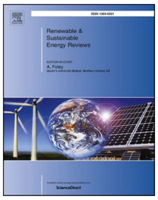
Renewable and Sustainable Energy Reviews 118 (2020) 109509

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser



Dynamic thermal and hygrometric simulation of historical buildings: Critical factors and possible solutions

G.G. Akkurt [a], N. Aste [b], J. Borderon [c], A. Buda [b], M. Calzolari [d], D. Chung [e], V. Costanzo [f], C. Del Pero [b], G. Evola [f], H.E. Huerto-Cardenas [b], F. Leonforte [b,*], A. Lo Faro [g], E. Lucchi [h], L. Marletta [f], F. Nocera [g], V. Pracchi [b], C. Turhan [i]

[a] *Department of Energy Systems Engineering, Izmir Institute of Technology, Gulbahce Kampusu, 35430, Urla, Izmir, Turkey*
[b] *Architecture, Built Environment and Construction Engineering Department, Politecnico di Milano, Via Bonardi 9, 20133, Milano, Italy*
[c] *Equipe BPE, Cerema, F-44000, Nantes, France*
[d] *Department of Engineering and Architecture, University of Parma, Parco Area delle Scienze 181/A, 43124, Parma, Italy*
[e] *Department of Architecture, Design & Urbanism, Drexel University, 3501 Market Street, 4A20A, Philadelphia, PA, 19104, USA*
[f] *Department of Civil Engineering and Architecture, University of Catania, Viale Andrea Doria 6, 95125, Catania, Italy*
[g] *Department of Electric, Electronic and Computer Engineering, University of Catania, Viale Andrea Doria 6, 95125, Catania, Italy*
[h] *Institute for Renewable Energy, Eurac Research, Viale Druso 1, 39100, Bolzano-Bozen, Italy*
[i] *Department of Energy Systems Engineering, Atilim University, Ankara, 06830, Incek, Turkey*

ARTICLE INFO

Keywords:
Historical building
Cultural heritage
Dynamic building energy simulation
Simulation tools
Simulation uncertainty
Decision analysis

ABSTRACT

Building dynamic simulation tools, traditionally used to study the hygrothermal performance of new buildings during the preliminary design steps, have been recently adopted also in historical buildings, as a tool to investigate possible strategies for their conservation and the suitability of energy retrofit scenarios, according to the boundary conditions.

However, designers often face with the lack of reliable thermophysical input data for various envelope components as well as with some intrinsic limitations in the simulation models, especially to describe the geometric features and peculiarities of the heritage buildings. This paper attempts to bridge this knowledge gap, providing critical factors and possible solutions to support hygrothermal simulations of historical buildings.

The information collected in the present work could be used by researchers, specialists and policy-makers involved in the conservation of building's heritage, who need to address a detailed study of the hygrothermal performance of historical buildings thorugh dynamic simulation tools.

1. Introduction

In the last decade, the issue of energy efficiency in historical buildings has become increasingly important. Proofs of this increasing interest are the constant growth in the scientific literature [1–12], the funded project at European level [13–17], the publication of several guidelines for the improvement of energy efficiency on historic buildings [18–21], together with the campaign "Class An Unesco sites" [22] in the framework of the "2018 European year of cultural heritage" [23].

The popularity of the topic is due to many factors: (i) the amount of buildings considered as historical, which is equal to 30% of the total amount of the existing stock [24], (ii) the need to balance energy efficiency improvement with the requirements of preservation, and (iii) the scarce knowledge about their thermal behaviour.

First of all, in order to identify the subject of the present work, it is pivotal to clarify the differences between "historical" and "historic" buildings: the first expression is related to buildings built in the past that however may be not important from the History's point of view, whereas a historic building is important by definition [25]. In such respect, the present paper deals with historical buildings that, even if not characterized by artistic or aesthetical significance, are built with different materials and techniques than modern one, and as such perform in a different way.

Historical buildings, in fact, were traditionally built using local resources and materials to take advantage of every potentiality that a correct shape, location and exposure can offer. Modern designers and building modellers are often not enough aware of the adopted

---

* Corresponding author.
E-mail address: fabrizio.leonforte@polimi.it (F. Leonforte).

https://doi.org/10.1016/j.rser.2019.109509
Received 11 July 2019; Received in revised form 28 August 2019; Accepted 21 October 2019

Abbreviations

ACH	air change rate per hour
BES	building energy simulation
CFD	computational fluid dynamics
HFM	heat flow meter
IRT	infrared thermography
LDT	Low Destructive Testing
NDT	Non Destructive Testing
VI	visual inspections
c_p	specific heat [$\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$]
ε	thermal emissivity [−]

λ	thermal conductivity [$\mathrm{W \cdot m^{-1} \cdot K^{-1}}$]
μ	vapour resistance factor [$\mathrm{s \cdot m^{2} \cdot Pa \cdot kg^{-1}}$]
ρ	density [$\mathrm{kg \cdot m^{-3}}$]
τ_v	visible transmittance [%]
χ	point thermal transmittance [$\mathrm{W \cdot K^{-1}}$]
ψ	linear thermal transmittance [$\mathrm{W \cdot m^{-1} \cdot K^{-1}}$]
n	pressure difference [−]
g	solar transmittance factor [%]
k	constant [−]
r	reflection factor [%]
U-value	thermal trasmittance [$\mathrm{W \cdot m^{-2} \cdot K^{-1}}$]
SHGC	solar heat gain coefficient [%]

construction techniques and material properties, and for this reason, historical buildings show very different features compared to new buildings, resulting in a very complex hygrothermal behaviour [26].

Consequently, dynamic simulation tools must be used in the field of historical buildings in order to Refs. [27–35]: (i) analyse the possible degradation risks to materials determined by specific environmental temperature and relative humidity ranges; (ii) estimate some phenomena that cannot be easily evaluated such as the verification of surface condensation; and (iii) assess multiple energy retrofit scenarios.

Now, although building dynamic simulation tools are potentially a suitable way for accurately assessing the thermal performance of buildings, they are more time-intensive, usually need several data inputs, require a period of user training and are not specifically designed for historical buildings. In general, a discrepancy between simulated and real behaviour can be observed (and accepted) for each kind of new or existing building [36–40]; however, in historical ones the discrepancy between actual performance and simulations seems to be too large to be acceptable [41–45].

Particularly, three major limitations in the simulation of historical buildings can be highlighted [46]: (i) the lack of reliable information about input parameters such as the thermo-physical data of envelope components, (ii) calculation's limits of the tools used to describe the geometric features (e.g. in presence of thermal bridges and the construction heat flow model restricted to one dimensional flow) and (iii) the adoption of wrong or incomplete models of certain physical phenomena of interest in historical buildings [47].

In such respect, bridging the gap between predicted and measured performance is pivotal in order to provide serious and reliable advice to designers, architects, buildings' owners and policy makers, on the real performances of the buildings.

This will increase the awareness amongst clients and design teams on the energy behaviour and performances of the building, estimating the effectiveness of different energy efficient solutions and ensuring the achievement of the forecasted energy performance.

Moreover, such information can be adopted to plan and to schedule effective interventions and maintenance programs as well as to reduce the risk for owners and investors (i.e. damage, structural problems, and so on). The enforcement of energy performance guarantee, in fact, allow the decreasing of the uncertainty about the final outcome. This latter factor can offer a significant contribution to the development of new rules and strategies for real estate and energy finance, innovating the traditional conservative approaches (i.e. restoration or planned conservation).

In this framework, even if a large number of simulation tools have been developed over the last few decades (the Building Energy Simulation - BES tool web page lists over 200 tools [48]), only few of them are able to take into account properly some specific issues related to historical buildings. According to this literature review, in approximately half of the analysed papers the code used to evaluate the thermal performance of historical buildings is EnergyPlus (26%) or other tools based on its calculation engine, such as DesignBuilder (22%), while the other half uses a great diversity of codes: Trnsys (15%), Wufi Plus (12%), IDA-ICE (10%), HAMbase (7%), IESVE (4%), ENER-WIN, DOE, AECOsim (see Fig. 1).

Moreover, as shown in Fig. 1, it should be also noted that the number of articles published yearly dealing with dynamic simulation of historical buildings, counting only the publications identified by using the keywords "Simulation", "Historical building" and "Cultural heritage", in

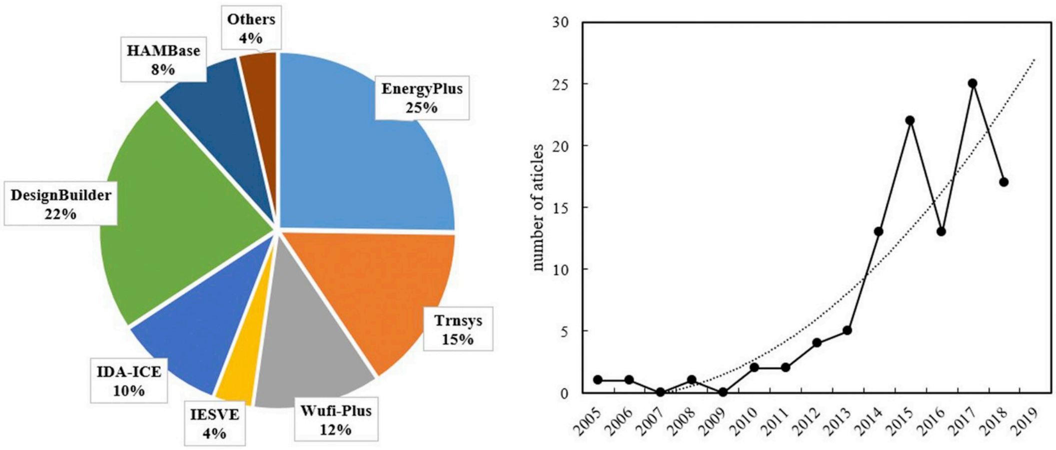


Fig. 1. Percentage of the most adopted simulation tools in the simulation of historical buildings (left); Number of published articles per year dealing with dynamic simulation of historical buildings (the papers dealing with CFD analysis are not included) (right).

Google Scholar, Scopus and Science Direct, are increasing exponentially. However, no complete and deep review of the main issues related to the use of simulation tools for historical buildings has been yet developed.

Indeed, although several conferences on building simulation (e.g. Building Simulation – BS, Building Simulation and Optimization – BSO, ASHRAE Building Performance Analysis Conference, etc.) and energy efficiency of historical buildings (e.g. International Conference on Energy Efficiency in Historical Buildings – ECHB, etc.) are arranged separately, and thus some papers dealing with both issues are presented, no events, conferences or other academic initiatives with the aim to develop a shared research agenda about simulation of historical building have been presented.

This paper attempts to bridge this knowledge gap, providing critical factors and possible solutions to support thermal hygrometric simulations of historical buildings. In such regard, in the framework of the International Energy Agency (IEA) Task 59, "Deep renovation of historic buildings Towards lowest possible energy Demand and CO_2 emission (nZEB)" and more in particular in the subtask B.5 "Characterization and simulation of historical buildings", the most significant researches in building simulation applied to historical buildings have been reviewed, studying issues of model creation, set up, and experimental validation. It should be noted that the use of CFD software in the built heritage has been already addressed in other works [49–57], and a deep review has been already published [58]. For this reason, this topic is not covered in the present review.

2. Material and methods

The general purpose of the paper is to discuss common themes, problems, and research needs concerning the dynamic simulation of historical buildings with BES. In detail, this paper aims to identify and quantify the most critical factors that affect the simulation outputs through a detailed state-of-the-art review.

The paper tries to answer the following questions [59]:

- Model realism: how well (and to what resolution) does the model represent reality?
- Input parameters: what values should be used in the absence of measured data?
- Simulation program capabilities: what uncertainties are hidden in the algorithms used to model the various heat and mass transfer processes?

The research methodology is based on two steps: (i) literature review based on keywords to determine the most important issues that affect BES for historical buildings (i.e. opaque and transparent envelope, thermal bridges, thermal inertia, damages, infiltrations, comparison between *in situ* measurement and predicted data, geometric features); and (ii) deeper investigation of specific topics suggested by the literature.

The literature background includes academic studies (i.e. scientific papers, conference proceedings, published books on conservation, energy efficiency, building simulation, and engineering), "grey literature" (i.e. professional guides, technical reports, and governmental guidelines), to consider scientific aspects and theoretical approaches as well as technical advice and practical methodologies. The selection process started with searching main keywords ("Simulation", "Historical building", "Historic building" and "Cultural heritage") in titles, abstracts and keywords of papers within journal papers indexed in Sciencedirect and Scopus. Amongst all retrieved papers only relevant papers related to the use of BES tools in historical buildings have been selected. Finally, in the last step, the references of previous reviewed papers have been included, in order to ensure that all relevant published papers are covered in the present study.

3. Main sources of uncertainty in the simulation output

Virtual modelling of historical buildings is generally considered identical to that of new buildings, since it requires the same steps, hereafter listed [60]:

- realization of a geometric virtual model;
- description of thermo-physical properties of the building envelope, such as thickness of the walls, conductivity, density, specific heat, emissivity, infiltration rate and optical properties of glazed surfaces;
- setting up the operational schedules of the building in terms of internal gains, ventilation patterns, human behaviour and HVAC systems set point;
- definition of the outdoor climate data relative to the study location.

However, according to the features and complexity of historical buildings, several simplifications have to be introduced [2,61]; these represent uncertainties to take into account in the interpretation of the results.

In fact, historical buildings are generally characterized by a complex geometry that involves both the organization of the internal space and the external envelope. Some elements of the architectural language of the past, such as basements, columns frames, portals, cornices, are integral parts of the building and may affect its thermal behaviour. Their presence is often overlooked by current modelling tools because these have been developed to represent more recent buildings. This excess of simplification can unintentionally lead to underestimate thermal bridging effects, whose magnitude may not be negligible [62]. The accurate representation of all discrete spaces comprising the historical building, including zones such as ceiling voids, shafts, staircase etc., also affects the amount of thermal mass in the building and thus its thermal performance [63]. Finally, in the simulation of historical buildings, the shape of openings such as double/triple arched-windows is often simplified [64]: even if the total glazed surface is kept constant to consider the effect of solar radiation and ventilation, this simplification can introduce errors to be considered in the interpretation of the results.

Once the geometrical model is ready, the description of the properties of the building envelope, which include all the thermo-physical features of the technological components, is required. In this regard, the knowledge of the technical and constructive solutions adopted, such as the thickness of the wall (e.g. the bricks texture), the roof, ceilings and floor typology, and all the elements which allow to describe the stratigraphy of the building's components, are pivotal to obtain reliable results [65]. However, the collection of these data can very often be difficult, and several assumptions must be made (Section 3). In addition, the difficulty to assess the correct air change rate of interior spaces - often with huge volume - and the air leakage through wall's cracks, windows' frames or chimneys, add further errors to the final result.

