SBE21 Sustainable Built Heritage

14-16 April 2021,
Online conference

DRAFT PAPER

The SBE21 Heritage Conference is co-financed by:

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The dynamic thermal energy simulation of historic buildings in Mediterranean climate: knowledge and simplification

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Abstract. The European built heritage is strongly characterized by "historic buildings". This built heritage represents an important cultural resource, constitutes a *public good* and testifies the community identity. The current challenge to reduce the consumption of energy resources is aimed at the requalification of this built heritage. To meet this challenge, energy analysis is increasingly being used also for historic buildings through complex building energy simulation program. Although their application to modern buildings leads to significant results, in the modelling of historic buildings there are numerous approximations and uncertainties relating to materials, thermal bridge, geometry and construction techniques which can lead to inaccurate results. Furthermore, the lack of input data and the complex geometries make even more difficult to determine the correct energy performance of the simulated built heritage. To the aim of investigates the validity, accuracy and reliability of Open BIM software, widely used by Architects and Engineers, based on the simple hourly method (EN ISO 52016-1), an energy analysis of historic building was performed.
The work is intended to provide a calculation method to evaluate energy performance (heating, cooling, lighting, etc) of historic buildings (load bearing masonry structure with vaults) with the use of simple dynamic models, which comply with Italian energy laws and regulations, and to predict the energy saving potentials related to building retrofit actions.

1. Introduction

The first law on the correct management of energy sources was introduced in Italy in 1976, n. 373 "Standards for the containment of energy consumption for thermal uses in buildings" which laid down the first provisions concerning the performance of the components, their installation and the insulation characteristics of the new buildings. Subsequently, new regulations were introduced that improved the correct management of energy sources, also applied to historic buildings. Directive 2009/29/CE entered into force in June 2009 and will be valid until 2013 to 2020 [1]. This Directive plays an important role in slowing down global warming: in fact, it contains the "20-20-20 Plan". In May 2010, the European Union issued Directive 2010/31/UE, which revised the previous one to clarify, simplify and strengthen certain provisions and broaden the scope. This Directive reinforces the objectives and fundamental principles of Directive 2002/91/CE; however, it provides not only for the strengthening of the role of energy certification, but also to require that all buildings undergoing major renovations meet the desired requirements (established by the Member States) as far as technically, functionally and economically possible. According to the new provisions, buildings that will be built after 31 December 2020 will have to guarantee energy self-sufficiency through the supply of renewable sources. New public buildings are required to meet this "zero energy buildings" target by 31 December 2018 [2]. Directive 2010/31/UE maintains the distinction between new and existing buildings, reaffirming that listed buildings may be excluded from the adaptation, if the interventions may cause damage to their character or appearance. The most important aspects introduced by the European directives concerning the existing building stock are the following: the compliance with the minimum energy performance requirements is mandatory for buildings subject to major renovations, extensions or extraordinary maintenance relating to the envelope or systems; the energy certification of the building in case of construction, renovation, sale or rental is mandatory; the periodic maintenance of existing boilers is mandatory.

Directive 2012/27/UE further reinforces the objectives of energy efficiency and reduction of greenhouse gas emissions expected for 2050, establishing a progressive increase in the rate of property restructuring [3].
On 22 January 2014 the European Commission presented the framework for energy and climate policies to be implemented by 2030. The main objectives are the 40% reduction in CO2 emissions by 2030 compared to 1990 levels; the use of at least 27% of energy consumption from renewable energy; greater energy efficiency through possible amendments to the Energy Efficiency Directive; key indicators for measuring progress. Efficiency, energy saving, and environmental sustainability have long been the strategic objectives of the European Union. Historic buildings are one of the symbols of Europe's cultural heritage, but they contribute to increasing energy needs and CO_2 emissions, at the same time. According to this point of view, the importance to improve historic buildings energy performance is evident.

