Energy efficiency and preservation of 20th century architecture

The case of the Urbino University Colleges

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Abstract – This paper follows the discussion on the energy efficiency of heritage buildings by dealing with the task of preserving 20th century buildings and making them more sustainable. It is confirmed that a thorough analysis of each case is needed, since the cultural value of modern heritage risks being overwhelmed by the effort to improve its energy efficiency. The Urbino University Colleges are a masterpiece of the 20th century. They were designed by architect Giancarlo de Carlo, built between 1962 and 1983 and still host 1000 students. A conservation plan was outlined in 2016 with the aim of developing the long-term and sustainable preservation of such a huge complex. A specific goal in terms of sustainability was lowering the heating costs to save funds for conservation activities. The efforts were thus to balance building conservation, energy efficiency and users' comfort. A thermal analysis, an energy retrofit design, a test on a pilot site, a comparison between before and after, are the tools that have been used to achieve this objective. Results provide some operational indications to merge conservation and sustainability in a 20th century heritage building.

Keywords – monitoring, energy retrofitting, building-plant design, 20th century architecture, pilot site

1. INTRODUCTION

1.1 THE URBINO UNIVERSITY COLLEGES

The Urbino University Colleges were built between 1962 and 1983 on the Cappuccini Hill, approximately 1.5 km from the Renaissance city. They were designed by architect Giancarlo De Carlo (1919–2005) as a part of an overall strategy of urban development, promoted by Carlo Bo, at that time Rector of the University. The five buildings, namely "Colle", "Tridente", "Serpentine", "Aquilone" and "Vela", are equipped with 975 rooms that can accommodate up to 1136 people (net usable area = 32,396 m^2, gross heated volume = 127,059 m^3). The residential units consist of single and double rooms, with personal or shared toilets and kitchens. Public spaces, such as reception, canteens, dining rooms, conference and meeting rooms, classrooms, offices, technical rooms and a theater, are located in the central body of each college. The general layout follows the contours of the landscape, branching and distributing the buildings from the Cappuccini Hill to the valley [1].

The load bearing facing brick walls and the exposed concrete beams and slabs are not insulated, just as many other buildings inspired by the “New Brutalism”. The original windows are mainly of two kinds: timber frame windows with single glazed glass, and iron-framed skylights with a simple glazed panel. Many original windows have already been replaced with different types of new windows. There are many issues concerning the conservation of these buildings: decay of the reinforced concrete, poor waterproofing and leakage through the roofs, decay and faults in tightness of windows and doors, compliance with laws and regulations for safety and fire prevention, limited or lacking maintenance.

As regards the HVAC systems, the original power station was renewed in 2012: three pressurized boilers with a rated output of 1650 kW each, reverse flame, three burners with 2 stage progressive/modulating, a CHP (electrical power 637 kWel, thermal power 770 kW, thermal power introduced 1620 kWth), different systems of storage of technical water, rapid heat exchangers of modules for the production of sanitary hot water, solenoid valves, plate-fin heat exchangers. A grid connected photovoltaic system (270 panels, 81 kW peak power) was then installed on the roof of the “Tridente” building. The district’s heating circuit consists of a basement distribution ring with substations. The heat emitting subsystem consists in cast iron radiators at high temperature.

