Energy Modelling of Historic Buildings: Applicability, Problems and Compared Results

R.S. Adhikari, E. Lucchi, V. Pracchi[1]

ABSTRACT

Thirty percent of European building stock is considered historic. The problem of improving energy performance in this sensitive context has not been addressed yet, despite the latest recent European Directives declaring the need to work on existing buildings. However, the mandatory requirements to reduce GHG emissions and to increase the energy production from renewable sources, together with the rapidly changing user comfort requirements, requires a very careful design of building envelope and HVAC systems especially in a logic of preservation of cultural heritage. At present problems related to energy behaviour of historical buildings are somehow still unresolved because of the attempt to use the same evaluation methods, thermal parameters and criteria used for modern constructions, due to the limited knowledge of the ancient building construction techniques. In this paper, the energy performance of three different listed buildings is evaluated through static (used for energy certification in Italy), sketch design and dynamic computer simulations, in order to understand which energy audit schemes better simulate the actual energy performances of the historic buildings and to identify the strengths and the limits of each software. The simulations are carried out using experimental data on the thermo-physical parameters of building envelope components, energy bills, temperature and relative humidity of air. The final goal is to define the appropriate intervention for "particular" types of heritage so as to optimise the energy efficiency requirements along with the preservation of their inherent cultural values.

Keywords

Historical buildings, conservation, energy behaviour, energy simulation tools.

1. Introduction

European Commission has decided to cut the CO_2 emissions drastically by 2020 (Directives 2002/91/CE and 2010/31/UE), to increase the share of renewable sources (Directive 2009/28/CE) and to enhance the energy performances of existing buildings by retrofit (Directive 2012/27/UE). The European building sector is characterized by a consistent part of historic buildings that can significantly affect the urban settlement. In the near future this process will involve major acceleration of the energy requalification of existing buildings. For this reason, retrofitting requires a precise definition of energy and environmental strategies, in order to preserve their specific building characteristics and to improve quality of life, economic management and sustainability. At present, the tendency is to apply the same rules without considering the value of historic buildings. In some European Countries, in fact, the solution to the conflict between conservation and technical requirements is obtained with a reductive use of the instrument of "derogation". The lack of detailed studies on these issues and the application of technologies used for new or existing buildings, thereby, generates problems of excessive invasiveness in historical ones and of inapplicability in listed buildings. Interventions on historic buildings require widespread knowledge of history, dimensions, building techniques, structures, materials, and management procedures. It is also necessary to create a tight collaboration between the experts of restoration and building physics.

2. Methodology

This study aims at understanding the issues related to the energetic behaviour of historic buildings. An accurate audit is the first step to identify the need for suitable intervention. Also, retrofit action based on an incorrect understanding of the energy performances may give way to serious physical damage and possible legal claims. Moreover, current criteria, parameters and tools for energy evaluation are thought mainly for modern buildings. The weaknesses concern the lack of suitable information on building techniques and materials, the difficulty of entering data related to ventilation, moisture contents, surface mass etc. of the structures. In order to verify the reliability of several tools for the energy evaluation of existing buildings, the authors carried out some experimental measurements to determine the most relevant parameters and the average thermo-physical data of historic building envelope. First of all, the thermal transmittance of ancient masonry (U-value) was measured; it identifies the heat losses due to transmission through building envelope, one of the most important thermal parameter for describing the overall energy performance of a building. Also, the Italian legislation, in accordance with the European Directives, asks to improve the thermal performances of building envelope with very restrictive U-value limits. Subsequently, the experimental data were used for the simulation of energy performance of three historical churches with static, sketch

1 Politecnico di Milano, Italy, elena.lucchi@polimi.it

design and dynamic computer models. The performance of the buildings was evaluated by energy audit and environmental monitoring. The study permits to distinguish the better simulation of the real energy performances of the ancient buildings and to identify the strengths and the potentials of each simulation model. A more adherent energy evaluation may calibrate the retrofit actions, avoiding strategies or technological solutions that may bring negative effects.