2. Methodology

The interventions on historic buildings have to be conducted in a conscious manner to preserve them for the future generations. In this sense, dynamic energy simulation applied to historic buildings can be helpful to identify the more effective interventions for the reduction of energy consumption and the preservation of cultural, social and historical value. To this purpose, a simulation of the energy performance was carried out on an historic building located in the centre of Catania by a simple dynamic model (Epix- Termolog) complying with the Italian energy laws and regulations [4].
In accordance with EN 16883:2017 [5], it was carried on an investigation, analysis and documentation collection of the building including its heritage significance. This preliminary procedure is fundamental to have a quite realistic picture of the thermal physic behaviour of the building, to perform a quit realistic energy analysis and to select measures taking in account both the improvement of energy performance and the respect of the cultural and historic heritage. It is necessary a drawing collection and a visual inspection to understand if building underwent restoration work in the past and how they affect its actual thermo-physical behaviour. Onsite surveys have made possible to describe building construction techniques, hygrothermal behaviour and materials conservation conditions with accuracy.
Afterwards, an audit energy analysis was carried on to collect information on implants characteristics (HVAC systems, lighting systems, etc.), envelope features, energy consumption (electric bills, etc.), behaviour of the occupants, etc. [6, 7].
Although the model implementation and simulation of an historic building requires very similar procedure of a contemporary building (climate data, geometric characteristic, thermophysical features of element, occupants' behaviours, etc.), it was necessary the introduction of many simplifications and approximations due mainly to the complexity of geometric and architectural elements. Indeed, the commercial software for the professional field are conceived only for contemporary buildings. In detail, the simplifications introduced in the model are the followings: the ornamental elements (i.e moulded frameworks, columns, portals) were neglected even though they constitute thermal singularities; the thickness of envelope components were considered constant; the air temperature were calculated uniformly in each thermal zone; the vaults were modelled as flat elements; the materials were considered homogeneous; all thermal bridges were calculated with plug-in based on FEM (finite element method). In the light of the above, the validation of the model needs a specific procedure of calibration avoiding build-up a model that is not representative of actual behaviour. To this aim, several monitoring campaign was carried out to collect experimental data to be used for the model calibration. The measurements were conducted in a room located at the first floor of the building. It was recorded indoor and outdoor air temperature, inner and outer superficial temperature, thermal parameters (U-values), and thermal fluxes. During the monitoring campaign, meteorological data were collected by the weather and solar station of University of Catania. These data were subsequently adopted to modify the Annual Time Reference Year (TRY) weather file of Catania used as input file. Once the model has been calibrated, different scenarios of energy efficiency measures were taken in account to improve heritage buildings energy performance trying to do not compromise the cultural value of the building.

3. Case study

San Giuliano Palace (Figure 1) was designed by the architect Giovan Battista Vaccarini (Palermo, 1702 - Milazzo, 1768) who was commissioned by the Paternò family (San Giuliano marquises). Palazzo San Giuliano was built in 1738 and it is an exemplification of the architecture that emerged following the earthquake that destroyed Catania in 1693. The building has been remodelled several times but the external elevations have remained almost the same. The palace was built with materials that are typical of Etna's territory. The doorway is flanked by two marble columns that were taken from near Roman ruins, furthermore. The building, currently used as offices, owned by University of Catania since 1981, develops on four elevations above ground, has a total floor area of 5.031 m^2 and it is characterized by an outstanding central courtyard with a monumental staircase that allows access to the eastern wing.

Figure 1 – Birdseye watch of S. Giuliano Palace and Catania historic centre

An onsite survey of the building was carried on to investigate the geometric and space distribution but also the peculiar historic stratification that involves principally interiors walls and roofs (Figure 2). Onsite survey and accurate knowledge of the construction history was carried on through archival data also. The modification in the original use has contributed to the increase the energy requirement. It was necessary to know building's *corpus*, that is to understand used materials and constructive elements.

Figure 2 – The more recent transformations in San Giuliano Palace.

