detrimental effects.
- The solutions considered in detail in the study ($R_t = 0.3$–1.0 m^{2}K/W), reduce heating demands and undercooling discomfort, but they tend to increase cooling needs and overheating discomfort. Thus, they lead to benefits and drawbacks. Nonetheless, in the scenarios considered, the benefits of thermal insulation overweight the drawbacks. Annual energy demands are reduced by 32% to 50% with mineral wool and EPS ($R_t = 1.0$ m^{2}K/W), and by 18–40% with thermal mortars ($R_t = 0.3$–0.6 m^{2}K/W). The former solutions lead to a decrease in the annual index of discomfort by 62–77%, and the letter ones by 22–59%. The best results are found in the climate of Porto, probably because of its milder summer temperatures which moderate the drawbacks of adopting thermal insulation.
- One thermal mortar-based system (S5, $R_t = 0.6$ m^{2}K/W), provides comparable performance to EPS and mineral wool. Reductions of 28–40% and 44–59% are observed for energy demands and index of discomfort, respectively, with S5. This outcome shows that thermal mortars with low thermal conductivity are competitive with traditional insulation materials and effective for application in historic and traditional buildings with massive walls. This result suggests that thermal mortars with advanced formulations (e.g., containing aerogel - $R_t \approx 1.3$ m^{2}K/W for 4 cm thickness) might offer benefits as high as typical solutions based on EPS and mineral wool, and even better.
- Considering the results of a complete year of simulations, the differences obtained based on the side of the insulation (internal or external) are not very relevant. When considering an R_t of 0.3–0.6 m^{2}K/W (thermal mortars), internal and external insulation lead to differences below 5% for annual energy demands, and lower than 7% for annual discomfort index. With an $R_t = 1.0$ m^{2}K/W (mineral wool and expanded polystyrene) higher difference are observed, up to 15%, and exterior insulation appears preferable.

In the scenarios considered, optimal energy reductions are provided with less stringent U-values than in standard regulations, 4 cm-thick insulation emerges to be very effective, and insulation thicknesses above 7 cm present a threat of counterproductive effects. Hence, adopting thermal insulation with low thickness and moderate thermal resistance is more effective than one may think, and it appears to be the most suitable solution for retrofitting traditional and historic massive, thick walls in Southern European countries.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors used ChatGPT (chat.openai.com) for the grammar checking and English polishing of minor parts of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Magda Posani: Conceptualization, Investigation, Writing – original draft. **Rosário Veiga:** Conceptualization, Supervision, Writing – review & editing. **Vasco Freitas:** Conceptualization, Methodology, Supervision, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Acknowledgments

The authors thank the Post-Doc funding provided by ETH Zürich, IBI, Chair of Sustainable Construction, and the PhD funding given by FCT - Fundação para a Ciência e a Tecnologia [PD/BD/135192/2017]. The support of CONSTRUCT (LFC—Laboratory of Building Physics) - Research Unit Institute of R&D in Structures and Construction at FEUP (Faculty of Engineering of the University of Porto) and Project PRESERVE – Preservation of renders of built cultural heritage at LNEC (National Laboratory for Civil Engineering) is acknowledged. We also express our appreciation for the collaboration of the public institutions that allowed for the indoor monitoring of the case study and that provided the documentation concerning the building. In particular, Dr. Lucinda Oliveira. Finally, we would like to thank ARPAE for providing the meteorological data of Porto, which were used in the calibration and validation process.

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