3. Evaluation of Thermal Performance of Walls

The thermal losses for heat transmission of the opaque envelope have an important role in the energy balance of buildings (EN ISO 13790, 2008). Today in Italy the thermal performances based on U-value may be estimated with four methods:

- simplified method: used only for energy assessments of existing buildings, in case a rigorous calculation based on inspections or other more reliable sources, is not possible;
- abacus of masonry structures: which provides guidance on the main wall technologies;
- analytic calculation: used where the stratigraphy of the masonry is known;
- in situ measurement: used where it is not possible to make destructive tests to determine the properties of the construction element.

The first two methods are based on Italian standard (UNI TS 11300, 2008). They define the U-values related to compositions, materials and thicknesses of different construction techniques. The simplified method standardizes the U-values for five typologies of walls (brick walls plastered on both surfaces, stone walls plastered on both surfaces, semi-solid bricks or tuff, concrete walls without insulation and cavity brick walls). So, only two of them (bricks and stone walls) can be used for ancient masonries. In the first case, the standard thicknesses measure from 15 to 60 cm, while in the second case they measure from 30 to 60 cm, both too low for ancient walls. The standard U-values consider only few historical constructive technologies and, normally, the thermal proprieties are referred to new construction materials. Therefore, these data are insufficient as compared to actual case studies of historical buildings.

The abacus of masonry structures considers most historic building technologies related to ancient construction (brick, stone, mixed materials, tuff, wall carved stone and ancient stone and brick walls) and there are no limits for thicknesses. Nevertheless, the thermal performances of materials are referred to new construction. Furthermore, the information about the performance of the stone is not provided.

The analytic calculation according to the International standard (EN ISO 6946, 2007) requires detailed information on the stratigraphy and properties of the single materials. For a new building the data on thermal conductivity, vapour pressure resistance, and other thermo-physical properties have to be certified by the manufactures, while for existing buildings these data are missing. The information must be taken from a database developed for current materials and construction techniques (UNI 10351, 1994; UNI 10355, 1994; EN 1745, 2012). These do not correspond to the characteristic of ancient artefacts, especially concerning the proprieties of different materials (conductivity, vapour pressure resistance, density, thermal masses, etc.), the construction techniques (dry or with mortar), and the role of moisture and internal humidity. The variation of the U-values of bricks walls are very wide in relation to thermal mass of materials, that it is connected to the thermal conductivity (Fig. 1)

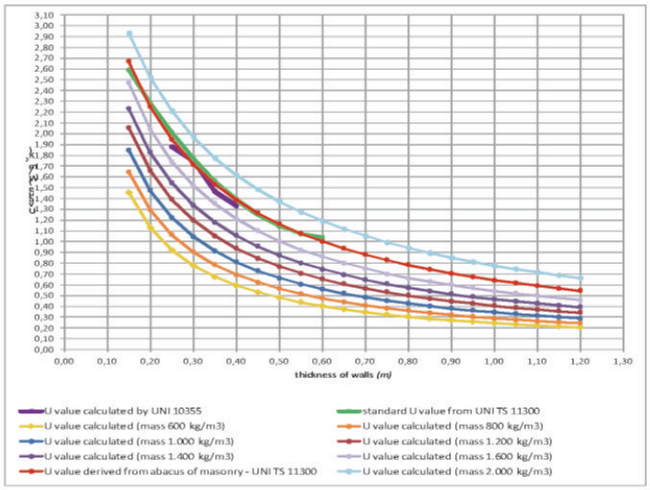

Figure 1 Variation of U-values of bricks walls due the different thermal mass of bricks (100-225%).

In brick masonries the percentage of mortar do not affect the final U-value (± 3-4%) due to the similar thermo-physical properties of bricks (λ= 0.72 W/mK with a density of 1800 kg/m^3) and mortar (λ = 0.9 W/mK).

The European norms (EN 1745, 2012 and UNI 10361, 1994) propose different values of thermal conductivity of stones. For this reason there is a variation of U-values of limestone walls (Figure 2).