The technical-constructive reading, through the decomposition of the factory into components and sub-components, was possible thanks to the study of the construction techniques of the Etna territory, the direct observation and the data collection from the many survey campaigns that have followed over the years [8].
The building presents a traditional structure with masonry made by basaltic stones of irregular shape and medium to small size held by mortar of lime and volcanic aggregate (so called *azolo*) with size between 0,5 and 4 mm. Masonry's thicknesses are variable from 80 cm up to over a meter, without thermal insulation. The floors have structures realized with vaults in pumice-stone and gypsum mortar (thickness 15 - 20 cm) [9]. Sometimes, we can find floors with steel beams. Moreover, they are characterized by flat upper surface. The spacing within the steel beams ranges from 50 to 80 cm. The roof is clad with typical Sicilian tiles, has a pitch of 19°, it rests on wooden trusses and is uninsulated. The windows are single pane and have a timber frame without thermal break, and they are provided with internal wooden shields (so called *alla palermitana* windows). A monitoring campaign was carried out from 19/02/2013 to 23/02/2019 and from 12/03/2013 to 19/03/2019 to determine in situ thermal parameters (U-values) of load bearing masonry walls. The figure 3 reports some recurring constructive elements (taken from vertical and horizontal envelope) and their U-values.

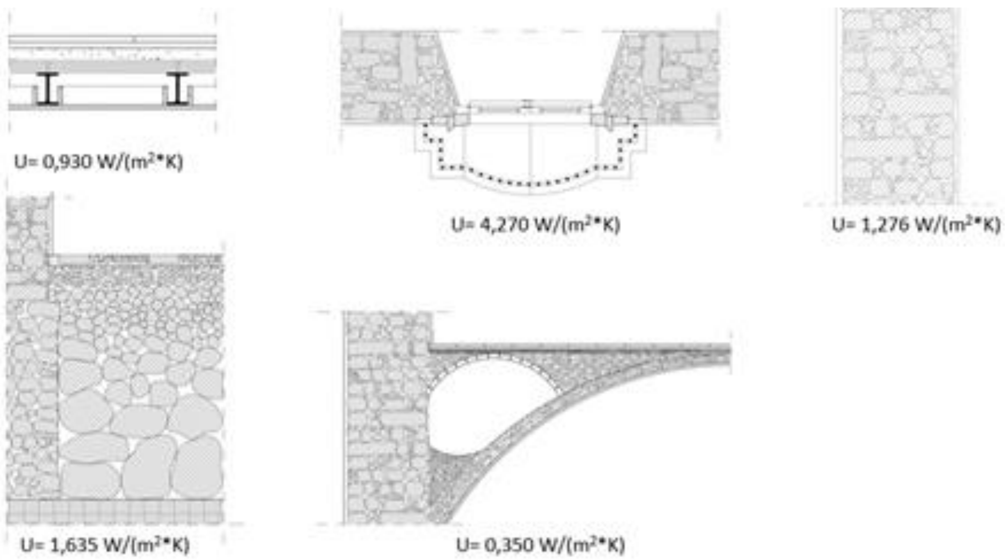

Figure 3. Some constructive elements and their thermophysical characteristics

The building is heated and cooled by an air-to-water type heat pump (bluebox ZETA REV), with 155 kW heating capacity and 150 kW cooling capacity, (COP= 3). A wing of building is also heated and cooled by a VRF system (Aermec) with 28 kW heating capacity and 32 kW cooling capacity (COP=3.50). Two-pipes fan coil units placed in the false ceiling or under the windows are the terminals of the heating and cooling system. Currently, the building does not have a mechanical ventilation system and it does not use any on-site renewable energy source. The temperature set-points for space heating and cooling were fixed, respectively, at 20 °C from 1 December to 31 March (heating period), and at 26 °C from 1 June to 30 September (cooling period). The lighting system consists of fluorescent lamps installed in rooms, corridors and service areas. No control systems are installed.