After the envelope characterization, the operation of thermal zones (related to the building function and the users' behaviour) must be set. The function of historical buildings may range from private/residential to public buildings such as museums, libraries, schools and universities. However, this variety requires to record this information *in situ* with interviews and questionnaires submitted to the occupants, or to assume reference values from Standards [46]. For this reason, the parameters related to user behaviour are not deeply discussed in the present work. Moreover, it should be noted that the temperature set point and the human behaviour are typical uncertain variables even in modern building [66], while the paper aims to underline the peculiarity of the historical building.

Similarly, the choice of weather data does not depend on the features of the buildings, and the corresponding uncertainty has the same magnitude as in new constructions, so it will not be explored in the present paper.

Finally, since some errors can also be due to the numerical model that may not adequately capture certain physical phenomena, the

Table 1
Main geometrical and topological constraints for several BES software (adapted from Ref. [75]).

Ref.	Geometrical and topological constraints	Effect's description
[76]	Walls should not contain holes.	Is not possible to model holes or voids without a virtual applicant of a glazed component
[76, 77]	Thermal zones should ideally be convex	Not convex surfaces have to split in convex surface
[77]	Curves should be avoided	Curves should be discretized as several segments
[78]	The direction of the outward-facing normal for the roof overhangs should be downwards.	–

following further limitations mentioned in the Standard [67] are discussed along the work:

- the thermo-physical properties of the materials are time independent (i.e. phenomena like degradation along the time is not considered);
- the various surfaces of the room or zone elements are isothermal (i.e. the walls are considered homogeneous);
- the heat conduction through the room/zone elements is assumed to be one-dimensional (i.e. thermal bridges cannot be considered in the overall simulation);
- the air temperature is uniform throughout the room or zone (i.e. the air stratification in big volumes such as in churches are not take into account).

In the following sub-sections, the main above-mentioned uncertainties related to opaque and glazed envelope (Sections 3.1 and 3.3), thermal bridges (Section 3.2), air infiltration and air stratification (Section 3.4) are discussed.

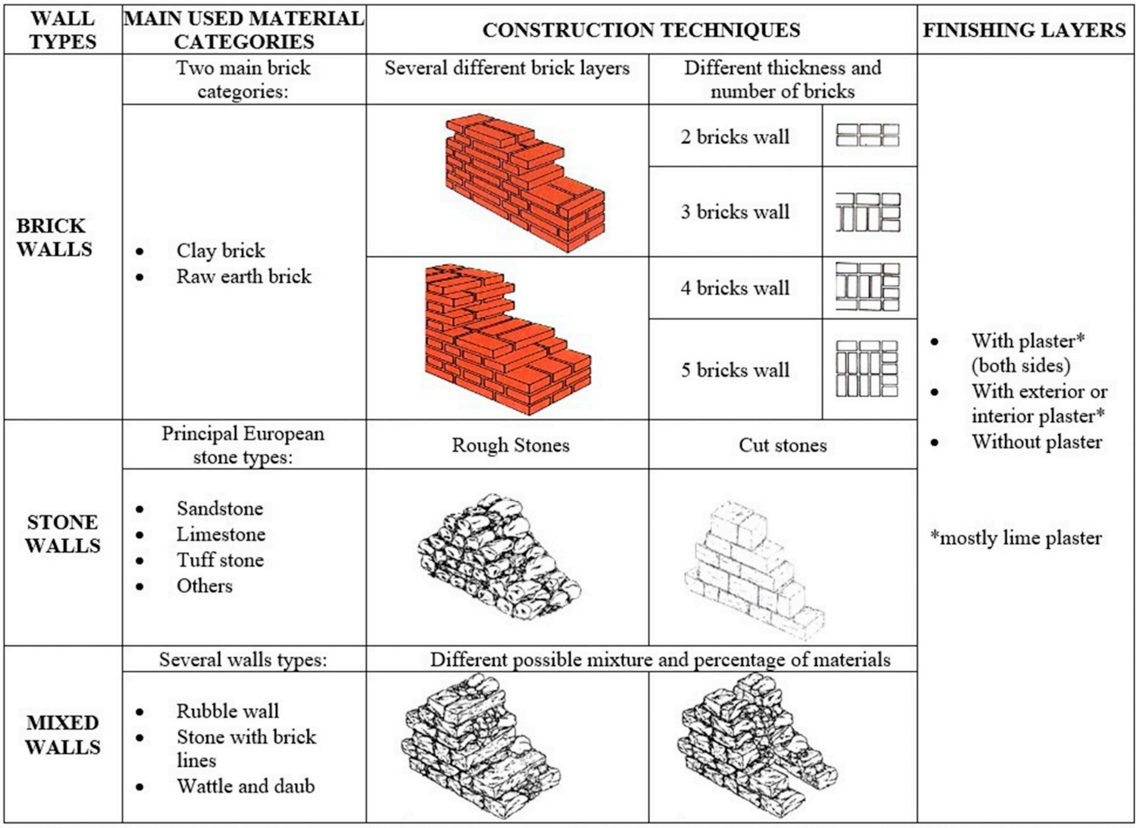
3.1. Opaque envelope

The ISO 13789 Standard defines the thermal envelope area as the "(…) *total area of all elements of a building that enclose thermally conditioned spaces through which thermal energy is transferred, directly or indirectly, to or from the external environment*" [68]. The building envelope provides a thermal barrier between the indoor and outdoor environment and hence the characterization of its thermal properties is a key issues with possible serious effects on the simulation outcomes [62,69]. Heat losses through the opaque surfaces play a predominant role in the energy balance of the building [2,70–72]: in historical buildings, they are reported to range from 10% to 45% [73], depending on climatic conditions, geometry of the building, wall surface area and degree of material degradation.

The most important challenges for the thermal assessment of historical opaque walls are related to the correct definition of (i) the geometry of the building; (ii) the technical features of the envelope; (iii) the thermal properties of the materials. The following paragraphs will discuss the way researchers and designers deal with these issues in the attempt of adopting reliable input values.

3.1.1. Geometric features

The main geometrical features of historical buildings are related to: (i) irregular and complex shapes (e.g. vaults, arches, tapered wall, pilasters, moldings, ornamental parts); and (ii) variable thickness of walls



WALL TYPES	MAIN USED MATERIAL CATEGORIES	CONSTRUCTION TECHNIQUES		FINISHING LAYERS
BRICK WALLS	Two main brick categories:	Several different brick layers	Different thickness and number of bricks	• With plaster* (both sides) • With exterior or interior plaster* • Without plaster *mostly lime plaster
	• Clay brick • Raw earth brick		2 bricks wall	
			3 bricks wall	
			4 bricks wall	
			5 bricks wall	
STONE WALLS	Principal European stone types:	Rough Stones	Cut stones	
	• Sandstone • Limestone • Tuff stone • Others			
MIXED WALLS	Several walls types:	Different possible mixture and percentage of materials		
	• Rubble wall • Stone with brick lines • Wattle and daub			

Fig. 2. Classification of historical building masonries according to the studies on construction history.

and ceilings, in some cases also due to damage problems.

This geometric features can be detected using geometrical surveys but, in many studies, a simplified geometry and a mean wall thickness were considered as an acceptable approximation [62,74], whereas inaccuracies due to oversimplifications in the geometrical features (e.g. columns, barrel vaults, etc.) are instead reported in a research paper about the influence of different architectural configurations on the indoor microclimate of the Malatestiana Library in Italy [62]. Here, although a validation of the thermal model was not performed, the simulations carried out through the CFD module in IESVE presented differences in terms of indoor air temperature and air velocity up to 3 °C and $0.15\,\mathrm{m\,s^{-1}}$, respectively, due to geometrical simplifications. Another study underlined that oversimplifications about the thickness and the thermo-physical properties of the envelope significantly modify time shift and weekly peaks of the simulated temperatures [72].

In conclusion, the main geometrical simplifications required by *EnergyPlus*, shared by several other BES software (e.g. *Trnsys, Open Studio*) [75], are outlined in Table 1, which suggests that idealized models are required rather than detailed building geometries.

3.1.2. *Technical features*

The knowledge of the technical features (e.g. stratigraphy and composition, homogeneity of the building element) is very important for defining the thermo-physical proprieties of the materials.

As a first step, one can rely on historical research based on the knowledge of the local materials and construction techniques. Indeed, the selection of construction materials in the past was related to the geographical location and to the availability of quarries in the local territory, especially for natural stones and cobbles [79]. The studies on construction history classified the historical masonries in three main types: brick walls, stone walls, mixed masonry. Each of them can be divided into further sub-categories, depending on the type of material, the constructive composition and the presence or absence of the plaster (Fig. 2).

Then, a survey based on visual inspections (VI), Non Destructive Testing (NDT) or Low Destructive Testing (LDT) is necessary [2,80]. VI and NDT allow the analysis of the following characteristics: (i) type of building elements; (ii) stratigraphy and masonry wall texture; (iii) wall typology and random nature of its amalgamation; (iv) percentage and proportion of different materials; (v) construction details (i.e. presence of steel chain, connections between vertical and horizontal elements); and (vi) damage, cracks and moisture problems. Particularly, the infrared thermography (IRT) survey provides useful information to identify the thermal anomalies related to the presence of: (i) different thicknesses in the same building element [69,81] (ii) materials with different thermal properties (i.e. concrete/bricks, stone/bricks, steel/stone); [69]; (iii) masonry wall and ceiling textures [80,82–84]; (iv) thermal bridges and excessive heat loss areas [80,81,85,86]; (v) thermal insulation [80–84]; (vi) air leakages [80,81,84,85,87]; (vii) damage, moisture and water [80,86]; (viii) thermal emissivity (ε) [−] of the surface materials [80].

Such information is at the basis of BES for historical buildings [2,19,32,71] but, unfortunately, the above-mentioned techniques provide mainly qualitative data. Therefore, more in-depth tests (e.g. LDT such as endoscopic examinations and extraction of core samples) are needed to have a complete knowledge of: (i) stratigraphy of building envelope; (ii) thicknesses and dimensions of building components; (iii) percentage of materials used; (iv) thermal properties of building materials; and (v) moisture content of building materials. In addition, the extracted samples can be subject to the gravimetric test for an accurate assessment of moisture content [88,89]. However, because of their traditional nature, LDT are not feasible or should be limited to few parts especially in building characterized by aesthetic or historic significance.

3.1.3. *Thermo-physical properties of the materials*

The most important thermo-physical properties needed to describe the behaviour of a building material are: (i) thermal conductivity -λ or λ-value; (ii) density - ρ; (iii) specific heat - c_p; (iv) thermal emissivity - ε; (v) reflection factor - r and (vi) vapour resistance factor – μ [80,90]. Although these values can be either calculated or measured, in the practice of BES the users normally relies on tabulated values provided by various standards [91,92], which are typically obtained from laboratory tests on real building materials. These standards also provide corrective coefficients to consider the impact of the humidity content on the thermal properties [91,92].

Table 2
Classification of bricks used in historical buildings [70,71,95–103]

Type	λ-value (W/mK)	Density (kg/m^3)	Notes
Pre-industrial bricks (XIII-XVIII Centuries)	0.50 ÷ 0.55	1400	Due to clay composition, and to the proportion of sand, raw materials and air
XIX Century's bricks	0.41–0.83	1400–1600	Manufactured with pre-industrial or industrial techniques
XX Century's bricks	0.72	1800–2000	–

To identify the specific thermal properties of a historical material, several methods are available [93]. As an example, the λ-value can be measured through the *guarded hot plate method*, an experimental testing box that imposes on a plane sample a one-way heat flow, and measures the temperature difference -ΔT at its boundaries while also preventing the heat transfer by convection [94]. However, this test requires the extraction of building samples, which is not always possible on heritage materials. For this reason, in several cases, the λ-value is estimated based on the results of *heat flow meter* (HFM) measurements: indeed, if one knows the thickness and the percentage of building materials from geometric reliefs and historical analysis, the measurement of the heat flow transferred through the wall under a certain -ΔT leads to the calculation on an (equivalent) λ-value.

Table 2 reports an attempt to classify the bricks used in historical buildings, based on the results of HFM measurement. On the other hand, the diversity of stones makes it difficult to establish a range for their thermal performance [95–97]. Some general data was reported by Ref. [73], without details about the type of stone ($\rho = 2500\,\mathrm{kg/m^3}$; $\lambda = 2.40\,\mathrm{W/mK}$). Data were reported also for walls made of bricks and stone: (i) brick (60%) and stone (40%) ($s = 0.80\,\mathrm{m}$; $\rho = 2080\,\mathrm{kg/m^3}$; $\lambda = 1.40\,\mathrm{W/mK}$); (ii) brick (20%) and stone (80%) ($s = 0.80\,\mathrm{m}$; $\rho = 2360\,\mathrm{kg/m^3}$; $\lambda = 2.06\,\mathrm{W/mK}$).

As for historical plasters, they are divided in internal ($\rho = 1400\,\mathrm{kg/m^3}$; $\lambda = 0.70\,\mathrm{W/mK}$) and external ($\rho = 1800\,\mathrm{kg/m^3}$; $\lambda = 0.70\,\mathrm{W/mK}$) [103]. No measured data are available for historical mortars. The same applies also to other properties such as ρ and c_p, for which it is usual to rely on available published data and refer to the properties of the materials more similar to that under study [41]. To this purpose, a study on a medieval building located in Bolzano (Italy) verified the impact of the use of a same ρ and c_p for all stone walls on BES, also neglecting the variability of the mortar. The impact was respectively of 19% and 37%, compared to a calibrated model [72].

Apart from the thermal properties of the single materials, building modellers often need to assess the thermal transmittance (U or U-value) of the envelope components as a concise way to characterize them. The U-value is usually assessed through different approaches [80]: (i) by using the standard calculation method, (ii) through analogies with other coeval buildings; and (iii) by measuring it through the HFM or the IRT surveys.

The procedure for the "analytical calculation" for homogeneous and multi-layer masonries is standardized by theISO 6946 [90]. This approach requires detailed input data on stratigraphy, position, and thermal properties of each building material [80,90]. In absence of specific values, their estimation refers to standard values [91,92] or databases [104–106]. The standards also introduce simplified methods to consider the effect of different hygrothermal conditions [90–92]; however, a "standard" surface resistance [90] is adopted, which does not consider the presence of decay, dirt or superficial injury [79].

The analogy with coeval buildings assumes the U-value by referring to similarly-aged buildings with well-known materials, masonry textures, geometric features and thermal characteristics [70,80]. In historical and existing buildings this approach has several uncertainties related to wrong information on construction features, possible unawareness of refurbishments, and presence of damages, ageing, and moisture [71,80]. Moreover, one main limitation of this approach is that the European databases [104–106] identify only one age-class for historical constructions (building built before 1945).

To overcome the inaccuracies related to the methods previously described, HFM measurements are used [2,32,71,72,107,108], according to the standard ISO 9869 [108] to avoid errors affecting the measurement accuracies. These affects are related to: (i) location of the probes; (ii) non-homogeneity of the materials; (iii) heat flux perturbation generated by the HFM itself; (iv) thermal inertia of the wall; (v) data processing techniques; and (vi) influence of boundary conditions. Furthermore, the literature suggests some further advices for the proper installation of the probes in order to reduce their impact, especially on massive and historical masonries [79,95,98,99,108–110].