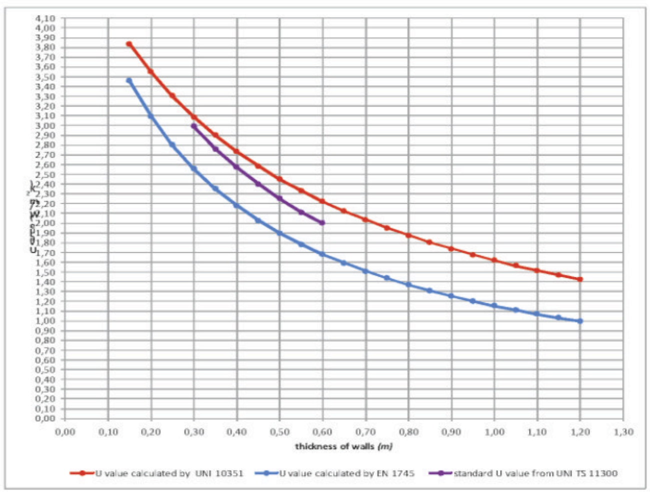

Figure 2 Variation of U-values of stone walls due to the thermal conductivity of limestone (9-30%).

Unlike brick masonries, the presence of air and mortars affects the final U-values of stone-walls. As a matter of fact, the stone blocks are not perfectly square (a common occurrence in old buildings) and there is a certain amount of air and mortar.

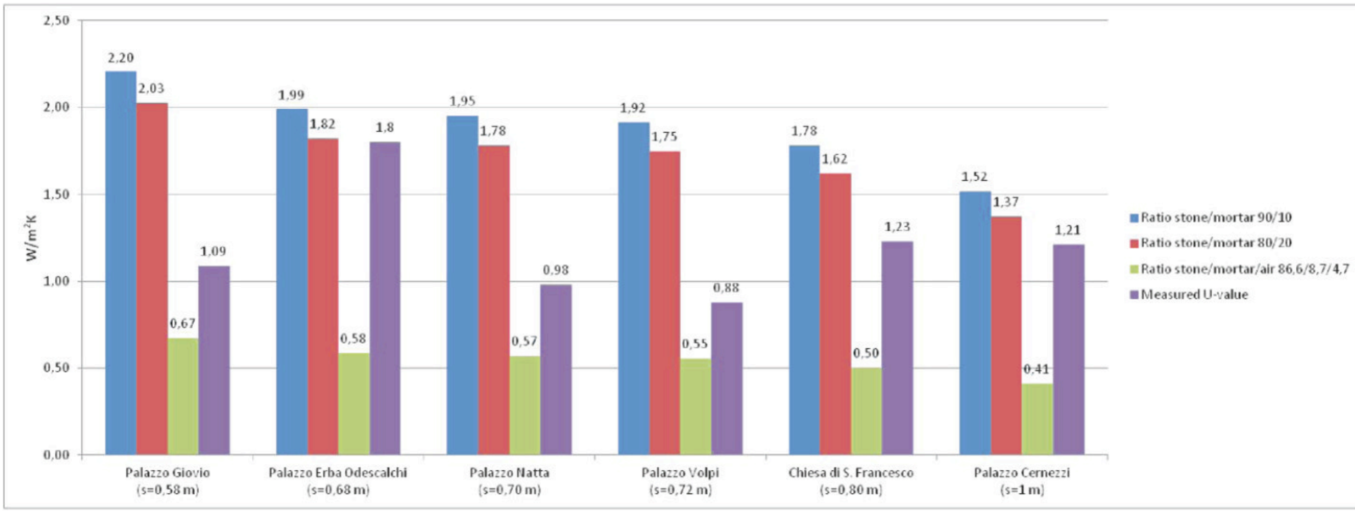

Figure 3 Effect of the presence of mortar and air on U-values calculations of stone walls with different thicknesses.

A destructive analysis was carried out to quantify these percentages on some representative stone walls located in the same geographical area and made by the same construction techniques. The percentage of mortar and especially of air affect the final calculated U-values (± 8-10% considering only mortar but 66.5-70.5% considering also air). This is due to the fact that no air movement is considered (Figure 3).