3.1 Model construction and calibration

A quasi-steady-state simulation [7] to obtain the heat balance over each month or a whole season, taking into account dynamic effects by the simplified determination of a utilization factor and semi-dynamic simulation that perform the heat balance over short time steps and take into account the heat storage properties of the building were carried out using the software tool EPIx Termolog (Figure 4). The construction of the model has encountered many difficulties due to the complex structures, to non-homogeneous materials and thermal bridges. To overcome the above drawbacks, a preliminary sensitivity analysis and two different calibration procedure has conducted. The sensitivity analysis was addressed to the aim of identify variables characterized by the highest uncertainty and the largest impact between simulated and measured values.

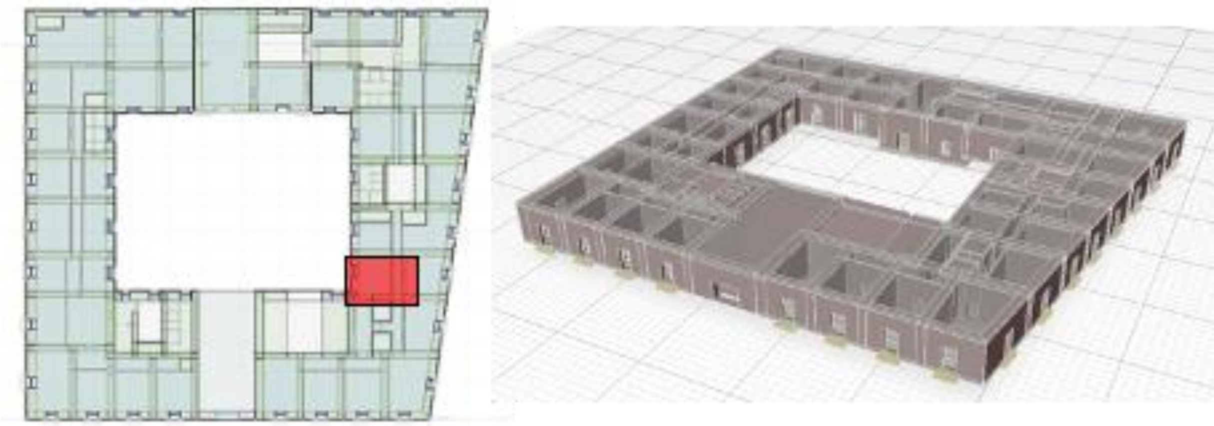

Figure 4 – Building energy simulation model of first floor of San Giuliano Palace and investigated room (Red Box)

The infiltration and ventilation rates were used in the model to assess the sensitivity of the model in free running conditions. At the end, it was set 0.8 as average air change rate per hour (ACH) and 0.2 as infiltration rate (h^{-1}). A calibration was based on the comparison between operational energy rating (OR) and tailored energy rating (TR) to assess the electricity consumption in the current state only for the first floor of the Building (Table 1).

Table 1 - Comparison between operational energy rating (OR) and tailored energy rating (TR)

Electric Consumption		**OR**	**TR**	**%**
Heating	KWh	25,408.75	24,535.98	3.56
Cooling	KWh	22,677.50	23,053.94	-1.63
Lighting	KWh	111,993.41	117,081.08	-4.35
Total	KWh	160,079.67	164,671.00	-2.79

Another calibration was based on experimental data collected during a monitoring campaign with microclimatic station (LSI – Lastem) from 7 to 14 June 2019. The measurement point considered for the survey was located in the meeting room at the first floor (Figure 4). During the monitoring campaign, indoor and outdoor air temperatures were recorded (Figure 5, 6). The model was calibrated comparing measured and simulated air temperature values in free running conditions. The input climate file was the Annual Time Reference Year (TRY) weather file of Catania modify with the data recorded by the University of Catania Weather Station during the experimental survey period. The figure 5 shows the good match between the measured and simulated temperatures trend.