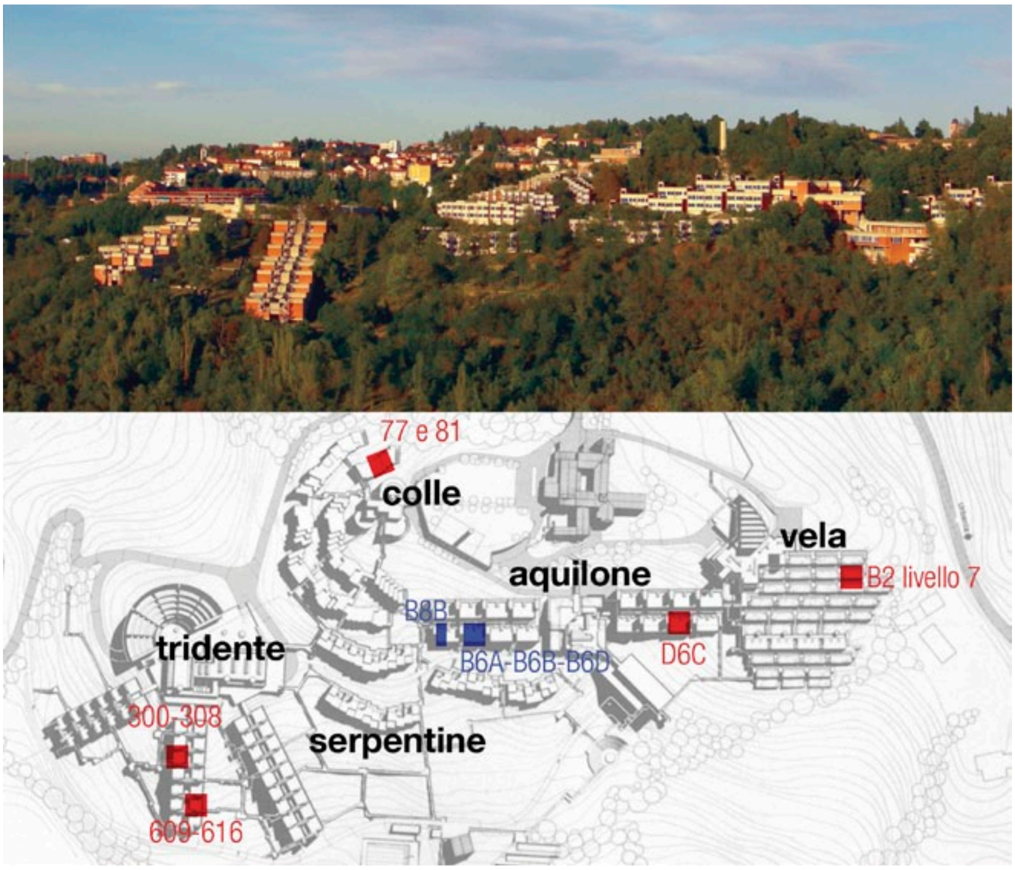


Figure 1. General plan: position of the rooms continuously (blue) and seasonally (red) analysed.

2. INDOOR CLIMATE MONITORING

The indoor climate was monitored to assess whether the heating system complied with its set points or not, and to locate the areas where local imbalances affected the comfort. The analysis was also helpful to detect if such imbalances were due to the type of heating system, to a faulty installation or to a lack in the control system. The authors monitored surface temperatures, indoor and outdoor air temperature and humidity throughout a whole year (12/2015–12/2016). Although surveys were seasonally repeated within all the colleges (Figure 1), the monitoring system was only set in the "Aquilone" building and specifically in two couples of bedrooms and a common area, which displayed the most typical layouts of the complex. Sensors were installed

- in a couple of overlapping rooms located on different floors (rooms B6B and B6D), still retaining their original windows,
- in room B8B, which is situated in a similar position but has a new aluminum frame without thermal break,
- in room B6A, which is representative of the rooms without a cold wall (Figure 2,3).

Ten sensors monitored temperature (T [°C], accuracy: ±0,1 °C at –25 °C/+80 °C) and relative humidity (RH [%], ±2 % at 0 %/100 %); four of them also measured surface temperature (Tsup [°C]). A total of twenty-two measuring points were thus operative and wireless-connected (UNI EN 15758:2010, UNI EN 16242:2012). An infrared camera was used to detect heat losses, thermal bridges and heat gains due to solar radiation (accuracy ±2 °C at –40 °C/+500 °C, 640x480 pixels, 40mK at 30 °C). Temperature and relative humidity distribution were mapped by means of a digital psychrometer (accuracy 0.1 °C, resolution 0,01 °C) patented by Politecnico di Milano [2]. Data have been processed according to UNI 10829:1999. Maximum, minimum, average, and standard deviation, daily and annual temperature range, time profiles, frequency distribution and cumulative frequency were determined for each parameter. The information resulting from

Figure 2. Position of the monitored rooms on the SW façade of the "Aquilone" building.