Furthermore, the procedure does not consider the effects of the presence of humidity inside the component on final energy performance. At the same time, in the mixed walls, it is difficult to know (and therefore to calculate) the correct stratigraphy due to the many possibilities of composition and variation of materials. When the stratigraphy of walls is not known, the real U-values can only be measured with heat flow-meter measurement (HFM), a Non Destructive Testing (NDT) that permits to determine the thermal transmission properties of the envelope. In this study, in order to verify the suitability of the standard and calculated U-values of walls, a series of experimental measurements have been carried out according to International standard (ISO 9869, 1994) on a representative part of the whole element.

3.1 Heat flow-metre measurements

The *in situ* measurement has been applied on several ancient solid masonry made of stone, bricks and mixed materials, both in monumental and traditional buildings. They are realised in different historical ages with different thicknesses, materials, internal humidity percentages and damages. The selected case studies are representative of the historical construction techniques prevailing in the Lombardy Region[1] (Italy).

The study compared the national standards, with U-values calculated and measured *in situ*. The different results depend on the type of walls. In all cases, the measured U-values of ancient walls are better than standard and calculated ones. For the brick walls, it is not convenient to utilise standard and calculated U-values because they overestimate excessively the thermal losses of opaque envelope. The real performances are better than 3-56% referred to standard data and of 2-57% referred to calculated data (Figure 4).

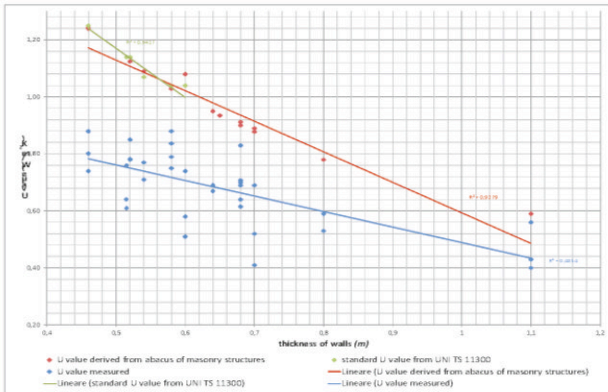

Figure 4 Comparison among standard, calculated and measured U-values of ancient brick masonries.

The analysis has not shown any correspondence between historical ages and thermal performances of bricks.

In stone walls, it was not possible to make a similar analysis because the thermal properties of stones are very different. The U-values calculated in the Italian standard are based on the average value of thermal conductivity of stones and do not coincide to Moltrasio stone; also the standard thicknesses are too low.

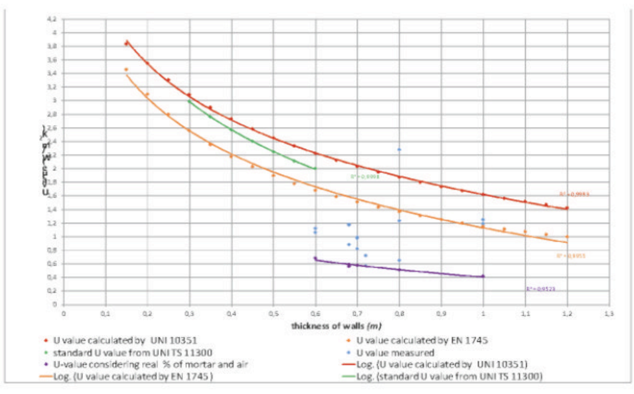

Figure 5 Comparison among standard, calculated and measured U-values of ancient stone masonries.

4. Case studies

The research was focused on the evaluation of different currently available energy software testing their ability to simulate historical buildings properly. The different software have been tested on three historic churches that have been chosen for their simple shape, but built with a wide range of building technologies. The study was conducted on the Church of San Rocco in Cornaredo, the Church of the Purification of Santa Maria in Caronno Pertusella and Santo Stefano Oratory in Lentate sul Seveso. These three buildings are located in Province of Milan. First of all, the energy audit was conducted. The real energy consumption was measured using the energy bills of electricity and gas. At the same time, a deep diagnostic study was carried out. The details are described in Table 1.

