Static and Dynamic Evaluation Methods for Energy Efficiency in Historical Buildings

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ABSTRACT: This paper presents the comparative results of energy evaluation of two historical churches. The thermal performance is evaluated by means of static and dynamic computer simulations. The experimental data serve as verification of the thermo-physical parameters of the building envelope components for carrying out energy performance simulations: energy bills, temperature and relative humidity of air. In particular, the simulations are performed using the thermal transmittance values defined by Italian standards, calculated according to the European standard and measured in situ on several ancient buildings with different wall thicknesses and construction techniques. The present study aims to understand which energy audit schemes, more or less evolved, simulate better the real energy performances of the historic buildings and identify the strengths and the limits of each software for static and dynamic energy simulations. The final goal includes the need of intervening on a "particular" type of heritage to optimize the requirements of energy efficiency and effectiveness together with the preservation of their cultural values. An accurate diagnosis is the first step to identify the suitable intervention. Finally, the evaluation of energy retrofit obtained by dynamic simulation permitted to assess the real energy performance improvement and demonstrate that, in some cases, the conservative interventions have a proven effectiveness.

INTRODUCTION

The energy performance enhancement in existing buildings is an important theme of the European policies on environmental sustainability. The transformation of the on-going energy consumption model towards its conscious management, damage reduction, progressive introduction of renewable energy sources, as a matter of fact, permits to improve the sustainability of the urban environment and reduce the environmental pollution. Energy and environmental programs should be developed starting with a thorough understanding of the behaviour of the historical buildings. This means to recognize the historical transformation of building, its present conditions, material and immaterial values, critical points and issues, and opportunities for the requalification. In this context, the evaluation of energy and environmental performances of the ancient buildings is important to optimize the energy efficiency and the preservation of their cultural values. The relevant issue of compatibility between the permanence of the existing "values" and the new ones related to sustainability can improve the energy performances and its adaptive use. Moreover, the specific study of the historical built heritage is very important to inspire new solutions based on empirical knowledge of the typical pre-industrial world.

THERMAL BEHAVIOUR OF ANCIENT BUILDINGS

The interventions on historical buildings require a widespread knowledge of history, dimensions, building techniques, structures, materials, and management procedures. Inaccurate understanding of the building characteristics can cause serious physical damage and possible legal claims. It is important to comprehend how modern materials and technical approaches affect the energy performance evaluation of ancient buildings. This theme is not addressed yet sufficiently because of its complexity; in addition there is not an agreement on how to upgrade the general performances, as well as preserve the cultural values. Moreover the current criteria, parameters and the tools of the energy evaluation are thought mainly for modern buildings. The main weakness is related to the lack of suitable information on the building techniques, materials and possible air leakages. An accurate diagnosis is the first step to identify the suitable actions. The perspective of the energy efficiency suggests to investigate the historical building techniques. For this reason, the authors accomplished some experimental measurements to determine the most relevant thermo-physical parameters and the average data of historical walls. The data constitute a wide base for a correct energy audit scheme (Adhikari *et al.*, 2012). Subsequently, the experimental data are used for simulation of the energy performance of two historical churches with static, semi-dynamic and dynamic tools. The study permits to distinguish the better simulation of the real energy performances of the ancient buildings and to identify the strengths and the potentialities of each software.

ENERGY AUDIT SCHEME

An Energy audit is a process to evaluate the energy consumption of the building in order to identify the opportunities for retrofit actions. The energy balances are primarily made in order to compare the energy performance of each building. The energy behaviour modelled by the software was compared with the energy consumption estimated from the energy bills. This means to inspect, analyse and survey the energy flow, for reducing energy consumption, improving comfort, health and safety. To carry out the audit, it is necessary to measure the energy performance of the envelope and mechanical plants and collect the management data. Particularly, in this study the following data are collected:

- location, urban planning, orientation and environmental context;
- dimensions of the buildings;
- construction features of the building envelope;
- efficiency, functioning and maintenance of mechanical and electrical systems;
- operational data;
- leakage rate or infiltration of air;
- monitoring of temperature and relative humidity;
- energy bills;
- conservation state of the building.

Technological data were estimated using visual testing, heat flowmeter measurements and IR thermography.

CASE STUDIES

The experimentation was conducted in two historical churches: the Church of the Purification of Santa Maria in Caronno Pertusella and the Santo Stefano Oratory in Lentate sul Seveso.