The measured U-values of historical masonries with various thicknesses and showing different stone to mortar ratios have been compared in several papers [79,95,96,98,100,102]. A further comparison among measured and standard values from the Italian technical norm [111] showed that, in the case of brick walls, the norm usually overestimates thermal transmittance values in the range by 2%–57%, according to the specific brick composition and construction technique.

On the contrary, the diversity of stones and the proportion of air voids or gaps make it very hard to establish a range for their thermal performance [100]. In particular, the U-values of stone masonries can vary by ± 8–10% when considering the presence of mortar, whereas, if accounting also for the numerous small air gaps, this variation can reach 70.5% [79,100]. This has been confirmed by Ref. [108]: here, the U-values were measured for calcarenite stone walls in a monumental building of Palermo (Italy) over a two-year period, and the results turned out to be 48.6% lower than the calculated values where voids and moisture content are neglected. Hence, when it comes to appraising the heat transfer through walls, the λ-value should be defined in terms of stone porosity as well. Particularly, this value for porous materials is affected also by deterioration mechanisms such as black crusts, which depend on the random presence of voids [112,113]. Finally, some research has been conducted proposing a method for accounting the influence of moisture on the thermal performance of such masonry structures [114], an aspect that will be more closely dealt with in the next section.

3.1.4. Moisture transfer and humidity content in the materials of the building envelope

The humidity content of the envelope materials may have a significant influence on heat transfer calculations, as well as on the appraisal of moisture transfer mechanisms and indoor thermal comfort conditions. As hygroscopic materials may be widely found in historical buildings, phenomena such as moisture buffering effect and varying λ-values depending on moisture content, should be taken into account.

Moisture buffering is the ability of indoor surface materials to moderate the indoor air humidity variations through adsorption and desorption cycles. In historical buildings, examples of materials with high buffering capacity are lime plaster, wood, gypsum plaster, daub and cob walls. To analyse these cycles, the concept of Moisture Buffer Value (MBV), indicating the amount of moisture uptake/release from a material when it is exposed to diurnal relative humidity variations [115, 116]. When it comes to simulate moisture buffering effects, Zhang et al. [117] indicated the combined Heat And Mass Transfer dynamic model (HAMT, refs. [117,118]) as the most appropriate to account for moisture exchange between the enclosure surfaces and the indoor environment. The HAMT model is available in several building simulation tools like EnergyPlus and TRNSYS, which could be used to assess the impact of moisture buffering on building energy consumption.

When considering a building's energy consumption, the impact of humidity content could be relevant especially during the cooling season in hot and humid climates, as demonstrated by Qin et al. who developed a model for predicting the whole building multi-zone hygrothermal-airflow transfer in MATLAB-Simulink [119]. Findings show that moisture transfer through hygroscopic envelope materials may have a strong influence in mitigating summer indoor relative humidity values in various climates. Moreover, the use of such materials can be successfully simulated only if considering the combined heat and moisture transfer. In fact, under these circumstances, the predicted cooling energy demand and the peak cooling loads in hot-humid climates have been found to be 16% and 33% lower respectively than those simulated using traditional BES tools. On the other hand, heating needs and peak load are almost unaffected by the different calculation approach. In addition, in dry climates, models that ignore moisture transfer may overestimate conduction peak loads up to 210% and underestimate the yearly integrated heat flux up to 59% [4]. This can lead to oversize the HVAC equipment and to underestimate the energy consumption in humid climates.

As far as variations in the λ-value of the materials through time are concerned, Stazi et al. [120] reported that the properties of mineral wool insulation layer in a historical building has been largely modified through 25 years of services. In particular, the degradation of the polymeric binder has caused the decrease of the hydrophobicity of the material allowing for a greater water sorption.

However, most BES software tools consider the λ-value of the different materials – along with other properties such as ρ and cp – through constant values. These values usually refer to the "dry" material, or to standard humidity content. Some research has been conducted in this field to define an effective (or apparent) λ for hygroscopic materials. As an example, a study on [121] the apparent λ-value of normal concrete, aerated concrete and clay bricks showed a correction of 2.0%, 6.7% and 4.3% respectively on the dry value when the water vapour pressure of outdoor air increases from 1000 Pa to 4000 Pa. Gomes [122] presented an investigation on the influence of moisture content on the thermal conductivity of seventeen external thermal mortars. The differences between dry theoretical values and operational conditions under actual moisture content, appraised via on-site measurements on seven points, showed that a correction is needed to account for increasing humidity contents. This correction can be done analytically by following the ISO 10456 Standard [92] without a significant loss in accuracy.

Finally, because of the heritage and cultural value of many historical buildings, for façades that are considered for interior insulation retrofits, the potential for moisture related damage due to driving rain and moisture penetration must be carefully assessed [123]. Particularly in cold climates, the addition of interior insulation to historical load-bearing masonry walls can significantly alter the thermal gradient within the walls such that a greater portion of the masonry is colder [124,125] and has less drying potential [126]. This can lead to masonry freeze-thaw damage [127] as well as salt migration when water evaporates leaving behind salts [17]. When the masonry experiences freeze-thaw and wetting cycles, damage and accelerated erosion of the masonry can occur, which may change the material properties of the masonry [128]. This is because interior insulation lets the masonry wall have less drying potential to the outside in cold weather while showing a larger potential to transport moisture towards the warmer inside and thus leading to unwanted moisture accumulation [129,130].

Table 3
Software tools for numerical calculation of thermal bridges (the list does not include those tools that are not available in English, and that are used only on a national basis).

Software	Software house	2D/3D	Capabilities[a,b]	Mesh shape[c]	Psi-value[d]	License
ANTHERM	Kornicki	3D	HT, SS/TR	R	YES	Commercial
BISCO/BISTRA	Physibel	2D	HT, SS/TR	FF	YES	Commercial
FLIXO	Infomind Gmbh	2D	HT, SS	FF	YES	Commercial
HEAT 2	Buildingphysics.com	2D	HT, SS/TR	R	YES	Commercial
HEAT 3	Buildingphysics.com	3D	HT, SS/TR	R	YES	Commercial
THERM	LNBL	2D	HT, SS	FF	NO	Free
TRISCO/VOLTRA	Physibel	3D	HT, SS/TR	R	YES	Commercial
WUFI 2D	Fraunhofer IBP	2D	HAM, TR	FF	NO	Commercial

[a] HT: Heat transfer only; HAM: Heat, Air and Moisture Transfer.
[b] SS: Steady state calculation; TR: Transient calculation.
[c] R: Rectangular mesh only; FF: Free Form mesh.
[d] This field indicates if automatic calculation of the psi-value is provided.

3.2. *Thermal bridges*

According to the EN Standard 10211 [131], a thermal bridge is "*a part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity, and/or a change in the thickness of the fabric and/or a difference between internal and external areas*". Thermal bridges are called "linear" when they show a uniform cross-section along one of the three orthogonal axes, and their size can be described in terms of length (e.g. a balcony or a pillar). However, in some cases *point thermal bridges* can be identified, such as small metal studs or dowels: even if their size is small, their effect can be non-negligible.

In a portion of the envelope affected by a thermal bridge, the temperature field shows significant deviations from the otherwise monodimensional profile typical of homogenous walls. This implies a local increase in the heat transfer rate by conduction. In order to quantify the influence of a linear thermal bridge on the total rate of heat flow transferred through the envelope, the *linear thermal transmittance* is used, which is also called "psi-value" (ψ) [$W{\cdot}m^{-1}{\cdot}K^{-1}$], and quantifies the rate of heat flow transferred through the thermal bridge per unit length and per unit temperature difference, in addition to that transferred through the undisturbed envelope component. Analogously, a *point thermal transmittance* (χ) [$W{\cdot}K^{-1}$] is associated to a point thermal bridge.

When dealing with linear thermal bridges in BES, a major difficulty is the possibility to identify a reliable *psi-value*. To this aim, the ISO Standard 10211 [131] suggests that numerical calculations using a two-dimensional geometrical model of the detail including the thermal bridge should be used. In case of point thermal bridges, even three-dimensional numerical calculations are needed.

Many software tools are available to perform this kind of calculation; the most widely used are reported in Table 3. Their reliability has been validated by comparison with the results of some test reference-cases reported by the ISO Standard 10211, meaning that the resulting point or linear thermal transmittance diverges by no more than 5% from reality.

As an alternative to numerical calculation, which in some cases may be arduous and time-demanding, it is possible to make use of databases or "atlases". Here, the linear thermal transmittance for a high number of common linear thermal bridges is provided through tables or by means of simplified analytical formulations. However, their validity is normally limited to an assigned range of the most relevant parameters describing the envelope components (s, U-value, λ-value of the insulating material); moreover, a deviation by around 20% from reality should be expected. Examples of this approach can be found in Ref. [132] or in the so-called "CENED atlas" [133], which is implemented in many software tools for energy certification of buildings in Italy. Finally, other "default" values for the linear thermal transmittance of a limited number of common and rather simplistic thermal bridges can be found in the ISO Standard 14683 [134]; however, these values are affected by a deviation by up to 50% from reality. A special case of an interactive atlas is "KOBRA"; in this atlas, the dimensions, the thermal conductivities and the boundary conditions of predefined topologies can be changed and the value of the linear thermal transmittance is accurately recalculated for the precise case.When it comes to the dynamic energy simulation of the whole building, it must be observed that most of the common software tools do not allow rigorous addressing of the heat transfer through thermal bridges. In particular, since each surface of the building is described by only one temperature node, the equations to calculate the heat transfer by conduction in the opaque components cannot explicitly include thermal bridging effects.

In this case, the user has to resort to expedients to bypass this limitation and to include the effect of thermal bridges. As an example, in EnergyPlus and OpenStudio it is possible to introduce small sub-surfaces with no thermal mass, whose thermal resistance is assigned by the user so that the same heat transfer rate as in the thermal bridge occurs. Of course, in this case the user needs to perform a preliminary calculation of the thermal bridge through other tools. Similarly, in DesignBuilder and IES it is possible to assign a modified U-value to each opaque component so that it includes the thermal bridging effects, as in the following equation:

$$U_{\mathrm{mod}} = \frac{U{\cdot}A + \sum_{j=1}^{n}\left(\psi_j{\cdot}L_j\right) + \sum_{k=1}^{p}\left(\chi_k\right)}{A} \tag{1}$$

An example of this approach is provided in Ref. [135]. Once again, the user has to assess preliminary the linear and point thermal transmittance through other tools.

It is then obvious that the modelling of thermal bridges in dynamic energy simulation tools is an important source of inaccuracy. In fact, a first approximation comes from the choice of the tool used to calculate the point or linear thermal transmittance (numerical calculation, database, atlases). Then, a further source of approximation is introduced when the user calculates the modified U-value. In this sense, a more effective approach is followed by the Ladybug Tools, a set of open-source applications working in the Grasshopper environment. Here, it is possible to set a parametric workflow where a routine based on THERM calculates the linear thermal transmittance for each thermal bridge; the results are then transferred to another routine that calculates the thermally bridged U-value according to Eq. (1), and communicates it to Honeybee, i.e. the tool that allows dynamic energy simulations based on the EnergyPlus calculation engine. Through this workflow it is then possible to reduce the sources of inaccuracy. This methodology has been seldom used in the literature; as an example [136], applied it to a modern residential building in South Korea.

The outlined problem in the description of standard thermal bridges is common for all type of buildings (new and existing ones) when BES are used. But, in the case of historical buildings, the criticality is more

Table 4

Papers dealing with the calculation and the solution of thermal bridges in historical buildings.

Ref.	Building typology	Age	Location	Envelope	Insulation	(IN/ OUT)	Thermal bridges	Psi-value calculation	Mould verification	Calculation approach
[143]	Listed manor house	1720	Slovakia	Brickwork, decorated with frontons and capitals	MULTIPOR® calcium-silicate boards (250 mm)	IN	Window sills, slab/wall junctions	NO	YES	TEPLO 2015 (numerical, 2D)
	Residential	Non specified	Slovakia		STYRCON polystyrene/cement boards (250 mm)					
[144]	Residential	1900s	UK	Brickwork	Expanded polystyrene (90 mm)	OUT	Wall/roof junction (eaves)	YES	YES	TRISCO 12.0 (numerical, 2D)
[28]	–	Late 1800s	Sweden, Norway	Brickwork with wooden beams	Vacuum Insulating Panels (VIP, 20 mm)	IN	Wall/beam junction	NO	YES	WUFI 2D (numerical, 2D) and laboratory measurements
[145, 146]	Residential	1930	Sweden	Brickwork (ground floor), wood (top floors)	VIP (20 mm) + glass wool (30 mm)	OUT	Around windows, between VIP boards	YES (modified U-value)	YES	WUFI 2D (numerical, 2D) and onsite measurement
[147]	Residential	1952	Italy	Reinforced concrete and brick walls	Expanded polystyrene (20 mm) + insulating plaster (20 mm)	OUT	Balconies, pillars and beams, wall corners, slab/wall junctions	YES	YES	THERM 7.2 (numerical, 2D)
[148]	Dormitory	1820	Denmark	Masonry walls	MULTIPOR® calcium-silicate boards (100 mm)	IN	Spandrel, dowels	NO	YES	IRT imaging, onsite measurements
[149]	Residential	Early 1900s	Austria	Brick walls, wooden slabs	Insulating plaster with perlite or aerogel (20–50 mm), expanded polystyrene (20 mm)	OUT	Natural stone cornices, slab/walls junction, window casement	YES	YES	ANTHERM 7.125 (numerical, 2D)
[150]	Residential	Late 1800s	Denmark	Brick walls and wooden beams	Mineral wool and aerogel (40 mm), rigid phenolic insulation (40 mm)	IN	Wall/wooden slab junction	NO	YES	HEAT 2 (numerical, 2D)
[151]	Residential	Early 1900s	Denmark	Brick walls and wooden beams	Timber studs and mineral wood (95 mm)	IN	Wall/roof junction, Wall/wooden slab junction	NO	YES	HEAT 2 v.5.0 (numerical, 2D)
[152]	Residential	Non-specified			Insulating plaster, insulating boards	IN or OUT	Window sills and reveals	YES	NO	Non-specified

important because of the difficulty in identifying them and in describing their exact geometry. This is especially true in historical buildings, where the superposition of several interventions made in different time periods may significantly modify the composition of walls and slabs, thus making them very different from what is described in the original design documentation, if available.

To this aim, the IRT survey has been recently proposed as an effective strategy to identify and describe thermal bridges in historical buildings [137–139].

One point that emerges from this literature review is that the heat losses through thermal bridges in uninsulated historical buildings are often neglected, as also discussed by Cornaro et al. [140] for a historical building near Rome, built in the XVI century, where the vertical walls are mainly made of a mixture of different types of stones like tuff, basalt, typical spur stone of Colli Albani and bricks, held together by a mortar volcanic pozzolan.