Table 1 Diagnostics performed on the case study buildings

Test	Cornaredo	Caronno Pertrusella	Lentate sul Seveso
Historical analyses	X	X	X
Survey	X	X	X
Relief	X	X	X
IR Thermography	X	X	X
Gravimetric tests	X	-	X
Analysis on mortars and plasters	X	-	X
Psychometric tests (T°C/RH)	-	-	X
T and RH monitoring	1 outside 1 inside	1 outside 3 inside	1 outside 2 inside
HFM	X	X	X
Energy bills	X	X	X

The Church of Cornaredo is a small chapel dating from the Renaissance built with very simple geometry and arrangement. The supporting structure is made of masonry solid bricks (thickness 46 cm) and the outer walls are finished with plaster mortar. The floor is laid over a slab placed on the ground (with only a waterproof membrane interposed). The nave has a wood ceiling covered by two layers of tiles. On the long sides there are two small openings with wooden frames and single glazed glass. In the front there is a double glazed window pierced by two air vents. The building is not heated and is only opened on appointment.

The Church in Caronno Pertusella was built between the years 1483 and 1500. The building, which is east-west oriented, has a single nave plant, and one small chapels along the longer sides. The nave has three bays, and each bay has a brick-cross vault as the ceiling. The supporting structure is made of masonry solid bricks (thickness 52 cm). The openings (7 half circle windows) in the upper part of the walls, close to the vaults basis. In the apse there are 2 rectangular windows, as well as in the chapels. The heating system consists of a modern gas condensing boiler and radiant floor panels. The thermal power is 19 kW, while the operating temperature is 50/30 °C.

The Oratory of Lentate was built in 1369, adjacent to other buildings. The masonries of the perimeter walls have very different patterns due to the building techniques and the dimensions of the quoins. The western and southern sides have brick solid masonry with regular horizontal courses. The northern and eastern sides were built in solid masonry with alternated horizontal courses of pebbles and bricks. The openings are few and small: they was substituted with recent metallic ones, double glass panels and an opening operated by an electric system. Five wooden trusses supporting the secondary structure and the timber boards compose the roofing of the nave. Recently a insulating layer was added. It has also a Hypothermos Tempering system to prevent the rising damp. The Oratory is only open to visitors on appointment.

5. Energy simulation

The systems for assessing the energy performance of buildings currently available are static, sketch design and dynamic. Each software uses specific algorithm for the calculations, have different input mode and can produce different typology of output. In general, more powerful and complete is the software, more detailed and precise input is required.

The simplified programs realise an energy assessment in stationary regime considering a limited number of factors. They are used for energy labelling in order to compare the different performances in standard condition of use. The simulation may be realised with simplified (synthetic method) or complex procedure (analytic method), that are different considering the quantity and the accuracy of data requested. In the synthetic method, the technological data of envelope and plants can be obtained by simplified determination, abacus of masonry structures, analytic calculation or *in situ* measures. In the analytic method the data can be obtained by diagnostic tests. The correctness and accuracy of the input data, of course, carry fundamental importance for determining the final results. The software simulates only partially the real performance of building because of their standard heating periods, prefixed data for internal and external air temperature, as well as the fact that they do not consider the periodic changes of temperature and the managing data.

The sketch design software (also called sketch design software) stands in between simplified and detailed simulation tools. It requires a simplified input in term of climatic data, geometry and building description. In addition, it takes the thermal inertia[2] into account, but has limited range for data input of envelope and plants (that are strongly referred to the modern building technologies). Other problems are related to the impossibility of considering unheated buildings and to the difficulties of insert moisture level of walls and natural ventilation rate.

Finally, the dynamic simulation software analyses in detail the contributions of thermal inertia of walls, variability of the outside temperature, solar radiation, natural ventilation and users' management. Detailed data have to be used both for describing climatic conditions, geometry and building properties.

5.1 Results of energy simulation

The simulations are carried out with DOCETpro 2010 (static software), Casanova (sketch design software) and BEST Openstudio (dynamic software that work with EnergyPlus engine). Particularly, the simulations are realized in the following conditions:

- static software (three simulations based on synthetic method -using respectively standard and measured U-value- and analytic method);
- sketch design software;
- dynamic software (two simulations using standard and real management data).