The Purification Church in Caronno Pertusella

The Church in Caronno Pertusella, a village in Varese area of northern Italy, was built between 1483 and 1500. Its polygonal apse contains a remarkable series of frescoes by Giovan Paolo Lomazzo and his staff, and an altar piece painted by Bernardino Campi. The building, East-West oriented, has a single nave plant, and one small chapel along the longer sides. The nave has three bays, and each bay has a bricks cross vault as ceiling. The solid masonry is 52 cm thick, and 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 main door is in the façade, but the mostly used entrance is from the southern side. Other two smaller doors are on the northern side, towards the sacristy and the parish building. 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.

During the last restoration (2009-2010), a thermo-hygrometrical investigation of the masonry was completed. Thermal scanning is served to identify the building techniques and their conditions, those were otherwise not detectable through visual analysis. The results of IR thermography together with the gravimetric tests allowed to localize few areas of rising damp on the northern side due to a leakage from the pipes or a localized accumulation of rain. As an example, the following images show the results of the investigation on the northern chapel (Fig. 1 e 2). In addition, there is also a water infiltration from the roof.

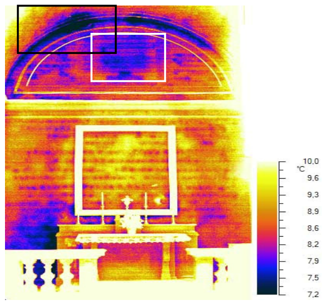

Figure 1: The Northern chapel before the restoration
Figure 2: Composite of thermograms, showing the texture of the masonry underneath the plaster; emissivity 0.92, T° 12°C, RH 64%, active approach.

At last, in the left corner, at the bottom, the surface has a lower temperature due to the evaporation flux occurring there. Gravimetric tests of samples from this surface confirmed that high water content was due to a localized rising damp. Without the application of a thermal stimulation the passive approach allowed the measurement of surface temperature representing the balance condition between the surface and the ambient air. The thermal bridge due to the thinner infilled wall opening is clearly detectable with IRT. During 2009-2010, the hourly measurements of RH and Air temperature, inside and outside the building, have been carried out. The results show a trend of the air temperatures and RH values with smooth and gradual seasonal variations (Fig. 3 and 4).

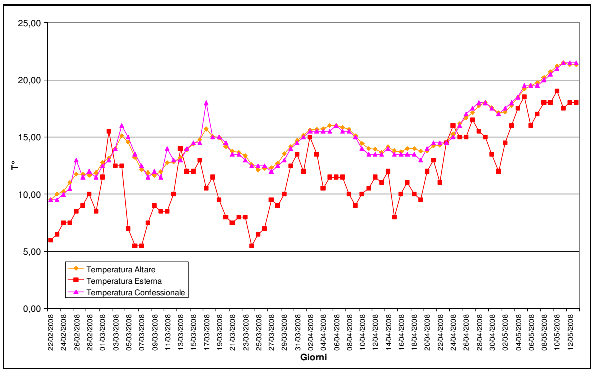

Figure 3: Daily average air temperature (February 22- May 13, 2008)

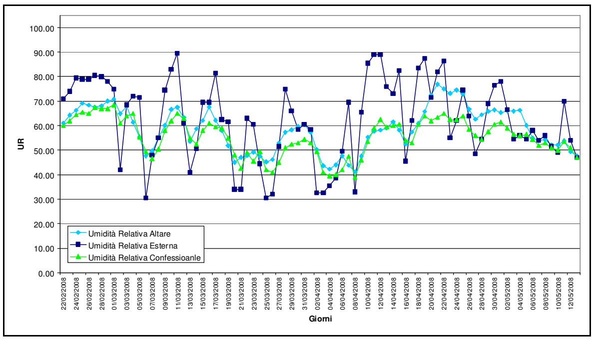

Figure 4, Daily average RH (February 22- May 13, 2008)

The climatic variation outside affects the interior microclimatic condition only if the variation outside has a large gradient (several degrees) and it lasts at least 12 hours, otherwise the thermal inertia of the structures and, probably, the limited thermal-hygrometric exchange with the air naturally occurring, determine the stability of the interior microclimate.