However, the role of thermal bridges can no longer be neglected when designing energy retrofit interventions that imply an improvement in the insulation level of a historical building, especially if the insulating material is applied on the inner side [141]. Indeed, although internal insulation is not the ideal solution to reduce heat losses, it is still a very common strategy to preserve the integrity of historical façades. In this case, the effectiveness of the insulation is limited as a result of its breakage in the joints between outer walls and vertical/horizontal partitions: this means that the thermal bridges must be modelled in detail to verify their impact on the overall energy balance as well as the risk of mould growth, induced by low local inner surface temperatures.

Even if in some papers the calculation of thermal bridges in historical buildings is oversimplified, which may underestimate their effect [142], a considerable number of works in the literature addressed the thermal calculation of thermal bridges for insulated historical walls through a thorough approach, with the aim to optimize the main construction details. A list of the most significant works is reported in Table 4, where it is possible to find information about the approach used for the calculation of the thermal bridges and the kind of results produced by the study (calculation of the psi-value, verification of the mould growth).

Amongst the thermal bridging details discussed in the references of Table 4, some noticeable solutions can be underlined. In particular, Glew et al. considered the possibility to install internal covings to correct the thermal bridge occurring at the junction between walls and roof, where the presence of the eaves breaks the continuity of the outer insulation. Six different coving shapes are investigated, and the most performing one allowed reducing the psi-value by around 25%. On the other hand, Harrestrup et al. found out that, in the thermal bridge resulting from the junction between brick walls and wooden beams, it is possible to reduce the risk of mould growth in the beams by stopping the inner insulation 200 mm above the floor.

However, it must be observed that only in one of the above-listed papers the results of the numerical calculation for the thermal bridges are then used to improve the precision of a dynamic energy simulation model including the whole building [150]. This suggests that the inclusion of thermal bridging effects in dynamic energy simulation of is still far from being mature for historical buildings, and that numerical calculation tools are mainly used as a support to design the construction details and to verify that no mould growth occurs.

3.3. Transparent envelope

Transparent elements in buildings are generally windows, skylights, glazed surfaces of opaque doors and glass blocks [153]. In particular, windows play a vital role for any type of buildings to admit light during the day and to provide an external view. Historical buildings are typically characterized by small window areas if compared to modern buildings: as an example, a group of historical residential buildings in Italy reported a Window to Wall Ratio (WWR) of about 4% [154]. Nevertheless, windows are still responsible for a significant heat transfer rate.

Table 5
Typical geometrical and topological constrains of Energy Plus and other BES software (Adapted and elaborated from Ref. [75]).

References	Geometrical and topological constraints	Effect's description
[76,159]	In several tools, openings must be rectangles or triangles	Windows with complex shape must split in several smaller windows with simplified shape
[76,77, 159]	Openings must not "touch" each other	Two or more windows cannot share the same frame, and have to be ficticiously split
[76,77]	Openings must not share two edges with walls or floors or roof	The window cannot be placed exactly in a corner of the wall surface
[160]	There cannot be a wall that is only a window	A surface cannot be totally glazed
[77]	A window or door should not be placed inside a subsurface	Doors cannot be drawn with glazed part. Double windows cannot be modelled.

3.3.1. Geometric features

Historical windows can have very different shapes and dimensions. Windows used in traditional buildings, especially palaces and villas, usually have square and rectangular shapes that can be easily modelled with BES. However, windows used in churches, castles, and other peculiar buildings, are characterized by circular, mullioned or irregular shapes that require some geometrical and structural simplification to be successfully modelled [32,155–157]. This is because BES software tools present geometrical and topological constraints to comply with in the modelling process [75], as summarized in Table 5. It should be noted that, even if Table 5 refers to the *EnergyPlus* features, since it is the most adopted tools, several other software tools (e.g. Trnsys, Open Studio) shows the same constrains [75].

The user should be aware that, in the process of geometrical simplification of complex windows shapes, the overall area of a window must be kept equal to the actual value [158]. Otherwise, the simplification might result in discrepancies with the original heat transfer area of the windows, thus affecting the magnitude of the heat flow through the transparent component.

3.3.2. Technical features

Peculiar technical features of transparent elements in historical buildings are: the homogeneity of the materials employed, alterations of the same materials and damaged transparent elements. Typically, historical buildings have single-glazed windows or "box windows" (also called "isolated window units", "double window units", "storm windows", "kastenfenstern" or "secondary glazing") composed by double-skin windows with two layers of wooden side hung sashes, each with a single pane of glass [161,162]. Single-glazed windows are more used in warm and hot climates, while double windows - originally used as a closed system for creating a thermal buffer zone [161] - are mainly used in cold climates, despite their application has been reported also in the Mediterranean area [161].

In terms of frame materials, historical windows may present metallic or wooden frames, which typically account for a large portion of the total window area [163]. Old wooden frames hold moisture from the air and may contribute to decrease indoor air quality as well as the thermal and the structural performance of wood.

3.3.3. Thermo-physical properties

For a correct description of the thermo-physical properties of window panes and frames, the knowledge about the thermal and the optical properties of the glazing panes are crucial. Then, the energy characterization of the transparent building envelope requires the knowledge of:

Table 6
Glass dirt-correction factors for windows of historical buildings [178].

Type of location	Vertical glazing	Sloped glazing	Horizontal glazing
Clean	0.9	0.8	0.7
Dirty	0.7	0.6	0.5
Very dirty	0.6	0.5	0.4

(i) the U-value of the whole window (frame and glazing); (ii) the solar transmittance factor (g or SHGC); (iii) the visible transmittance (τ_v). The latter however is not compulsory, since it affects the daylighting performance of the building only. In general, in the absence of experimental measurements of λ-value, the U-value of old clear glazing can be easily derived considering the standard value of the float glass - equal to 1 W/(m·K) [164] - and its thickness, along with the standard surface heat transfer coefficients. Generally, the windows of historical buildings are manufactured with timber or metallic frames, resulting in a wide variety of thermal performance and airtightness [165]. The wood frames, very often, were constructed with high quality wood, such as old growth wood which is extremely dense, strong, and resists warping. However, the U-value of such materials depends on several parameters that are difficult to accurately measure, including the λ-value of the different type of woods, their moisture content, and their homogeneity. Similarly, the U-value of metallic frames depend on physical properties of different metals (i.e. iron, aluminium, steel) as well as on the presence of voids and non-homogeneity.

As reported by Refs. [161,162], the U-value of windows is finally estimated in three major steps: (i) standard calculation of the centre-of-glazing values using one dimensional (1D) models [166,167]; (ii) standard calculation of multi-dimensional and frame effects on window using 1D or 2D heat transfer thermal models [168–170]; and (iii) simulation of the energy behaviour of the window as a combination of glazing and frame [169,170]. Remarkably good agreement between calculation and measurement are reported in the literature, especially for manufactured windows [162]. The application of these calculation procedures requires detailed input data and laboratory test, especially for the determination of the U-value of frames. For this reason, its determination for historical single-glazed windows with wooden or metallic frames turns out to be problematic [2,97,154,171]. The type of frame affects not only its thermal performance but also the air infiltration. The air-tightness of timber-framed windows is, in fact, often considerably worse than metallic-framed windows due to the presence of cracks and gaps between timber frame and walls [172]. A detailed assessment of air infiltration issues throught the envelope is discussed in section 3.4.

Of course, some specific software tool can be used to identify the detailed features of typical windows, amongst which Windows is worth mentioning [173]: it is a freeware tool that allows the integration with BES such as EnergyPlus. In particular, it calculates the U-value, the g-value, the shading coefficient, as well as the visible transmittance for the whole window system. Although this value is typically calculated according to standards [164,174], or provided by windows manufacturers for new installations, in the case of historical windows it is hard to unambiguously define its value because of dirt accumulation through time, which may have significantly lowered the original value [171]. In such respect, some researchers used glass-dirt correction factors to reach more accurate results in their simulation studies [156,175–177]. The first studies on dirt and dust on transparent surfaces date back to the 1980s [176], where an analytical model for surfaces covered with a thin layer of dust was derived. Tregenza et al. [177] studied the impact of dirt effects on glasses, showing that the g-value was reduced by 4–8% in comparison with clean glazing.

Table 7
Air change rate per hour for different tightness of envelope construction.

Tightness of envelope construction	Average air change rate per hour (ACH)
Tight	0.2–0.6
Medium	0.6–1.0
Loose	1.0–2.0

The value of the glass dirt-correction factor to apply to the original (clean) optical features of the glass mainly depends on air pollution, slope of the glazing and its cleaning schedule, as reported in Table 6.

Moreover, some technical solutions often adopted in historical building, such as the use of "double windows unit", cannot be easily modelled in BES. To overcome this issue the U-value can be calculated manually [179], after that the equivalent thermal proprieties can be applied to the glazed surface in BES.

Other issues are related to the knowledge and modelling of the thermo-physical proprieties of windows characterized by several materials within the same frame, such as the stained glass windows. They consist in coloured glass used to form decorative or pictorial designs, typically by setting contrasting pieces in a lead framework like a mosaic and used often for church windows. In order to proper set the thermal and optical features in BES, detailed experimental measures are suggested even if theoretical calculation can be carried out. Wolf et al. [180] calculated the U value of a stained glass taken from Vitromusée Romont's in a climatic chamber, reporting a U-value of 5.78 W/m^{2}K. Even if such windows are generally characterized by high U-value, according to the abovementioned research the thermal losses through the stained glass windows can be neglected if compared with the losses through the walls, because the glazed area is about 5% of the opaque one.

The spectral transmission and reflection coefficients of the stained-glass windows have to be measured on each sample belonging to the window through a spectrophotometer. The results in term of solar transmission and visible transmission can vary drastically according to the type of glass finishing, the colour of the glass and its age [181]. The experimental measurement on several coloured samples carried out in compliance with UNI 7885 [182] and EN 410 [164] by Buratti [181] showed that the g-value can vary in the range between 5 and 80%, while the reflection coefficients are always below 15%. The visible transmission of the tested component have generally lower values, in the range from 0.15% (violet colour) to 49% (yellow colour). Of course, it should be underlined that the reported values are related not only to the glazing colour but also to the type of application technique of the colour (e.g grisaglia, paste, glaze, etc).

3.4. *Infiltration and air stratification issues*

The standard EN 15759:2 [183] defines infiltration as the *"unintentional or accidental introduction of outdoor air into a building through gaps in the building envelope, often located in the frames and fittings of doors and windows"*. According to ASHRAE Handbook [184], "*infiltration is the flow of outdoor air into a building through cracks and other unintentional openings and through the normal use of exterior doors for entrance and egress. Infiltration is also known as air leakage into a building. Exfiltration is the leakage of indoor air out of a building through similar types of openings. Like natural ventilation, infiltration and exfiltration are driven by natural and/or artificial pressure differences*". Both definitions suggest the high dependency of infiltrations on building age, construction quality, building use and external boundary conditions. In such respect, one of the major difficulties in BES simulation is the possibility to identify a reliable input value for the infiltration rate: infiltration rate has been consequently ranked as one of the key variables affecting the accuracy of simulation results [185].

In BES software, infiltration rate is generally assigned through the parameter ACH (air change rate per hour), with a constant or variable value. To this aim, several empirical and theoretical models to evaluate the air change rate have been introduced [186], the most commonly adopted in historical buildings being:

Table 8
Infiltration rates in historical buildings for different typologies and locations.

Ref.	Building typology	Age	Location	Infiltration rate (h^{-1})	Main leakage sources	Infiltration estimation method
[200]	Church	13th century	Lisbon, Portugal	0.28–0.7	Openings	Tracer gas
[201]	Church	1851	Hamrange, Sweden	0.22–0.49	Doors	Tracer gas
	Church	16th century	Ludgo, Sweden	0.99	Doors	Tracer gas
	Church	1792	Söderfors, Sweden	0.81	Doors	Tracer gas
	Church	13th century	Valbo, Sweden	0.52	Doors	Tracer gas
	Church	mid-12th century	Visby, Sweden	0.62	Doors	Tracer gas
[202,203]	Church	14th	Tarnow, Poland	0.12–0.8	Openings	Tracer gas
	Church	15th	Krakow, Poland	0.34–2.4	Wooden structure	Tracer gas
[204]	Church	1365 to 1400	Krakow, Poland	0.17–0.27	Openings	Tracer gas
	Church	1736 to 1756	Szalowa, Poland	2.7–2.9	Doors,	Tracer gas
[205]	Church	1400	Loosdrecht, Netherlands	0.8–1	Roof (wooden)	Tracer gas
	Church	1869	Schiedam, Netherlands	0.5–0.6	Openings	Tracer gas
	Church	1456 to 1500	Zwolle, Netherlands	0.08–0.33	Doors	–
	Church	1720	Houthem, Netherlands	0.21	Openings	Tracer gas
	Church	1285 to 1470	Dordrecht, Netherlands	0.06–0.11	Openings	Tracer gas
	Church	1872 to 1873	Bemmel, Netherlands	0.06.	Openings	Tracer gas
	Church	1470 to 1512	Alkmaar, Netherlands	0.4–1.2	Openings	Tracer gas
[206]	Church	14th –17th centuries	Harju Risti, Estonia	0.3–0.6	Doors, windows	Tracer gas
[207]	Church	1642	Velika Mlaka, Croatia	Chapel: 0.8–1.5 Otherwise: 0.5	–	Assumption
[208,209]	Palace	19th century	Benevento, Italy	0.5–1.2	Windows	Standard value
[210,211]	Palace	1854	Trento, Italy	0.3–0.5	–	Standard value
[71]	Palace	16th century	Rome, Italy	0.1	–	Assumption
[32]	Palace	13th century	Bologna, Italy	0.224[a]	Windows	Blower door test
[193]	Palace	1513	Naples, Italy	1.5	User behaviour and poor airtightness	Assumption
[212]	Palace	1927	Benevento, Italy	1.5	Windows	Calculated
[213]	Palace	17th century	Modena, Italy	0.5/0.6	Wooden window frame	Calculated (ISO 13789)
[156]	Palace	12th century	Bolzano, Italy	0.8	–	–
[194]	Palace	1860	Agrigento, Italy	0.2	–	Assumption
[214]	Palace	17th –18th century	Perugia, Italy	0.7	–	–
[215]	Palace	20th century	Catania, Italy	0.25	–	–
[216]	Palace	1910	Norrköping, Sweden	0.2–0.4	Window frames	Tracer gas
[217]	School	1950	Vicenza, Italy	0.25	Windows	Calculated (EN 12831:2003)
[218]	School	1970	Galicia, Spain	0.19–0.83	Windows, user behaviour	Calculated (ASHRAE Handbook)
[219]	Museum	19th century	Krakow, Poland	0.1	–	–
[196]	Museum	17th century	Amsterdam, Netherlands	<0.1	Air leakages	Assumption
[220]	House	16th –19th century	Loire Valley, France	0.86	Windows	Blower door test
[221]	Houses	–	Coimbra, Portugal	0.64–1.63	Air leakages	Blower door test
[222]	Houses	1600–2000	Estonia, Finland, Sweden	0.23–1.92	Windows	Tracer gas
[223]	Dwelling	–	Grosseto, Italy	0.7	–	–
[17,18]	Dwelling	18th –19th century	Catania, Italy	0.5		Assumption
[224]	Tower	16th century	Thessaloniki, Greece	Tower: 0.9–1.5 Lower floors: 2.5	Windows, doors	Tracer gas
[225]	Monastery	10th century	Chalkidik, Greece	1.0	–	Assumption

[a] Calculated from the ACH at 50 Pa.