Thanks to the existing monitored data (annual energy bills, air temperature and relative humidity collected hourly for more than one year), it was possible to compare the software output with the real collected data and to verify the differences. In general, the software overestimated the real energy consumption, with very high energy consumption levels (Figure 6).

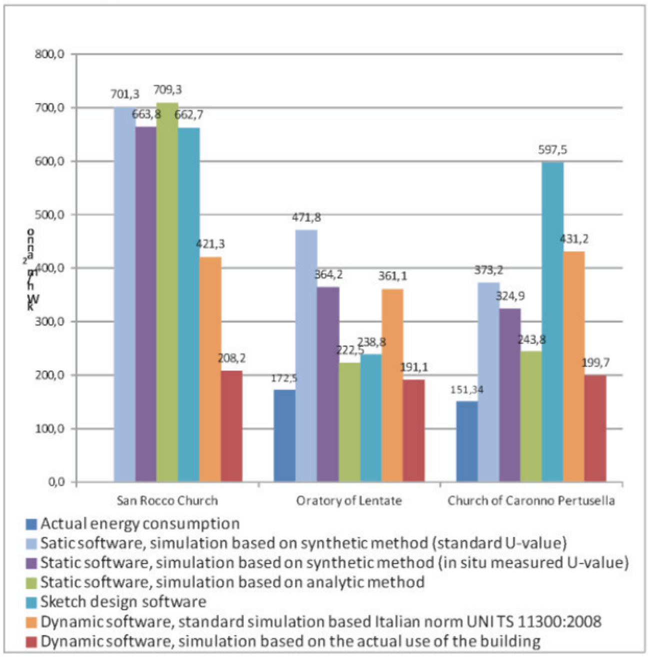

Figure 6 Comparison among the real energy bills and the energy consumptions simulated with static, sketch design and dynamic software.

The limits of the static simulation software applied to historic buildings include:

- presence of specific and simplified calculation algorithms designed for energy labelling;
- presence of standard climatic databases;
- difficulties in modelling complex shapes (i.e. domes, vaults, ...);
- difficulties in stimulating buildings without heating systems;
- presence of established internal temperatures (20°C in winter and 26°C in summer);
- do not consider the lighting systems;
- do not consider the management data.

Precisely because of these limitations, the static software highly overestimated the results compared to the real energy consumption. Furthermore, it is possible to make only a few "adjustments" to the simulation model, as the input data must be derived from standard data-bases. Therefore, it is necessary to simplify some basic information (internal temperate, climatic data, type of plants, absence of management data). The Church of San Rocco, the only unheated building, has the higher energy consumption. The simulations, in fact, define the energy needs that must be provided by the heating system for maintaining inside the prefixed temperature (20°C).

In other two buildings the worst results are obtained with the synthetic method (difference from the consumption ranges 52-63%), which requires significant simplifications for the data input, both for envelope and plants. The deviation from the real energy bills decreases by 7-10% by changing standard and measured U-values.

The static evaluation realised by the analytic method (used measured U-value) models much better, showing a difference from the consumption ranges 22-38%. The result is due to the higher precision of the data requested for heating and air conditioning systems.

The sketch design software showed quite unreliable results for historic buildings (difference from consumption ranges 28-75%). The limits include:

- presence of climatic databases referred only to the most important Italian cities (Rome and Milan), however, there is a provision to import climatic data;
- simulate only simple shapes (square and rectangle);
- presence of limited ranges of U-values;
- it is necessary to enter the same thermal performances of windows placed on the same façade of the building;
- difficult for coring out simulations of buildings without heating systems;
- presence of limited ranges of data input for heating and cooling systems (that are strongly referred to the modern building technologies);
- consider simplified management data and internal gains.

Furthermore, these softwares don't permit to calibrate the model with the input data measured *in situ*. For this reason, the final energy level is very different from the real.