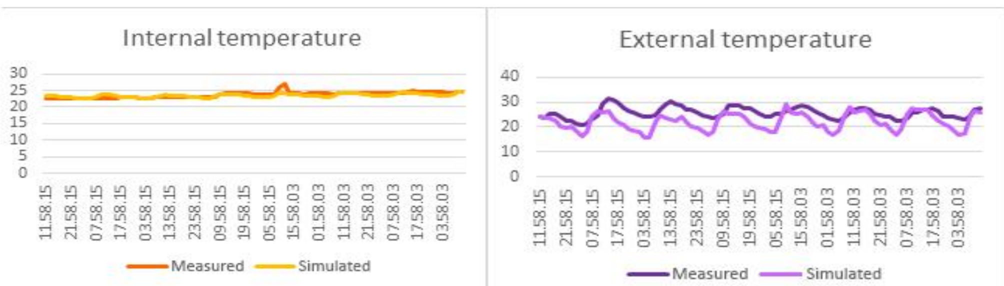

Figure 5. Measured and simulated external and internal temperatures

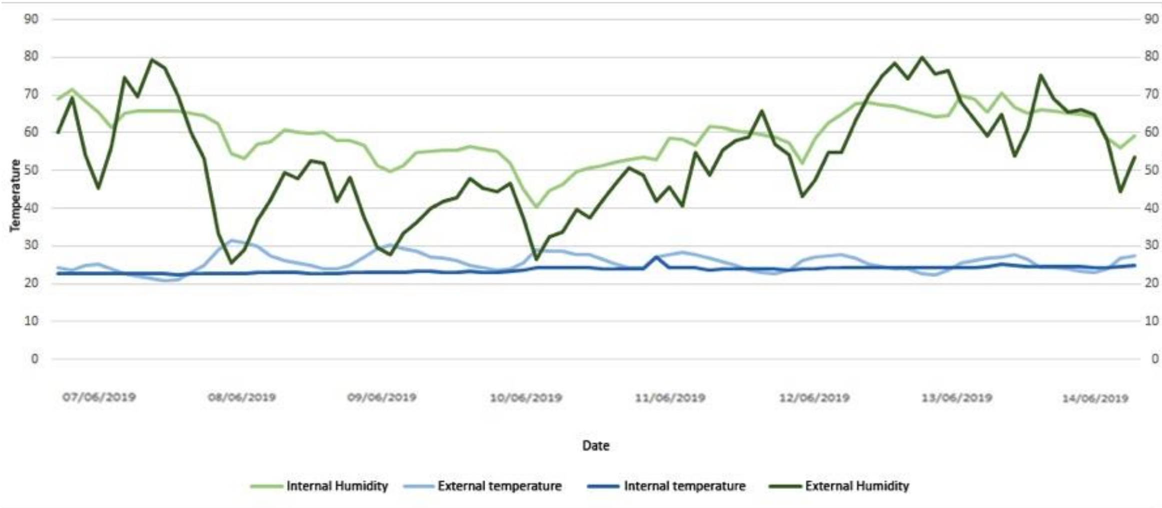

Figure 6. Measured external and internal humidity/temperature

Regarding the acceptable tolerances reported in Table 2, the model complies with ASHRAE Guidelines 14/2002 recommendations for internal air temperature but not for external air temperature, because results for CV(RMSE) and MBE calculated are 17.65 % for the former and -3.55% for the latter. However, all values are still within the values recommended by International Performance Measurement and Verification Protocol (IPMVP 2012), which are slightly higher.

Table 2 –Statistical indicators

RESULTS	OUTSIDE	INSIDE
MBE	-3.55	0.61
CV(RMSE)	17.65	3.81
Pearson index (R)	0.6	0.8

4. Retrofit Energy Efficiency Measure

Palazzo San Giuliano has undergone numerous transformations over the years, therefore suitable energy efficiency measures must be carefully defined and designed, particularly considering the historical or architectural constraints avoiding the retrofit can affect irreplaceable the built heritage. Only some of they were considered suitable with cultural value of the Palace, such as:

- wall insulation;
- replacement of window's glasses;
- replacement of HVAC generator;
- replacement of lighting fixtures.