Santo Stefano Oratory in Lentate sul Seveso

The oratory was build in 1369. It has one nave divided from the presbytery by a triumphal arch (Fig. 5). The tower bell basis is part of the Northern wall. The masonries of the perimeter walls have very different pattern due to the building techniques and the dimensions of quoins. The Western and Southern sides have bricks solid masonry with regular horizontal courses. The Northern and Eastern sides have a solid masonry with alternated horizontal courses of pebbles and bricks. The Eastern and Southern walls are adjacent to other buildings. The exterior elevation has just traces of plaster, whilst inside there is a frescoed lime plaster with an average thickness of 3 cm (Fig. 6).

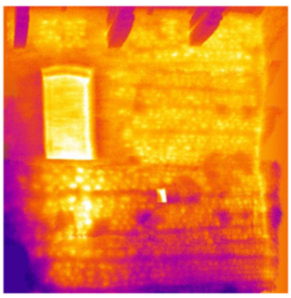

Figure 5: The facade of the Oratory

Figure 6: Composite of thermograms, showing the texture of the masonry

The roofing of the nave is composed by five wooden trusses supporting the secondary structure and the timber boards. Recently an insulating layer was added. The chancel has a cross vault of solid brick masonry. The floor has a brick tiles pavement dating back to 1935. Apart from a crawling space of 50x50 cm along the interior walls, the floor is directly founded on the soil.

The openings are few and small: the entrance door, the main window and other two small circular windows are in the façade. Other three small window are on the northern elevation. They were substituted in a previous maintenance intervention with recent metallic ones, double glass panels and opening are operated by an electric system.

The Oratory went under a restoration in 2006 regarding the roof, strengthening the exterior walls, fixing the plaster, cleaning the frescoes and installing a *temperierung* plant to prevent the risk of condensation during the winter. A recent check by IR thermography confirmed that the plant affects the temperature of the bottom of the masonry up to about 1 m from the floor.

Before starting the restoration, the authors collected the results of the previous investigation and made some further tests and monitoring to evaluate the condition for the conservation of the precious decoration and to determine the cause of their damage.

The results of the first investigation (1986-92) highlighted the urgent necessity to repair the roof, together with localized sources of rising damp. The microclimate monitoring and further investigation (IR Thermography, gravimetric tests, psychrometric tests) after the repair of the roof confirmed that the high water content in the masonry was reduced, but a localized source of rising damp remained on the southern side. Only during the restoration this source of water was isolated and the infiltration eliminated. It was due to the insulation of the adjacent building, where a waterproof membrane was applied on the masonry, and the lack of ventilation of the crawling space. The microclimate monitoring highlighted that the values trespassing the threshold for the conservation of frescoes during the weeks of prolonged heavy rains.

The psychrometric results indicate a homogeneous distribution of air temperatures and RH, apart from the zone in front of the entrance door, because of the poor airtighness of the door, the solar irradiation on the western facade and throughout the window.

SOFTWARE FOR ENERGY SIMULATION

Currently several simulation software are available for energy performance of buildings. Each software uses specific algorithm for the calculations, has different input mode and can produce output of different typology. In general the more powerful and complete is the software, the more detailed and precise input it requires. The systems for assessing the energy performance of buildings currently available are static, semi-dynamic and dynamic.

The simplified programs realize 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 first case, the technological data of envelope and mechanical plants can be obtained by standard references based on constructive analogies, calculated using national databases or monitored in situ with diagnostic tests. In the analytic method the data can be obtained by diagnostic tests. The software simulate only partially the real performance of building, because they do not consider the periodic changes of temperature for assessing overall energy efficiency. The correctness and accuracy of the input data, of course, have a fundamental importance for determining the final results.
The semi-dynamic software (also called sketch design software) uses a dynamic simulation to take into account the thermal inertia, but requires a simplified input in term of climatic data and building description. The user interface is normally based on graphical icons to which numerical values are related.
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 for describing both climatic conditions and the building properties.

RESULTS

First of all, the real energy consumption of the buildings was estimated using the energy bills of electricity and gas. After, it was possible to compare these data with the energy behaviour modelled by the different software. The simulations are carried out with DOCETpro 2010 (static software), Casanova (sketch design) and BEST Openstudio (dynamic software that works with EnergyPlus engine). Particularly, the simulations are realized in the subsequent 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 of the building).

The static software overestimate the real energy consumption (Fig. 7).