- tabular values based on the construction tightness;
- reduction of fan pressurization test data, also known as blower-door-test;
- tracer gas dilution method.

The first one relies on a database providing average air changes per hour according to the construction tightness [186–188], as shown in Table 7. In spite of its simplicity, this method cannot capture the specific features of the building (e.g. material porosity, cracks). Moreover, the values reported in similar databases are usually obtained from experimental campaigns on modern constructions, thus high inaccuracies are likely to occur when working on historical buildings.

The second method consists in the experimental evaluation of the air change rate under a pressure difference of 50 Pa (n_{50}), mechanically induced through a fan (blower door test). Starting from this value, the following simplified empirical relation can then be used to assess the infiltration rate for average operating conditions (n_{avg}):

$$n = k \cdot n_{50}$$

Here, k is a constant that ranges between 0.01 and 0.1, depending on the number of facades exposed to wind and on the presence of shields, such as trees or other buildings, in the surroundings [111].

The third listed method, i.e. the tracer gas dilution, is conducted at almost normal operating conditions and may provide more satisfying results under those conditions [189]. It consists in the introduction into the building of a uniform concentration of tracer gas, which is then allowed to decay naturally as a result of dilution by air infiltration from outdoors [190,191]. The ACH value can be calculated according to the concentration decay.

Due to its reliability, the tracer gas dilution method is the most used in historical churches, which have a unique huge volume [192].

According to this literature review, even if in some papers the

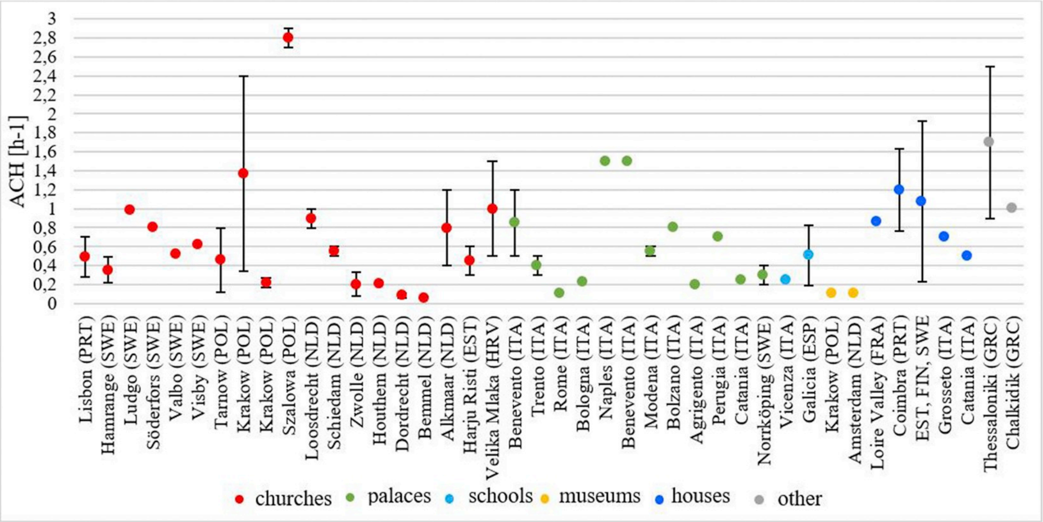


Fig. 3. ACH values estimated for different typologies of historical buildings.

calculation of infiltration rate in historical buildings is oversimplified [71,193–199], a considerable number of works have addressed the calculation through detailed evaluation. A list of the most significant works is reported in Table 8, which displays the main information about the approach used for the calculation of the air infiltration rate and the kind of results provided. Different typologies of historical buildings (churches, palaces, schools, museums, etc.) placed in different locations were considered. Such data can be regarded as a useful reference when detailed data about the building under investigation is missing.

In order to improve the readability and the understanding of the data, in Fig. 3 the ACH ranges for each case study shown in Table 8 are grouped according to the building typology.

The literature review outlines that in the different building typologies the range of variation of the ACH is high, but no specific trend can be identified. The ACH goes from minimum levels for those buildings that have good construction tightness and relatively small openings, to high levels in buildings with poor construction tightness. These are made with materials permeable to the air or even damaged (as wooden construction elements), and usually present relatively large openings (which could be affecting by the user behaviour). The only exception is represented by schools and museums, where more uniform infiltration rates are observed. In particular, museums require a proper control of the indoor microclimate and show very low infiltration rates.

In conclusion, due to the uncertainty in the input values, which then affect BES results, users should be very responsible in introducing proper ACH value according to specific surveys and measurements.

Moreover, as already introduced, in BES simulation the air temperature is considered uniform throughout the room or zone. Such assumption can introduce significant inaccuracies in high-rise indoor spaces such as churches, since the vertical temperature gradient due to thermal stratification is not taken into account. The extent of the vertical temperature gradient in an indoor space depends on its height and on the type of heating system, if available. It can be neglected when the height is below 3 m, but usually in historical buildings this height is overcome. The gradient is normally positive in the heating season, i.e. the air temperature increases with height, and is particularly evident in case of convective heating systems.

As an example, Varas-Muriel et al. measured the vertical stratification in a 5 m high navy of a heated church, and they found that close to the ceiling the air temperature was 4 °C and 3 °C higher than at the ground level, respectively without and with congregation [226]. Camuffo et al. [227] investigated the temperature distribution in the Giant Hall, a magnificent 8.6 m high ceremony room in a mediaeval palace in Italy. The vertical temperature gradient turned out to lie between 0.1 °C/m and 0.2 °C/m, except when the doors are open and thus the gradient is enhanced by the penetration of cold air.

Hence, ignoring this issue in BES can introduce a significant underestimation of the energy demand for space heating. Indeed, when the ground level is kept at a comfortable temperature for the occupants, the upper air layers are much hotter, and higher heat losses occur – especially through the ceiling – than with uniform air temperature.

In order to predict the temperature – and humidity – vertical distribution, some simplifying modelling approaches can be used. As an example, the so-called zonal modelling was implemented by De Backer et al. in TRNSYS to a 15-m high church in Belgium, where a vertical temperature gradient of 5 °C was observed [228]. On the other hand, Semprini et al. simulated an 18-m high church in Italy with Design Builder and Energy Plus, by dividing the volume with a series of fictitious horizontal and vertical partition [33]. The model was successfully validated and showed a vertical gradient of 1.5 °C from 2 m to 8 m height.

4. Conclusions

The proper simulation of the thermal and hygrometric behaviour of historical buildings is a challenging task and has several implications on the evaluation of possible retrofit strategies, on the correct conservation of structures/artworks and also on the indoor comfort. In particular, an inaccurate simulation may lead to inadequate conclusions, which could lead to inappropriate and dangerous actions for the building's heritage conservation. In such respect, more attention must be paid to reduce the gap in the model results, thus avoiding risky choices for the precious artefacts, building's finishes and structures.

Thus, the present work aims to bridge the knowledge gap about thermal and hygrometric behaviour of historical buildings, highlighting those aspects that need to be carefully checked when performing dynamic simulations. The main outcomes of the work are summarized hereafter:

- a simplified geometry is often unavoidable (e.g. curved surfaces can be represented as a series of flat surfaces) to meet the requirements of BES tools, but inaccuracies due to oversimplification in some geometrical features must be avoided;
- prolonged exposure to weathering processes, especially to wind, rain-water and air pollution, increases the natural process of ageing of historical materials, causing mechanical damage such as micro-

cracks; this usually increases the porosity and thus the thermal conductivity, while also altering the reflection coefficient of the outermost material;

- the humidity content of the envelope materials may have a significant influence on heat transfer calculations, thus the assessment of the actual content of water is recommended;
- specific tools/interactive atlas must be used to properly assess thermal bridges and report corrected U-values in BES tools, also by adopting modelling expedients (e.g. introduce small sub-surfaces with no thermal mass, whose thermal resistance is assigned by the user so that the same heat transfer rate as in the thermal bridge occurs);
- modelling of transparent envelope requires attention in determining the correct U-value (with particular reference to the windows frame) and solar transmittance. Several reference values are provided in the paper to this aim;
- the infiltration rate of historical buildings is extremely variable (from 0.2 to 3 ACH), depending on many factors (poor airtightness of the envelope, openings necessary for the passage of visitors/church-goers, etc.); thus, for a correct modelling, its quantification must preferably be performed according to experimental tests such as the tracer gas dilution method;
- if the height of the indoor environment is greater than 3 m, a vertical temperature gradient due to thermal stratification must be considered in the BES process;
- LTD such as endoscopic examinations and extraction of core samples, must be carried out when possible to have a complete knowledge about the technical features of building elements;
- HFM measurements and infrared thermography (IRT) are always suggested as means to correctly estimate the U-value and identify the thermal anomalies;
- EnergyPlus is currently the most used tool to simulate historical buildings, but other specific tools can be coupled for hygrothermal calculation or thermal bridges assessment. The combination of several tools is a key factor to obtain accurate results.

In conclusion, the information collected in this work may be used by researchers, specialists and policy-makers involved in the conservation of building's heritage, who need to address a detailed study of the hygrothermal performance of historical buildings thorugh dynamic simulation tools. However, it is important to recognize that, in order to obtain reliable results from the energy simulations, a preliminary calibration phase should be required. Further research works will deal with the calibration of historical buildings' simulation models.

Acknowledgements

The research presented in this paper has been developed in the framework of the Task 59 of the International Energy Agency – Solar Heating anc Cooling Programme (IEA-SHC), “Renovating Historic Buildings Towards Zero Energy” and more in particular in the subtask B.5 “Characterization and simulation of historical buildings”.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] Keoma A, M Z. Energia e restauro. Il miglioramento dell'efficienza energetica in sistemi aggregati di edilizia preindustriale tra istanze conservative e prestazionali. 2013. Milano.
[2] Franco G, Magrini A, Cartesegna M, Guerrini M. Towards a systematic approach for energy refurbishment of historical buildings. The case study of Albergo dei Poveri in Genoa. Italy. Energy and Buildings 2015;95:153–9. https://doi.org/10.1016/J.ENBUILD.2014.10.051.
[3] Magrini A, Franco G. The energy performance improvement of historic buildings and their environmental sustainability assessment. J Cult Herit 2016;21:834–41. https://doi.org/10.1016/J.CULHER.2016.03.012.
[4] Galatioto A, Ciulla G, Ricciu R. An overview of energy retrofit actions feasibility on Italian historical buildings. Energy 2017;137:991–1000. https://doi.org/10.1016/J.ENERGY.2016.12.103.
[5] Martínez-Molina A, Tort-Ausina I, Cho S, Vivancos J-L. Energy efficiency and thermal comfort in historic buildings: a review. Renew Sustain Energy Rev 2016;61:70–85. https://doi.org/10.1016/J.RSER.2016.03.018.
[6] Galatioto A, Ricciu R, Salem T, Kinab E. Energy and economic analysis on retrofit actions for Italian public historic buildings. Energy 2019;176:58–66. https://doi.org/10.1016/J.ENERGY.2019.03.167.
[7] Ginks N, Painter B. Energy retrofit interventions in historic buildings: exploring guidance and attitudes of conservation professionals to slim double glazing in the UK. Energy Build 2017;149:391–9. https://doi.org/10.1016/J.ENBUILD.2017.05.039.
[8] Di Pilla L, Desogus G, Mura S, Ricciu R, Di Francesco M. Optimizing the distribution of Italian building energy retrofit incentives with Linear Programming. Energy Build 2016;112:21–7. https://doi.org/10.1016/J.ENBUILD.2015.11.050.
[9] Lidelöw S, Örn T, Luciani A, Rizzo A. Energy-efficiency measures for heritage buildings: a literature review. Sustain Cities Soc 2019;45:231–42. https://doi.org/10.1016/J.SCS.2018.09.029.
[10] Di Ruocco G, Sicignano C, Sessa A. Integrated methodologies energy efficiency of historic buildings. Procedia Eng 2017;180:1653–63. https://doi.org/10.1016/J.PROENG.2017.04.328.
[11] Vieites E, Vassileva I, Arias JE. European initiatives towards improving the energy efficiency in existing and historic buildings. Energy Procedia 2015;75:1679–85. https://doi.org/10.1016/J.EGYPRO.2015.07.418.
[12] Rabani M, Madessa HB, Nord N. A state-of-art review of retrofit interventions in buildings towards nearly zero energy level. Energy Procedia 2017;134:317–26. https://doi.org/10.1016/J.EGYPRO.2017.09.534.
[13] EURAC. 3encult - Efficient Energy for EU Cultural Heritage n.d. http://www.3encult.eu/en/project/welcome/default.html (accessed June 25, 2019).
[14] TECNALIA Research & Innovation. Effesus - Energy Efficiency for EU Historic Districts' Sustainability n.d. https://www.effesus.eu/(accessed June 25, 2019).
[15] Co2ol Bricks - Climate change, cultural heritage & energy efficient monuments 2013. http://www.co2olbricks.eu/index.php?id=43 (accessed June 25, 2019).
[16] ITABC - CNR. SECHURBA - Sustainable energy communities in historic urban areas | CNR ITABC n.d. http://www.itabc.cnr.it/progetti/sustainable-energy-communities-in-historic-urban-a (accessed June 25, 2019).
[17] Danish Building Research Institute at Aalborg University Copenhagen. RIBuild - Robust Internal Thermal Insulation of Historic Buildings. n.d. https://www.ribuild.eu/about (accessed June 25, 2019).
[18] de Santoli L. Guidelines on energy efficiency of cultural heritage. Energy Build 2015;86:534–40. https://doi.org/10.1016/J.ENBUILD.2014.10.050.
[19] Webb AL. Energy retrofits in historic and traditional buildings: a review of problems and methods. Renew Sustain Energy Rev 2017;77:748–59. https://doi.org/10.1016/J.RSER.2017.01.145.
[20] Historic England. Energy efficiency and historic buildings - application of Part L of the building regulations to historic and traditionally constructed buildings | historic England. Historic England; 2017.
[21] European Committee for standardization (CEN). Conservation of cultural heritage. Guidelines for improving the energy performance of historic buildings, EN 16883:2017 2017.
[22] MiBACT. Class A UNESCO sites - Anno europeo del patrimonio culturale 2018 n.d. http://annoeuropeo2018.beniculturali.it/en/eventi/siti-unesco-classe/ (accessed June 11, 2019).
[23] MiBACT. Anno europeo del patrimonio culturale. n.d, http://annoeuropeo2018.beniculturali.it/en/. [Accessed 11 June 2019].
[24] Eurostat. Census hub HC53. https://ec.europa.eu/CensusHub2/query.do?step=selectHyperCube&qhc=false. [Accessed 11 June 2019].
[25] Mazzarella L. Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. Energy Build 2015;95:23–31. https://doi.org/10.1016/J.ENBUILD.2014.10.073.
[26] Camuffo D. Microclimate for cultural heritage: conservation, restoration, and maintenance of indoor and outdoor monuments. Elsevier Science; 2013.
[27] Rospi G, Cardinale N, Negro E, Rospi G, Cardinale N, Negro E. Energy performance and economic feasibility study of historical building in the city of matera. Southern Italy. Energies 2017;10:2009. https://doi.org/10.3390/en10122009.
[28] Johansson P, Hagentoft C-E, Sasic Kalagasidis A. Retrofitting of a listed brick and wood building using vacuum insulation panels on the exterior of the facade: measurements and simulations. Energy Build 2014;73:92–104. https://doi.org/10.1016/J.ENBUILD.2014.01.019.
[29] Simona PL, Spiru P, Ion IV. Increasing the energy efficiency of buildings by thermal insulation. Energy Procedia 2017;128:393–9. https://doi.org/10.1016/J.EGYPRO.2017.09.044.
[30] Mancini F, Cecconi M, De Sanctis F, Beltotto A. Energy retrofit of a historic building using simplified dynamic energy modeling. Energy Procedia 2016;101:1119–26. https://doi.org/10.1016/J.EGYPRO.2016.11.152.
[31] Laurini E, De Vita M, De Berardinis P. Energy simulation and optimization of a double ventilation chimney in a historical building in L'Aquila (Italy). Energy Procedia 2018;147:34–41. https://doi.org/10.1016/J.EGYPRO.2018.07.030.
[32] Giuliani M, Henze GP, Florita AR. Modelling and calibration of a high-mass historic building for reducing the prebound effect in energy assessment. Energy Build 2016;116:434–48. https://doi.org/10.1016/j.enbuild.2016.01.034.