Only the dynamic software, in real conditions, slightly overestimated the energy performance of the heated churches (10-24%). The software models simultaneously thermal, electrical, air flows, and user' management data, providing a comprehensive energy assessment of all the parameters that characterise the energy balance of the building, both in winter and in summer. The model is calibrated with measured U-values, temperature and humidity and real performances of plant and lighting. Also, it allowed access to non-standard data of the ground temperature, considering the effects of the storage and the release of heat produced by the ground. It was not possible only to measure the change of air, due to the enormous volumes of the churches. Also, only the dynamic software considers the incidence of the presence of structures huddled to the building, a situation very common in urban centres. These lead to a positive energy effect, particularly, when the walls have a reduced thickness (<50cm).

Finally, the dynamic software permitted to verify the role of management data for improving energy efficiency. Particularly, the comparison between three different internal scenarios (real, standard and during religious function) shows how the presence of internal gain caused of occupants, lighting, and so on, in winter reduces the need for heating and in summer increases the need for air-conditioning (Figures 7-8).

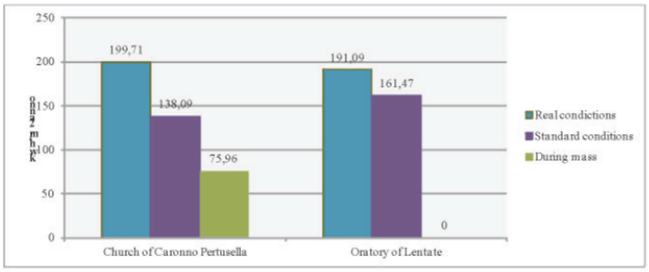

Figure 7: Energy demand for heating simulated with dynamic software.

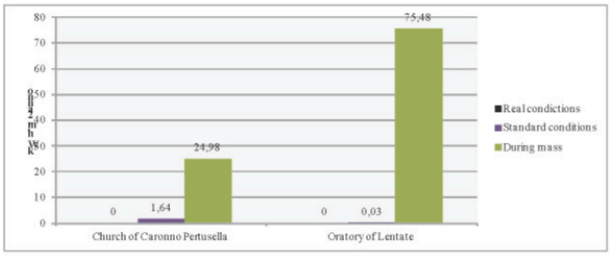

Figure 8: Energy demand for cooling simulated with dynamic software.

In the dynamic simulation of a historic construction, the main problems are related to the level of precision of input data required for the simulation (especially for the building envelope and air flow). Standard databases, construction schedules and reference literature, however, are inappropriate for these buildings. For this reason, it is necessary to create specific databases, based on *in situ* measurements of some important parameters, such as thermal transmittance, thermal inertia and conductivity of envelope materials, role of humidity rating in increasing the U-value of walls, air flow rate and energetic performances of energy supply systems. In particular, the main difficulties concern the calculation and the measurement of air leakages through the building envelope.

5.2 Considerations on environmental data

In addition, the comparison of monitored and simulated trend of air temperatures (and relative humidity) permits to check if the software adequately takes into account the thermal inertia of the building envelope. A detailed assessment has been made for each season to verify whether the errors of the software model are more or less related to a particular time of year and see if the software works better/worse for the assessment of summer or winter period (for example, it might be the software does not take into consideration the phenomenon of time-lag). The environmental assessment shows different results using sketch design and dynamic software. The first do not correctly simulate the trend of temperature and relative humidity, obtaining values that significantly deviate from the reality (Figure 9).

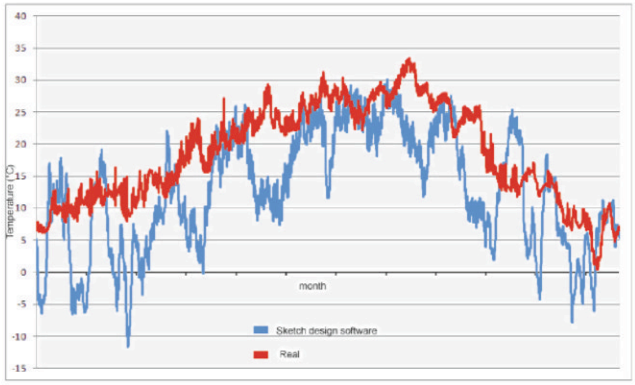

Figure 9: Comparison between real monitored data and those estimates by sketch design, in the Church in Caronno Pertusella (Jan-Dic 2012).