The most disadvantaged condition is during the summer, in Mediterranean climate: it is not possible to provide solar shadings because they would modify the facades. We preferred to intervene with *light solution* that will be applied on the internal surfaces and on the equipment, therefore. The reduction of the thermal transmittance U offers the chance, for example, to reduce heat loss through the building envelope. Even if the insulation of historical building walls often is not easy to plan, verifying this possibility is useful for a more complete analysis of the measures to adopt for the reduction of the energy consumption and of the management costs of a building. These actions are difficult to realize and, in any case, they must be evaluated with care: thermal insulation, when applicable, may cause worse hygrometrical behaviour of the walls.

After making a detailed analysis of all possible improvements, a comparison it should be made between the actual situation and the combination of the chosen interventions.

Suitable energy efficiency measures for the preservation of heritage building, the technological characteristics of the proposed solution and their cost are reported in Table 3.

Table 3 - Interventions and proposed solutions

N	Energy efficiency measures	Proposed Solutions	Total Cost
1	Envelope Thermal Insulation (Internal)	Aerogel Panel s=20 mm; k=0.015 W/m K	184,413 €
2	Sun Control Window Film	3M Silver 35 Exterior	5,736 €
3	Energy Systems Replacement	Water-to-water Polyvalent HP for Space Heating, Cooling and DHW Heating Power =159 kW; Cooling Power=176 kW; COP=4.52	31,940 €
4	Light bulbs replacement	LED	4,390 €

Table 4 – Energy Performance Results

SCENARIO	Heating (kWh/m^2)		Cooling (kWh/m^2)		Lighting (kWh/m^2)	
	EP,nr	**EP,n**	**EP,nr**	**EP,n**	**EP,nr**	**EP,n**
Base	29	7.7	22.2	5.3	176	42.5
A: (2)+ (4)	29	7.7	22.1	5.3	136.9	33
B: (2)+ (3)+ (4)	17.5	25.8	22.1	5.3	136.9	33
C: (1)+(2)+(3)+ (4)	14.8	19.6	21.4	5.2	136.9	33

The table 5 reports the cost-benefit analysis of intervention of each scenario considering the interest rate (4% per year), the inflation rate (1% per year), the considered calculation period (10 years) and pay back period (8 years) [12, 13].

Table 5 – Cost- Benefit Results

SCENARIO	A	B	C
Investiment Cost (€)	10,125.9	42,065.9	238,223.4
Energy Cost Saving (€)	4,983.4	6,446.6	6,870.9
Net Present Value (year)	4,578	1,682	0.620
Return period (year)	2	6.5	34.7
CO_2 Saving (Kg/m^2)	18	20.7	21.7

The analysis of results suggests that the scenario B is a balanced optimal solution for the improvement of the energy performance and the heritage preservation of the building, because it has a low environmental impact and high energy saving compared to the other scenarios.

5. Conclusions

The use of accurate energy simulation models is pivotal to assess the environmental and energy-related impacts of historic buildings. Currently several dynamic simulation software are available for the evaluation of energy performance. However, these software, considering the complexity and multiplicity of input data required, are not affordable for everyone. The aim of the paper was to assess the accuracy and reliability of a calculation method to evaluate energy performance of historic

buildings with the use of simple dynamic models, which comply with Italian energy laws and regulations, and to predict the energy saving potentials related to building retrofit actions.
Despite the several simplifications, the methodology proposed has allowed to validate and calibrate the model with a good agreement between measured and simulated values, offering to designers a valid and simple alternative for the analysis of energy performance of historic building. In this way, it is possible to suggest energy efficiency measures to improve the energy performance enough representative of thermophysical behaviour of historic building in order to choose suitable interventions, in accordance with the provision of the EN 16883:2017 standard [5], balancing between conservation and energy performance improvement aims [14].

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