[33] Semprini G, Galli C, Farina S. Reuse of an ancient church: thermal aspect for integrated solutions. Energy Procedia 2017;133:327–35. https://doi.org/10.1016/J.EGYPRO.2017.09.395.

[34] Aste N, Adhikari RS, Buzzetti M, Della Torre S, Del Pero C, Huerto CHE, et al. Microclimatic monitoring of the Duomo (Milan Cathedral): risks-based analysis for the conservation of its cultural heritage. Build Environ 2019;148:240–57. https://doi.org/10.1016/J.BUILDENV.2018.11.015.

[35] Aste N, Torre S Della, Adhikari RS, Buzzetti M, Del Pero C, Leonforte F, et al. Sustainable church heating: the Basilica di Collemaggio case-study. Energy Build 2016;116:218–31. https://doi.org/10.1016/J.ENBUILD.2016.01.008.

[36] Kampelis N, Gobakis K, Vagias V, Kolokotsa D, Standardi L, Isidori D, et al. Evaluation of the performance gap in industrial, residential & tertiary near-Zero energy buildings. Energy Build 2017;148:58–73. https://doi.org/10.1016/J.ENBUILD.2017.03.057.

[37] de Wilde P. The gap between predicted and measured energy performance of buildings: a framework for investigation. Autom ConStruct 2014;41:40–9. https://doi.org/10.1016/J.AUTCON.2014.02.009.

[38] Menezes AC, Cripps A, Bouchlaghem D, Buswell R. Predicted vs. actual energy performance of non-domestic buildings: using post-occupancy evaluation data to reduce the performance gap. Appl Energy 2012;97:355–64. https://doi.org/10.1016/J.APENERGY.2011.11.075.

[39] Demanuele C, Tweddell T, Davies M. Bridging the gap between predicted and actual energy performance in schools. n.d.

[40] Bordass B, Bordass B, Associates WB. Energy performance of non-domestic buildings: closing the credibility gap. IN Proceedings OF the 2004 improving energy efficiency OF commercial buildings conference n.d.:21–22.

[41] Spanedda Francesco. Energia e insediamento. Una ricerca interdisciplinare per l'applicazione di principi di efficienza energetica nei centri storici. 2007.

[42] Bob Barnham, Nicholas Heath GP. Energy modelling analysis of a traditionally built Scottish tenement flat Report for Historic Scotland by Changeworks Changeworks Energy modelling analysis. 2008.

[43] Adhikari R, Lucchi E, Pracchi V. Energy modelling of historic buildings: applicability, problems and compared results. Proceedings of EWCHP 2013;3.

[44] Gaspar K, Casals M, Gangolells M. A comparison of standardized calculation methods for in situ measurements of façades U-value. Energy Build 2016;130:592–9. https://doi.org/10.1016/J.ENBUILD.2016.08.072.

[45] Calzolari M. Prestazione energetica delle architetture storiche: sfide e soluzioni: analisi dei metodi di calcolo per la definizione del comportamento energetico. ITA; 2018.

[46] Webb AL. Energy retrofits in historic and traditional buildings: a review of problems and methods. Renew Sustain Energy Rev 2017;77:748–59. https://doi.org/10.1016/J.RSER.2017.01.145.

[47] Macdonald IA. Quantifying the effects of uncertainty in building simulation. University of Strathclyde; 2002.

[48] IBPSA - USA. Best Directory, Building Energy Software Tools n.d. https://www.buildingenergysoftwaretools.com/(accessed June 12, 2019).

[49] Tang L, Nikolopoulou M, Zhao F, Zhang N. CFD modeling of the built environment in Chinese historic settlements. Energy Build 2012;55:601–6. https://doi.org/10.1016/J.ENBUILD.2012.09.025.

[50] D' Agostino D, Congedo PM, Cataldo R. Ventilation control using computational fluid-dynamics (CFD) modelling for cultural buildings conservation. Procedia Chemistry 2013;8:83–91. https://doi.org/10.1016/J.PROCHE.2013.03.012.

[51] D'Agostino D, Congedo PM. CFD modeling and moisture dynamics implications of ventilation scenarios in historical buildings. Build Environ 2014;79:181–93. https://doi.org/10.1016/J.BUILDENV.2014.05.007.

[52] Albero S, Giavarini C, Santarelli ML, Vodret A. CFD modeling for the conservation of the gilded vault Hall in the domus aurea. J Cult Herit 2004;5:197–203. https://doi.org/10.1016/J.CULHER.2003.08.001.

[53] Corgnati SP, Perino M. CFD application to optimise the ventilation strategy of senate room at palazzo madama in Turin (Italy). J Cult Herit 2013;14:62–9. https://doi.org/10.1016/J.CULHER.2012.02.007.

[54] Balocco C, Grazzini G. Numerical simulation of ancient natural ventilation systems of historical buildings. A case study in Palermo. J Cult Herit 2009;10:313–8. https://doi.org/10.1016/J.CULHER.2008.03.008.

[55] D'Agostino D, Congedo PM, Cataldo R. Computational fluid dynamics (CFD) modeling of microclimate for salts crystallization control and artworks conservation. J Cult Herit 2014;15:448–57. https://doi.org/10.1016/J.CULHER.2013.10.002.

[56] Aste N, Torre S Della, Adhikari RS, Buzzetti M, Del Pero C, Leonforte F, et al. CFD comfort analysis of a sustainable solution for church heating. Energy Procedia 2017;105:2797–802. https://doi.org/10.1016/J.EGYPRO.2017.03.603.

[57] Di Turi S, García-Pulido LJ, Ruggiero F, Stefanizzi P. Recovery of ancient bioclimatic strategies for energy retrofit in historical buildings: the case of the Infants' Tower in the Alhambra. Energy Procedia 2017;133:300–11. https://doi.org/10.1016/J.EGYPRO.2017.09.391.

[58] Grau-Bové J, Mazzei L, Strlic M, Cassar M. Fluid simulations in heritage science. Herit Sci, n.d. doi:10.1186/s40494-019-0259-9.

[59] Macdonald IA. Quantifying the effects of uncertainty in building simulation. n.d.

[60] Fabbri K. The study of historic indoor microclimate. Historic indoor microclimate of the heritage buildings. Cham: Springer International Publishing; 2018. p. 85–117. https://doi.org/10.1007/978-3-319-60343-8_4.

[61] Calzolari M, Davoli P. Instruments for the calculation of energy performance in historical buildings. Limits of Applicability and Tuning Proposal 2016;1:108–14.

[62] Tronchin L, Fabbri K, Tronchin L, Fabbri K. Energy and microclimate simulation in a heritage building: further studies on the Malatestiana library. Energies 2017;10:1621. https://doi.org/10.3390/en10101621.

[63] Verbeke S, Audenaert A. Thermal inertia in buildings: a review of impacts across climate and building use. Renew Sustain Energy Rev 2018;82:2300–18. https://doi.org/10.1016/J.RSER.2017.08.083.

[64] Misiopecki C, Gustavsen A. Numerical simulation of thermal performance of window retrofit options for historic buildings. 3rd european workshop on cultural heritage preservation. EWCHP; 2013. p. 195–202.

[65] Silvero F, Montelpare S, Rodrigues F, Spacone E, Varum H. Energy retrofit solutions for heritage buildings located in hot-humid climates. Procedia Struct Integr 2018;11:52–9. https://doi.org/10.1016/J.PROSTR.2018.11.008.

[66] Azar E, Papadopoulos S. Human behavior and energy consumption in buildings: an integrated agent-based modeling and building performance simulation framework n.d. doi:10.26868/25222708.2017.125.

[67] International Organization for Standardization (ISO). Energy performance of buildings - energy needs for heating and cooling, internal temperatures and sensible and latent heat loads – Part 2: Explanation and justification of ISO 52016-1 and ISO 52017-1, ISO/TR 52016-2:2017 2017.

[68] International Organization for Standardization (ISO). Thermal performance of buildings – transmission and ventilation heat transfer coefficients – calculation method. Standard ISO 13789 2017.

[69] Maldague X. Theory and practice of infrared technology for nondestructive testing. 2001.

[70] Ascione F, Ceroni F, De Masi RF, de' Rossi F, Pecce MR. Historical buildings: multidisciplinary approach to structural/energy diagnosis and performance assessment. Appl Energy 2017;185:1517–28. https://doi.org/10.1016/J.APENERGY.2015.11.089.

[71] Cornaro C, Puggioni VA, Strollo RM. Dynamic simulation and on-site measurements for energy retrofit of complex historic buildings: villa Mondragone case study. J Build Eng 2016;6:17–28. https://doi.org/10.1016/j.jobe.2016.02.001.

[72] Roberti F, Oberegger UF, Gasparella A. Calibrating historic building energy models to hourly indoor air and surface temperatures: methodology and case study. Energy Build 2015;108:236–43. https://doi.org/10.1016/j.enbuild.2015.09.010.

[73] Walker R, Pavía S. Thermal performance of a selection of insulation materials suitable for historic buildings. Build Environ 2015;94:155–65. https://doi.org/10.1016/J.BUILDENV.2015.07.033.

[74] Maldague X. Theory and practice of infrared technology for nondestructive testing. Wiley; 2001.

[75] Chatzivasileiadi A, Lannon S, Jabi W, Wardhana NM, Aish R. Addressing pathways to energy modelling through non-manifold topology. SimAUD; 2018.

[76] Holcik P, Agugiaro G. From CityGML-energy ADE to EnergyPlus and back: some experiences. 2016.

[77] NREL. Modeling Best Practices - OpenStudio User Docs n.d. https://nrel.github.io/OpenStudio-user-documentation/help/best_practices/(accessed June 12, 2019).

[78] f. Tips and tricks for using EnergyPlus. 2018.

[79] Adhikari RS, Lucchi E, Pracchi VN. Experimental measurements on thermal transmittance of the opaque vertical walls in the historical buildings. 2012. p. 1–6.

[80] Nardi I, Lucchi E, de Rubeis T, Ambrosini D. Quantification of heat energy losses through the building envelope: a state-of-the-art analysis with critical and comprehensive review on infrared thermography. Build Environ 2018;146:190–205. https://doi.org/10.1016/J.BUILDENV.2018.09.050.

[81] Lucchi E. Applications of the infrared thermography in the energy audit of buildings: a review. Renew Sustain Energy Rev 2018;82:3077–90. https://doi.org/10.1016/J.RSER.2017.10.031.

[82] RESNET. Revises interim guidelines for thermographic inspections of buildings. http://www.resnet.us/blog/resnet-revises-interim-guidelines-for-thermographic-inspections-of-buildings/. [Accessed 12 June 2019].

[83] Mak L, Hackett P. International organization for standardization (ISO) thermal manikin working group round robin testing of thermal resistance of suits. 2009.

[84] European Committee for standardization (CEN). Thermal performance of buildings - qualitative detection of thermal irregularities in building envelopes - infrared method, EN 13187. 1998. https://standards.globalspec.com/std/160264/EN 13187. [Accessed 12 June 2019].

[85] Balaras CA, Argiriou AA. Infrared thermography for building diagnostics. Energy Build 2002;34:171–83. https://doi.org/10.1016/S0378-7788(01)00105-0.

[86] Moropoulou A, Labropoulos KC, Delegou ET, Karoglou M, Bakolas A. Non-destructive techniques as a tool for the protection of built cultural heritage. Constr Build Mater 2013;48:1222–39. https://doi.org/10.1016/J.CONBUILDMAT.2013.03.044.

[87] Kylili A, Fokaides PA, Christou P, Kalogirou SA. Infrared thermography (IRT) applications for building diagnostics: a review. Appl Energy 2014;134:531–49. https://doi.org/10.1016/J.APENERGY.2014.08.005.

[88] European Committee for Standardization (CEN). Conservation of Cultural Heritage. Guide to the measurements of moisture content in materials constituting movable and immovable cultural heritage. 2013. Standard prEN 16682.

[89] Ente Nazionale Italiano di Unificazione (UNI). Beni culturali. Materiali lapidei naturali ed artificiali. Determinazione del contenuto d'acqua: metodo ponderale. 2003. Standard UNI 11085.

[90] International Organization for Standardization (ISO). Building components and building elements. Thermal transmittance and thermal resistance. Calculation method, Standard ISO 6946. 2017 n.d. https://www.iso.org/standard/65708.html (accessed June 12, 2019).

[91] Ente Nazionale Italiano di Unificazione (UNI). Materiali e prodotti per edilizia: pubblicata la UNI 10351 1994.

[92] International Organization for Standardization (ISO). Building materials and products. Hygrothermal properties. Tabulated design values and procedures for determining declared and design thermal values. 2007. Standard ISO 10456.

[93] Libessart L, Kenai MA. Measuring thermal conductivity of green-walls components in controlled conditions. J Build Eng 2018;19:258–65. https://doi.org/10.1016/J.JOBE.2018.05.016.