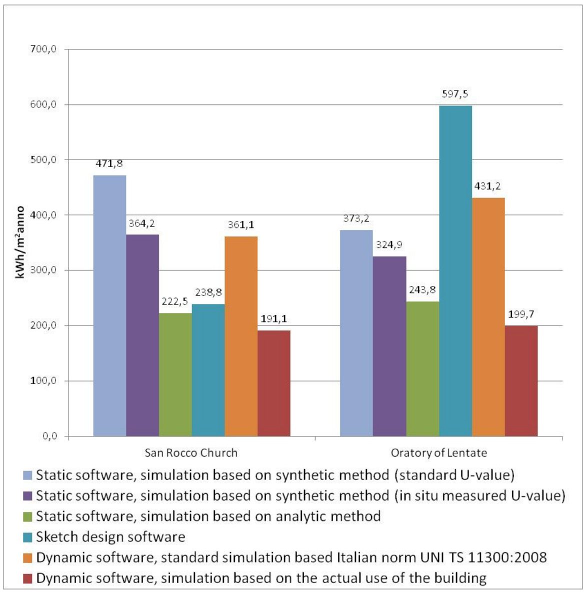

Figure 7: Comparative results on real energy consumption and simulation of energy behaviour in the two churches using static, semi-dynamic and dynamic software

The limits of the static simulation software applied to historic building include:
- presence of standard climatic databases;
- difficulties to model complex shapes (i.e. domes, vaults, etc.);
- difficulties to simulate buildings without heating systems ([i]);
- presence of established internal set point temperatures (20°C in winter and 26°C in summer);
- do not consider the lighting;
- do not consider the management of the building.

Precisely because of these limitations, the static software highly overestimate the results compared to the real energy consumption. The worst results are obtained with synthetic method (difference in consumption 52-63%), which requires significantly simplifications for the data input, both for envelope and mechanical plants. The deviation from the real energy consumption decreases to 7-10% by changing standard U-value with measured ones.
The static evaluation realized by analytic method (using measured U-value) models much better, showing a difference in consumption of 22-38%. The result is due to the greater precision of the data requested for heating and air conditioning systems.
The sketch design software has very little reliable results for historic buildings (difference in consumption 28-75%). The limits include:
- presence of climatic databases referred only to the most important Italian cities (Rome and Milan);
- simulate only simple shapes (square and rectangle);
- presence of limited ranges of U-values;

- no provision to define different kind of windows on the same façade of the building;
- do not carry out simulations of buildings without heating systems;
- consider simplified management data and internal gains.

Only the dynamic software in real conditions, overestimate slightly the energy behaviour of the 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 characterize the energy balance of the building, both in winter and summer. Only in the dynamic software, however, it is possible to enter non-standard data of the ground temperature, considering the effect of the accumulation and the release of heat produced by the ground. In unheated or weakly heated buildings this fact is very important because, considering standard temperature, the floor appears as a "hot plate".

In the historic constructions, 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 too 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 efficiency of mechanical plants. Particularly, the main difficulties concern the calculation and the measurement of air leakages through the building envelope.

The dynamic simulation allowed to highlight some general considerations. First of all, the presence of structures huddled to the building, a situation very common in urban centres, leads to a positive energy effect only when the walls have a reduced thickness (<50cm) ([ii]).

As always, the best retrofit solution is given by the mix of interventions on envelope, mechanical plants and management. The most convenient actions, both from the point of view of economic and energetic aspects, regard the insulation of horizontal opaque structures (roofs and basement), followed by the walls. In the last case, although it may have the same requirements in terms of energy, the position of the insulation (internal or external) creates very different internal conditions. External insulation has the benefits of reducing the risk of thermal bridges, condensation and temperature fluctuations, and of increasing thermal comfort while the internal insulation does not involve the thermal inertia of walls in the heating season. In practice, the wall accumulates and releases heat quickly, after switching off the plants. On the contrary, the worst intervention is the replacement of windows, which does not involve significant energy savings in the energy balance of buildings. Interventions with a good energy benefit are the inclusion of storm windows and the restoration of existing windows, which also ensure the conservation of historical value. Finally, management has a key role 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, because of occupants lighting, and so on, in winter reduces the need of heating and in summer increases the need of air-conditioning (Fig. 8-9).