The dynamic software simulates the real performance correctly. In winter, the modelling well approximates the monitored values, with differences never exceeding 2 °C and with a trend that is very close to the real one. In summer the modelling underestimates the internal temperature by 2-4 °C, though showing the same thermal trend of the monitored data. In spring and autumn, the lower temperature is 2-6 °C, with a trend that not always well approximates the real one (Figure 10).

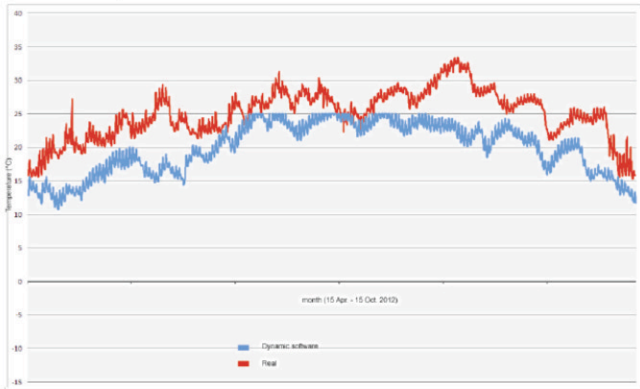

Figure 10: Example of the comparison between real monitored data and those estimated by the dynamic software, in the Church in Caronno Pertusella (Jen.-Dic. 2012).

6. Conclusion

The present work addresses the problems related to the evaluation of energy performance of historic buildings and also describes the limitations of the currently used energy simulation software to model these building. The most common calculation tools, both static and dynamic software, use the same evaluation methods and parameters for modern and ancient constructions. These calculation tools have poor flexibility for the application on historical buildings, and their modelling is reliable only by adjusting the inputs until the results are close to the experimental data. As might be expected, the dynamic software is better than other tools to assess energy performance of historical buildings. Unfortunately, it also does not contain a library of information sufficiently informed on the technical terms and the properties of historical elements and their interaction. This calls for the need to create and develop a new specific database for the construction techniques used in historical buildings. The future development of present research will be focused on the development of the methodological procedure and software dedicated for historical buildings through multidisciplinary collaborations.

7. Acknowledgements

The authors thank Paolo Sangalli, Alice Bellotti, managers, directors, technicians and conservators of the studied buildings.

8. References

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9. Note

1. For each material, several representative buildings have been selected, belonging to different historical ages and uses. Particularly, the analysis sample consists of 22 buildings built in different periods ranging from XII-XIX Century. They are used for cultural, residential and tertiary functions. The masonries studied are in Milan (Museo Nazionale della Scienza e Tecnologia, Istituto dei Ciechi, Pinacoteca of Brera, Politecnico Univerity, Palazzo Reale Villa Reale and two residential buildings), Monza (Duomo and Convento del Carrobiolo), Cornaredo (Church of San Rocco), Caronno Pertusella (Church of the Purification of Santa Maria) and Santo Stefano in Lentate (Oratory of Santo Stefano). The stone walls studied are in the subsequent edifices of Como: Villa Olmo, Palazzo Giovio, Palazzo Erba Odescalchi, Palazzo Natta, Palazzo Volpi, Chiesa di San Francesco and Palazzo del Municipio. The mixed walls studied are in the subsequent edifices: Sant'Alessandro University and Monastero of Lavello Calolziocorte. There are measured 58 points: 38 are brick walls (thickness 46-110 cm), 18 stone walls (thickness 56-100 cm) and 2 mixed materials (thickness 67-100 cm).

2. The highest surface mass considered is about 800 kg/m^2 that is considered a heavy envelope for modern architecture (about 45 cm thickness of heavy bricks), but it is not representative of a wall with a thickness more than double with a front mass of 2000-2500 kg/m^2.