[94] International Organization for Standardization (ISO). Thermal insulation. Determination of steady-state thermal resistance and related properties. Guarded hot plate apparatus. 1991. Standard ISO 8302.

[95] Rye C, Scott C. The SPAB research report 1. U-VALUE REPORT; 2012.

[96] Lucchi E. Thermal transmittance of historical brick masonries: a comparison among standard data, analytical calculation procedures, and in situ heat flow meter measurements. Energy Build 2017;134:171–84. https://doi.org/10.1016/J.ENBUILD.2016.10.045.

[97] Rhee-Duverne S, Baker P. Research into the thermal performance of traditional brick walls. London: English Heritage; 2013.

[98] Baker P. U-values and traditional buildings: in situ measurements and their comparisons to calculated values. Edinburgh: Historic Scotland; 2011.

[99] B-W J. In-situ monitoring of thermal refurbishment on pre-1919 properties in Scotland. Edinburgh: Scottish Energy Centre; 2013.

[100] Lucchi E. Thermal transmittance of historical stone masonries: a comparison among standard, calculated and measured data. Energy Build 2017;151:393–405. https://doi.org/10.1016/J.ENBUILD.2017.07.002.

[101] Genova E, Fatta G. The thermal performances of historic masonry: in-situ measurements of thermal conductance on calcarenite stone walls in Palermo. Energy Build 2018;168:363–73. https://doi.org/10.1016/J.ENBUILD.2018.03.009.

[102] Adhikari RS, Lucchi E, Pracchi V, Rosina E. Static and dynamic evaluation methods for energy efficiency in historical buildings. PLEA2013 - 29th conference. Munich, Germany: Sustainable Architecture for a Renewable Future; 2013. 10-12 September 2013 10–2.

[103] Magrini A. Thermal behaviour of historical buildings, materials and components: methodological framework, calculation, results. Historical buildings and energy. Cham: Springer International Publishing; 2017. p. 55–81. https://doi.org/10.1007/978-3-319-52615-7_4.

[104] Ballarini I, Corgnati SP, Corrado V. Use of reference buildings to assess the energy saving potentials of the residential building stock: the experience of TABULA project. Energy Policy 2014;68:273–84. https://doi.org/10.1016/J.ENPOL.2014.01.027.

[105] Intelligent Energy Europe (IEE) Program. Project episcope. http://episcope.eu/iee-project/episcope/. [Accessed 12 June 2019].

[106] Intelligent Energy Europe (IEE) Program. Project RePublic_ZEB. http://www.republiczeb.org/. [Accessed 12 June 2019].

[107] Abad B, Borca-Tasciuc D-A, Martin-Gonzalez MS. Non-contact methods for thermal properties measurement. Renew Sustain Energy Rev 2017;76:1348–70. https://doi.org/10.1016/J.RSER.2017.03.027.

[108] International Organization for Standardization (ISO). Thermal insulation. Building elements. In-situ measurement of thermal resistance and thermal transmittance. 2014. Standard ISO 9869.

[109] Ficco G, Iannetta F, Ianniello E, d'Ambrosio Alfano FR, Dell'Isola M. U-value in situ measurement for energy diagnosis of existing buildings. Energy Build 2015;104:108–21. https://doi.org/10.1016/J.ENBUILD.2015.06.071.

[110] Desogus G, Mura S, Ricciu R. Comparing different approaches to in situ measurement of building components thermal resistance. Energy Build 2011;43:2613–20. https://doi.org/10.1016/J.ENBUILD.2011.05.025.

[111] Ente Nazionale Italiano di Unificazione (UNI). Prestazioni energetiche degli edifici. Parte 1: determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale, Standard UNI 11300. Milano: UNI; 2014. 2014.

[112] Sarıışık A, Sarıışık G. Investigation of engineering characteristics of mardin stone used in eco-building. Cogent Eng 2016;3. https://doi.org/10.1080/23311916.2016.1275412.

[113] Fitzner B, Heinrichs K. Damage diagnosis at stone monuments-weathering forms, damage categories and damage indices. Acta-Universitatis 2001;27:677–90.

[114] Litti G, Khoshdel S, Audenaert A, Braet J. Hygrothermal performance evaluation of traditional brick masonry in historic buildings. Energy Build 2015;105:393–411. https://doi.org/10.1016/J.ENBUILD.2015.07.049.

[115] Rode C, Grau K. Moisture buffering and its consequence in whole building hygrothermal modeling. J Build Phys 2008;31:333–60. https://doi.org/10.1177/1744259108088960.

[116] Zhang M, Qin M, Rode C, Chen Z. Moisture buffering phenomenon and its impact on building energy consumption. Appl Therm Eng 2017;124:337–45. https://doi.org/10.1016/J.APPLTHERMALENG.2017.05.173.

[117] Woods J, Winkler J, Christensen D. Evaluation of the effective moisture penetration depth model for estimating moisture buffering in buildings. 2013. https://doi.org/10.2172/1219896.

[118] Qin M, Yang J. Evaluation of different thermal models in EnergyPlus for calculating moisture effects on building energy consumption in different climate conditions. Build Simul 2016;9:15–25. https://doi.org/10.1007/s12273-015-0263-2.

[119] Qin M, Walton G, Belarbi R, Allard F. Simulation of whole building coupled hygrothermal-airflow transfer in different climates. Energy Convers Manag 2011;52:1470–8. https://doi.org/10.1016/J.ENCONMAN.2010.10.010.

[120] Stazi F, Tittarelli F, Politi G, Di Perna C, Munafò P. Assessment of the actual hygrothermal performance of glass mineral wool insulation applied 25 years ago in masonry cavity walls. Energy Build 2014;68:292–304. https://doi.org/10.1016/J.ENBUILD.2013.09.032.

[121] Wang Y, Ma C, Liu Y, Wang D, Liu J. Effect of moisture migration and phase change on effective thermal conductivity of porous building materials. Int J Heat Mass Transf 2018;125:330–42. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2018.04.062.

[122] Gomes MG, Flores-Colen I, Manga LM, Soares A, de Brito J. The influence of moisture content on the thermal conductivity of external thermal mortars. Constr Build Mater 2017;135:279–86. https://doi.org/10.1016/J.CONBUILDMAT.2016.12.166.

[123] Straube J, Schumacher C. Interior insulation retrofits of load-bearing masonry walls in cold climates. J Green Build 2007;2:42–50. https://doi.org/10.3992/jgb.2.2.42.

[124] Finken GR, Bjarløv SP, Peuhkuri RH. Effect of façade impregnation on feasibility of capillary active thermal internal insulation for a historic dormitory – a hygrothermal simulation study. Constr Build Mater 2016;113:202–14. https://doi.org/10.1016/J.CONBUILDMAT.2016.03.019.

[125] Zhao J, Grunewald J, Ruisinger U, Feng S. Evaluation of capillary-active mineral insulation systems for interior retrofit solution. Build Environ 2017;115:215–27. https://doi.org/10.1016/J.BUILDENV.2017.01.004.

[126] Knarud JI. Comparative study of hygrothermal simulations of a masonry wall. Energy Procedia 2017;132:771–6. https://doi.org/10.1016/J.EGYPRO.2017.10.027.

[127] Zhou X, Derome D, Carmeliet J. Hygrothermal modeling and evaluation of freeze-thaw damage risk of masonry walls retrofitted with internal insulation. Build Environ 2017;125:285–98. https://doi.org/10.1016/J.BUILDENV.2017.08.001.

[128] Erkal A, D'Ayala D, Sequeira L. Assessment of wind-driven rain impact, related surface erosion and surface strength reduction of historic building materials. Build Environ 2012;57:336–48. https://doi.org/10.1016/J.BUILDENV.2012.05.004.

[129] Vereecken E, Roels S. A comparison of the hygric performance of interior insulation systems: a hot box–cold box experiment. Energy Build 2014;80:37–44. https://doi.org/10.1016/J.ENBUILD.2014.04.033.

[130] Rode C, Mortensen RH, Hansen LH, Harderup KK. Moisture buffering of building materials. 2005.

[131] International Organization for Standardization (ISO). Thermal bridges in building construction - heat flows and surface temperatures - detailed calculations. 2017. ISO 10211:2017.

[132] Capozzoli A, Gorrino A, Corrado V. A building thermal bridges sensitivity analysis. Appl Energy 2013;107:229–43. https://doi.org/10.1016/J.APENERGY.2013.02.045.

[133] CENED. Abaco dei ponti termici. n.d, http://www.cened.it/modulistica. [Accessed 12 June 2019].

[134] International Organization for Standardization (ISO). Thermal bridges in building construction — linear thermal transmittance — simplified methods and default values. ISO 14683:2017, https://www.evs.ee/tooted/iso-14683-2017. [Accessed 12 June 2019].

[135] Boafo FE, Ahn J-G, Kim J-T, Kim J-H. Computing thermal bridge of VIP in building retrofits using DesignBuilder. Energy Procedia 2015;78:400–5. https://doi.org/10.1016/J.EGYPRO.2015.11.683.

[136] Amoruso F, Dietrich U, Schuetze T, Amoruso FM, Dietrich U, Schuetze T. Development of a building information modeling-parametric workflow based renovation strategy for an exemplary apartment building in Seoul, Korea. Sustainability 2018;10:4494. https://doi.org/10.3390/su10124494.

[137] Asdrubali F, Baldinelli G, Bianchi F. A quantitative methodology to evaluate thermal bridges in buildings. Appl Energy 2012;97:365–73. https://doi.org/10.1016/J.APENERGY.2011.12.054.

[138] Bianchi F, Pisello A, Baldinelli G, Asdrubali F, Bianchi F, Pisello AL, et al. Infrared thermography assessment of thermal bridges in building envelope: experimental validation in a test room Setup. Sustainability 2014;6:7107–20. https://doi.org/10.3390/su6107107.

[139] Cantin R, Burgholzer J, Guarracino G, Moujalled B, Tamelikecht S, Royet BG. Field assessment of thermal behaviour of historical dwellings in France. Build Environ 2010;45:473–84. https://doi.org/10.1016/J.BUILDENV.2009.07.010.

[140] Cornaro C, Puggioni VA, Strollo RM. Dynamic simulation and on-site measurements for energy retrofit of complex historic buildings: villa Mondragone case study. J Build Eng 2016;6:17–28. https://doi.org/10.1016/J.JOBE.2016.02.001.

[141] Cirami S, Evola G, Gagliano A, Margani G, Cirami S, Evola G, et al. Thermal and economic analysis of renovation strategies for a historic building in mediterranean area. Buildings 2017;7:60. https://doi.org/10.3390/buildings7030060.

[142] Moran F, Blight T, Natarajan S, Shea A. The use of Passive House Planning Package to reduce energy use and CO2 emissions in historic dwellings. Energy Build 2014;75:216–27. https://doi.org/10.1016/J.ENBUILD.2013.12.043.

[143] Iringova A. Revitalisation of external walls in listed buildings in the context of fire protection. Procedia Eng 2017;195:163–70. https://doi.org/10.1016/J.PROENG.2017.04.539.

[144] Glew D, Brooke-Peat M, Gorse C. Modelling insulated coving's potential to reducing thermal bridging and moisture risk in solid wall dwellings retrofitted with external wall insulation. J Build Eng 2017;11:216–23. https://doi.org/10.1016/J.JOBE.2017.04.013.

[145] Johansson P, Geving S, Hagentoft C-E, Jelle BP, Rognvik E, Kalagasidis AS, et al. Interior insulation retrofit of a historical brick wall using vacuum insulation

panels: hygrothermal numerical simulations and laboratory investigations. Build Environ 2014;79:31–45. https://doi.org/10.1016/J.BUILDENV.2014.04.014.

[146] Johansson P. Assessment of the risk for mold growth in a wall retrofitted with vacuum insulation panels. n.d.

[147] Mortarotti G, Morganti M, Cecere C, Mortarotti G, Morganti M, Cecere C. Thermal analysis and energy-efficient solutions to preserve listed building façades: the INA-casa building heritage. Buildings 2017;7:56. https://doi.org/10.3390/buildings7030056.

[148] Odgaard T, Bjarløv SP, Rode C. Interior insulation – experimental investigation of hygrothermal conditions and damage evaluation of solid masonry façades in a listed building. Build Environ 2018;129:1–14. https://doi.org/10.1016/J.BUILDENV.2017.11.015.

[149] Proskurnina O, Pont UJ, Kornicki M, Mahdavi A. Application of aerogel-based plaster towards thermal retrofit of historical facades: a computational assessment. In: Proceedings of BSA 2015, the second IBPSA-Italy conference on "building simulation applications"; 2015. February 2015, Bozen (Italy).

[150] Harrestrup M, Svendsen S. Full-scale test of an old heritage multi-storey building undergoing energy retrofitting with focus on internal insulation and moisture. Build Environ 2015;85:123–33. https://doi.org/10.1016/J.BUILDENV.2014.12.005.

[151] Valdbjørn T, Valdbjørn Rasmussen T. Retrofitting listed buildings: measures , savings and requirements. Open Constr Build Technol J 2011;5:174–81. https://doi.org/10.2174/1874836801105010174.

[152] Troi A, Bastian Z. Energy efficiency solutions. Energy efficiency solutions for historic buildings: a Handbook. 2015. Birkhäuser Basel.

[153] ASHRAE. Energy guideline for historical buildings. Standards Michigan: ASHRAE 34P; 2017. June 12, 2019), https://standardsmichigan.com/ashrae-34p-energy-guideline-for-historical-buildings/.

[154] Ciulla G, Galatioto A, Ricciu R. Energy and economic analysis and feasibility of retrofit actions in Italian residential historical buildings. Energy Build 2016;128: 649–59. https://doi.org/10.1016/J.ENBUILD.2016.07.044.

[155] Roberti F, Oberegger UF, Gasparella A. Calibrating historic building energy models to hourly indoor air and surface temperatures: methodology and case study. Energy Build 2015;108:236–43. https://doi.org/10.1016/J.ENBUILD.2015.09.010.

[156] Roberti F, Oberegger UF, Lucchi E, Troi A. Energy retrofit and conservation of a historic building using multi-objective optimization and an analytic hierarchy process. Energy Build 2017;138:1–10. https://doi.org/10.1016/J.ENBUILD.2016.12.028.

[157] Roberti F, Filippi Oberegger U, Lucchi E, Gasparella A. Energy retrofit and conservation of built heritage using multi-objective optimization: demonstration on a medieval building. Building Simulation Applications; 2015. p. 189–97.

[158] Pretelli M, Fabbri K. Historic indoor microclimate of the heritage buildings - a | marco pretelli. Springer. Swizerland: Springer; 2018.

[159] Big Ladder Software LLC. How to create a curved roof in Open studio? - Unmet Hours n.d. https://unmethours.com/question/1313/how-to-create-a-curved-roof-in-open-studio/(accessed June 12, 2019).

[160] Niemasz J. DIVA for Rhino. goo.gl/H8RoJd. http://diva4rhino.com/forum/topics/viper-window-component-sensitive-to-geometry-output-null. [Accessed 13 June 2019].