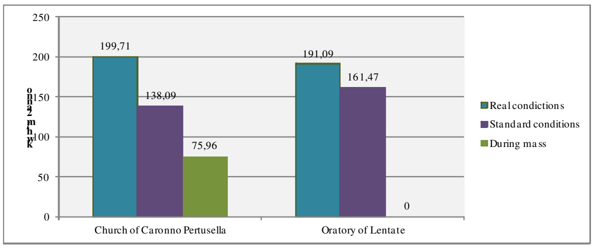

Figure 8: Energy demand for heating simulated with dynamic software

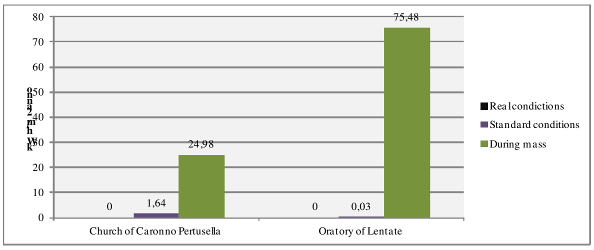

Figure 9: Energy demand for cooling simulated with dynamic software

In addition, the comparison of monitored and simulated trend of air temperatures (and relative humidity) permits to check if the software takes into account adequately the thermal inertia of the building envelope. A detailed assessment has been made for each season to verify if the errors of the software model are more or less related to a particular time of year, so if the software works better/worse for the assessment of summer or winter period (for example, the software might not take into consideration the phenomenon of time-lag). The environmental assessment shows different results using semi-dynamic and dynamic software. The first do not simulate correctly the trend of temperature and relative humidity, obtaining values that significantly deviate from reality (Fig. 10).

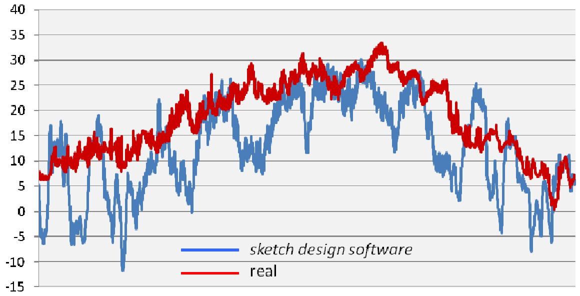

Figure 10: Example of the comparison between air temperature monitored and simulated by the sketch design software, in the Church of the Purification of Santa Maria in Caronno Pertusella

The dynamic software simulates quite correctly the real performance. In winter, the modelling approximates well the monitored values, with differences that never exceed 2 °C and with a trend very close to the real one. In summer the modelling overestimates the internal temperature of 2-4 °C, however showing the same trend of the monitored data. In spring and autumn, the overheating is between 2-6 °C, with a trend that not always well approximates the real one (Fig. 11).

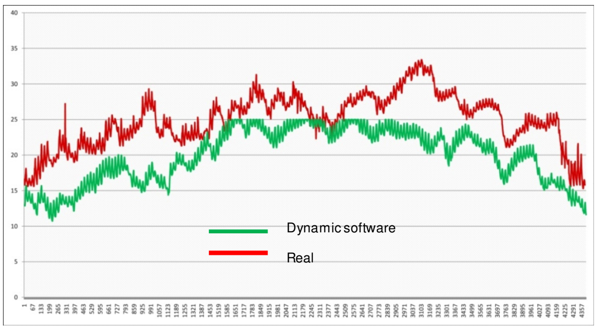

Figure 11: Example of the comparison between air temperature monitored and simulated by the dynamic software, in the Church of the Purification of Santa Maria in Caronno Pertusella

The system, therefore, underestimates the thermal inertia of the historic walls in summer, spring and autumn, when the microclimatic conditions are more affected by the variation of the surrounding environment.

CONCLUSION

Energy audit is the most appropriate scheme for the evaluation of energy behaviour of historic buildings while the energy labelling doesn't consider specific thermal data and management policies. The study shows that the use of dynamic software is necessary to assess correctly energy performance of historical buildings. The most common calculation tools, both static and dynamic software, use the same evaluation methods and parameters for energy performance evaluation of modern and ancient constructions. In all cases, the software do not contain sufficient library of information regarding the technical terms and the properties of historical elements and their interaction. As a result, these calculation tools have poor flexibility for the application on historical buildings, and their modelling is reliable only in the dynamic software adjusting the inputs until the results are close to the experimental data. For this reason, the experimental estimation of some important parameters (U-value, air leakage, temperature and relative humidity of air, energy consumption, etc.) is fundamental to create specific database of the construction techniques used in historical buildings.

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[i]. The software calculates the energy requirements for heating in order to maintain an internal temperature of 20°C. The systems are useful for sizing the heating plants.

[ii]. Only the dynamic software guarantee the control about the data related to other buildings located in the surroundings.