[161] Konstantinov A, Mukhin A. Providing thermal protection when replacing window blocks in historical buildings. IOP Conf Ser Earth Environ Sci 2018;177:012019. https://doi.org/10.1088/1755-1315/177/1/012019.

[162] Bakonyi D, Dobszay G. Simulation aided optimization of a historic window's refurbishment. Energy Build 2016;126:51–69. https://doi.org/10.1016/J.ENBUILD.2016.05.005.

[163] Bolorforoush M. Sustainable energy strategy for historic churches and cathedrals in the UK. 2014.

[164] Ente Nazionale Italiano di Unificazione (UNI). Vetro per edilizia - determinazione delle caratteristiche luminose e solari delle vetrate. UNI EN 2000 2011;410. http://store.uni.com/catalogo/index.php/uni-en-410-2000.html. [Accessed 24 June 2019].

[165] Ware EC. Historic windows and sustainability: a comparison of historic and replacement windows based on energy efficiency, life cycle analysis, embodied energy and durability. 2011.

[166] British Standard (BS). Glass in building. Determination of thermal transmittance (U value). Calculation method - BS EN 673:2011. BSI. 2011.

[167] International Organization for Standardization (ISO). Glass in building - calculation of steady-state U values (thermal transmittance) of multiple glazing - ISO 10292:1994. 1994.

[168] Internationa Organization for Standardization (ISO). Thermal performance of windows, doors and shading devices - detailed calculations - ISO 15099:2003. https://www.iso.org/standard/26425.html. [Accessed 24 June 2019].

[169] International Organization for Standardization (ISO). Thermal performance of windows, doors and shutters – Calculation of thermal transmittance - Part 1: general - ISO 10077-1:2017. 2017.

[170] National Fenestration Rating Council Incorporated (NFRC). Technical interpretations manual E1A14. 2010.

[171] Hegazy AA. Effect of dust accumulation on solar transmittance through glass covers of plate-type collectors. Renew Energy 2001;22:525–40. https://doi.org/10.1016/S0960-1481(00)00093-8.

[172] Van Den Bossche N, Janssens A. Airtightness and watertightness of window frames: comparison of performance and requirements. Build Environ 2016;110: 129–39. https://doi.org/10.1016/j.buildenv.2016.09.034.

[173] US department of energy. WINDOW software- Windows and Daylighting n.d. https://windows.lbl.gov/software/window (accessed June 25, 2019).

[174] International Organization for Standardization (ISO). Glass in building - determination of light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors - ISO 9050: 2003. 2003.

[175] Garg HP. Effect of dirt on transparent covers in flat-plate solar energy collectors. Sol Energy 1974;15:299–302. https://doi.org/10.1016/0038-092X(74)90019-X.

[176] Blinn JF FJ, Blinn FJ. Light reflection functions for simulation of clouds and dusty surfaces. In: Proceedings of the 9th annual conference on Computer graphics and interactive techniques - SIGGRAPH '82. 16. New York, New York, USA: ACM Press; 1982. p. 21–9. https://doi.org/10.1145/800064.801255.

[177] Tregenza PR, Stewart L, Sharples S. Reduction of glazing transmittance by atmospheric pollutants. Light Res Technol 1999;31:135–8. https://doi.org/10.1177/096032719903100401.

[178] British Standard. Lighting for buildings - Part 2: code of practice for daylighting | UCL institute for environmental design and engineering - BS 8206-2 - London's global university. https://www.ucl.ac.uk/bartlett/environmental-design/publications/2008/jan/british-standard-bs-8206-2-2008-lighting-buildings-part-2-code-practice. [Accessed 12 June 2019].

[179] Pracchi VN. Balancing different needs: enhancing energy efficiency and preserving historic windows. 2017. p. 581–91.

[180] Wolf S, Trümpler S, Wakili KG, Binder B, Baumann E. Protective glazing: the conflict between energy- saving and conservation requirements. 2013.

[181] Buratti C. Aging influence on the thermal and optical properties of artistic glasses: experimental data and comparison. In: The 6th ASME-JSME thermal engineering joint conference; 2003.

[182] Ente Nazionale Italiano di Unificazione (UNI). Prove sul vetro. Determinazione dei fattori di trasmissione dell energia solare. 1978. UNI 7885:1978.

[183] European Committee for standardization (CEN). EN 15759-2: 2018 Conservation of cultural heritage - indoor climate. Part 2: ventilation management for the protection of cultural heritage buildings and collections. 2018.

[184] ASHRAE. Chapter 27, ventilation and infiltration. 2005.

[185] Tian W, Heo Y, Wilde de P, Li Z, Yan D, Soo Park C, et al. A review of uncertainty analysis in building energy assessment. Renew Sustain Energy Rev 2018;93: 285–301. doi:.10.37//0033-2909.I26.1.78.

[186] Younes C, Shdid CA, Bitsuamlak G. Air infiltration through building envelopes: a review. J Build Phys 2012;35:267–302. https://doi.org/10.1177/1744259111423085.

[187] Bobenhausen W. Heat loss from buildings. Simplified design of HVAC systems. New York: John Wiley & Sons; 1994. p. 63–93.

[188] European Committee for standardization (CEN). EN ISO 13789 thermal performance of buildings - transmission and ventilation heat transfer coefficients - calculation method 2017;44.

[189] Patel T, Mitsingas C, Miller JP, Newell TA. Comparison of blower door and tracer gas testing methods for determination of air infiltration rates through building envelopes at normal operating conditions. 2012. https://doi.org/10.1115/es2011-54373. 1013–9.

[190] European Committee for standardization (CEN). EN ISO 12569: 2017 Thermal performance of buildings and materials - determination of specific airflow rate in buildings - tracer gas dilution method. 2017.

[191] International Organization for Standardization (ISO). Indoor Air-Part 8: determination of local mean ages of air in buildings for characterizing ventilation conditions. 2007. ISO 16000-8:2007.

[192] Sherman MH. Tracer-gas techniques for measuring ventilation in a single zone. Build Environ 1990;25:365–74. https://doi.org/10.1016/0360-1323(90)90010-O.

[193] Ascione F, De Masi RF, De Rossi F, Ruggiero S, Vanoli GP. NZEB target for existing buildings: case study of historical educational building in Mediterranean climate. Energy Procedia 2017;140:194–206. https://doi.org/10.1016/j.egypro.2017.11.135.

[194] Mauri L. Feasibility analysis of retrofit strategies for the achievement of NZEB target on a historic building for tertiary use. Energy Procedia 2016;101:1127–34. https://doi.org/10.1016/j.egypro.2016.11.153.

[195] Vanoli P, Fournier J. NZEB target for existing buildings: case study of historical educational building in Mediterranean climate. Energy Procedia 2017;140: 194–206. https://doi.org/10.1016/j.egypro.2017.11.135.

[196] Kramer R, van Schijndel J, Schellen H. Dynamic setpoint control for museum indoor climate conditioning integrating collection and comfort requirements: development and energy impact for Europe. Build Environ 2017;118:14–31. https://doi.org/10.1016/j.buildenv.2017.03.028.

[197] Gagliano A, Nocera F, Patania F, Moschella A, Detommaso M, Evola G. Synergic effects of thermal mass and natural ventilation on the thermal behaviour of traditional massive buildings. Int J Sustain Energy 2016;35:411–28.

[198] Evola G, Marletta L, Costanzo V, Caruso G. Different strategies for improving summer thermal comfort in heavyweight traditional buildings. Energy Procedia 2015;78:3228–33. https://doi.org/10.1016/j.egypro.2015.11.785.

[199] Todorović MS, Ećim-Đurić O, Nikolić S, Ristić S, Polić-Radovanović S. Historic building's holistic and sustainable deep energy refurbishment via BPS, energy efficiency and renewable energy—a case study. Energy Build 2015;95:130–7. https://doi.org/10.1016/J.ENBUILD.2014.11.011.

[200] Coelho GBA, Silva HE, Henriques FMA. Calibrated hygrothermal simulation models for historical buildings. Build Environ 2018;142:439–50. https://doi.org/10.1016/j.buildenv.2018.06.034.

[201] Hayati A, Mattsson M, Sandberg M. Single-sided ventilation through extern... evaluation in five historical churches. Energy Build 2017;141:114–24. https://doi.org/10.1016/j.enbuild.2017.02.034.

[202] Mleczkowska A, Strojecki M, Ł Bratasz, Kozłowski R. The effect of ventilation on soiling by particles of outdoor and indoor origin in historical churches. Build Simul 2017;10:383–93. https://doi.org/10.1007/s12273-016-0335-y.

[203] Mleczkowska A, Strojecki M, Ł Bratasz, Kozłowski R. Particle penetration and deposition inside historical churches. Build Environ 2016;95:291–8. https://doi.org/10.1016/j.buildenv.2015.09.017.

[204] Samek L, De Maeyer-Worobiec A, Spolnik Z, Bencs L, Kontozova V, Ł Bratasz, et al. The impact of electric overhead radiant heating on the indoor environment of historic churches. J Cult Herit 2007;8:361–9. https://doi.org/10.1016/j.culher.2007.03.006.

[205] Schellen HL. Heating monumental churches: indoor climate and preservation of cultural heritage. 2018. https://doi.org/10.6100/IR561673.

[206] Napp M, Kalamees T. Energy use and indoor climate of conservation heating, dehumidification and adaptive ventilation for the climate control of a mediaeval church in a cold climate. Energies 2015;108:61–71.

[207] Rajčić V, Skender A, Damjanović D. An innovative methodology of assessing the climate change impact on cultural heritage. Int J Archit Herit 2018;12:21–35. https://doi.org/10.1080/15583058.2017.1354094.

[208] Ascione F, De Rossi F, Vanoli GP. Energy retrofit of historical buildings: theoretical and experimental investigations for the modelling of reliable performance scenarios. Energy Build 2011;43:1925–36. https://doi.org/10.1016/j.enbuild.2011.03.040.

[209] Ascione F, Ceroni F, De Masi RF, de' Rossi F, Pecce MR. Historical buildings: multidisciplinary approach to structural/energy diagnosis and performance assessment. Appl Energy 2017;185:1517–28. https://doi.org/10.1016/j.apenergy.2015.11.089.

[210] Pernetti R, Prada A, Baggio P. On the influence of several parameters in energy model calibration: the case of a historical building. IBPSA Italy 2013:263–72.

[211] Pernetti R. Problematiche relative alla definizione e all ' utilizzo di modelli delle prestazioni energetiche di edifici esistenti. Università di Pavia; 2012.

[212] Ascione F, Bianco N, De Masi RF, De'Rossi F, Vanoli GP. Energy retrofit of an educational building in the ancient center of Benevento. Feasibility study of energy savings and respect of the historical value. Energy Build 2015;95:172–83. https://doi.org/10.1016/j.enbuild.2014.10.072.

[213] Lodi C, Magli S, Maria Contini F, Muscio A, Tartarini P. Improvement of thermal comfort and energy efficiency in historical and monumental buildings by means of localized heating based on non-invasive electric radiant panels. Appl Therm Eng 2017;126:276–89.

[214] Pisello AL, Petrozzi A, Castaldo VL, Cotana F. On an innovative integrated technique for energy refurbishment of historical buildings: thermal-energy, economic and environmental analysis of a case study. Appl Energy 2014;162:1313–22. https://doi.org/10.1016/j.apenergy.2015.05.061.

[215] Andrić I, Pina A, Ferrão P, Fournier J, Lacarrière B, Le Corre O, et al. Thermal inertia of heavyweight traditional buildings: experimental measurements and simulated scenarios. Energy Procedia 2017;133:42–52. https://doi.org/10.1016/j.egypro.2017.09.369.

[216] Rohdin P, Dalewski M, Moshfegh B. Indoor environment and energy use in historic buildings - comparing survey results with measurements and simulations. Int J Vent 2012;10:371–82. https://doi.org/10.1080/14733315.2012.11683962.

[217] Penna P, Cappelletti F, Gasparella A, Tahmasebi F, Mahdavi A. Multi-stage calibration of the simulation model of a school building through Short-term monitoring. J Inf Technol Constr 2015;20:132–45.

[218] Ogando A, Cid N, Fernández M. Energy modelling and automated calibrations of ancient building simulations: a case study of a school in the northwest of Spain. Energies 2017;10. https://doi.org/10.3390/en10060807.

[219] Sadłowska-Sałęga A, Radoń J, Sobczyk J, Wąs K. Influence of microclimate control scenarios on energy consumption in the gallery of the 19th-century polish art in the Sukiennice (the former cloth Hall) of the national museum in Krakow. IOP Conf Ser Mater Sci Eng 2018;415. https://doi.org/10.1088/1757-899X/415/1/012026.

[220] Caucheteux A, Stephan E, Ouest C. Transient simulation calibration of an old building using an experimental design: evaluating uncertainty results. In: 13th conference of international building performance simulation association; 2013. p. 677–84.

[221] Salehi A, Torres I, Ramos A. Assessment of ventilation effectiveness in exiting residential building in mediterranean countries: case study, existing residential building in Portugal. Sustain Cities Soc 2017;32:496–507. https://doi.org/10.1016/j.scs.2017.04.018.

[222] Eskola L, Alev Û, Arumägi E, Jokisalo J, Donarelli A, Kalamees T, et al. Airtightness , air exchange and energy performance in historic residential buildings with different structures, 3315; 2016. https://doi.org/10.1080/14733315.2015.11684066.

[223] Mariani S, Rosso F, Ferrero M. Building in historical areas: identity values and energy performance of innovative massive stone envelopes with reference to traditional building solutions. Buildings 2018;8:17. https://doi.org/10.3390/buildings8020017.

[224] Papadopoulos AM, Avgelis A, Anastaselos D. Low energy cooling of the White Tower, functioning as a contemporary museum. Energy Build 2008;40:1377–86. https://doi.org/10.1016/j.enbuild.2007.12.008.

[225] Šekularac ND, Šumarac DM, Čikić Tovarović JLJ, Čokić MM, Ivanović-Šekularac JA. Re-use of historic buildings and energy refurbishment analysis via building performance simulation (BPS) - a case study. Thermal Sci 2018:2335–54. https://doi.org/10.2298/TSCI171124089S.

[226] Varas-Muriel MJ, Fort R, Martínez-Garrido MI, Zornoza-Indart A, López-Arce P. Fluctuations in the indoor environment in Spanish rural churches and their effects on heritage conservation: hygro-thermal and CO2 conditions monitoring. Build Environ 2014;82:97–109. https://doi.org/10.1016/J.BUILDENV.2014.08.010.

[227] Camuffo D, Pagan E, Bernardi A, Becherini F. The impact of heating, lighting and people in re-using historical buildings: a case study. J Cult Herit 2004;5:409–16. https://doi.org/10.1016/J.CULHER.2004.01.005.

[228] De Backer L, Laverge J, Janssens A, De Paepe M. The use OF a zonal model to calculate the stratification IN a large building. n.d.