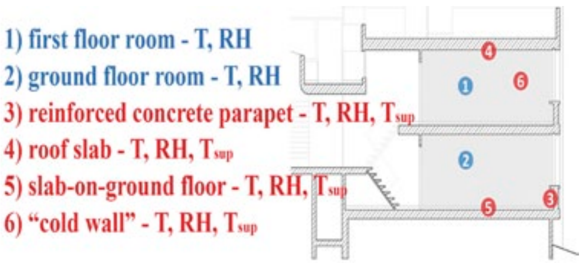


Figure 3. Position of the sensors along the cross section of the "Aquilone" building.

the monitoring of few rooms were extended to the whole complex by using a Performance Index, i.e. the percentage of time when parameters fall within an acceptable range.

For the winter season (01/12/2015 – 07/05/2016), two Failure Indexes were calculated:

- Cool Failure Index (% of time T_{iNdoor} falls below the lower limit of acceptability)
- Warm Failure Index (% of time T_{iNdoor} falls above the upper limit of acceptability).

Temperature ranges follow the heating set points. Relative humidity ranges follow UNI EN ISO 7730:2006 and ASHRAE 55 standards. Average daily temperature = 19 °C ≤ Tav,day ≤ 21 °C; 18 °C ≤ Tav,day ≤ 22 °C. Average daily RH = 40 % ≤ RHav,day ≤ 60 %; 30 % ≤ RHav,day ≤ 70 %.

A high percentage of Warm Failure Index resulted. Room B6a does not have a dispersing wall (Figure 4, right-side graph), so the high temperatures are due both to the possible over-heating and to the solar gains. The acceptability thresholds defined in the regulations are given by the need to protect the health of the occupants, considering their physiological reactions such as dry skin, irritation of the eyes and of the upper respiratory tract, and the need to prevent the proliferation of biological contaminants. All the sensors respected the RH acceptability intervals for 72 % of the days (considering a 40–60 % range) and for 96 % of the days (considering a 30–70 % range).

The average daily temperature was then compared to the average temperature calculated during the heating hours in order to verify whether they complied with the temperature set points. Temperature remained < 20 °C for 50 % of the days in the common areas that are directly connected with the outdoor environment. These large areas are only provided with few radiators placed along their perimeter, which is certainly not enough considering the huge volume that needs to be heated, the poor insulation and the lack of a temperature control system. Moreover, differently from the bedrooms, common areas do not benefit from free solar gains, due to the building orientation, nor from thermal gains due to the presence of people, as they are currently underused.

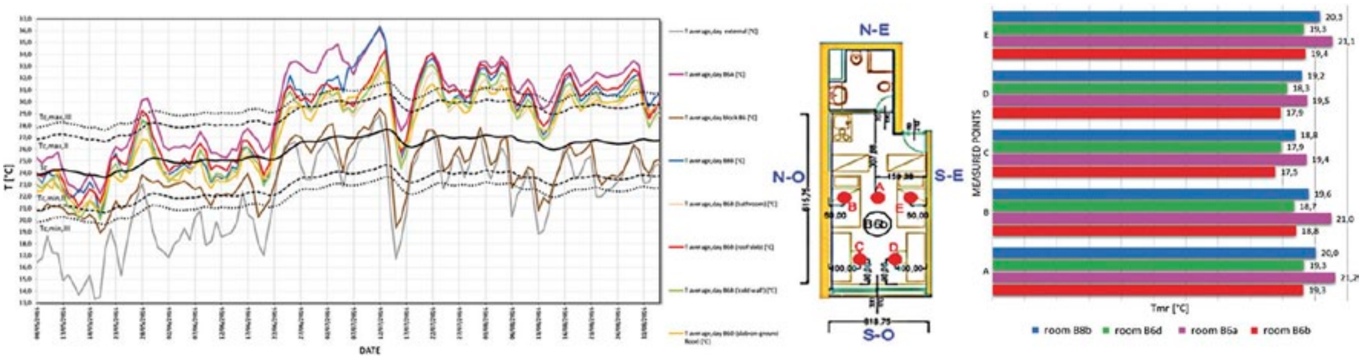
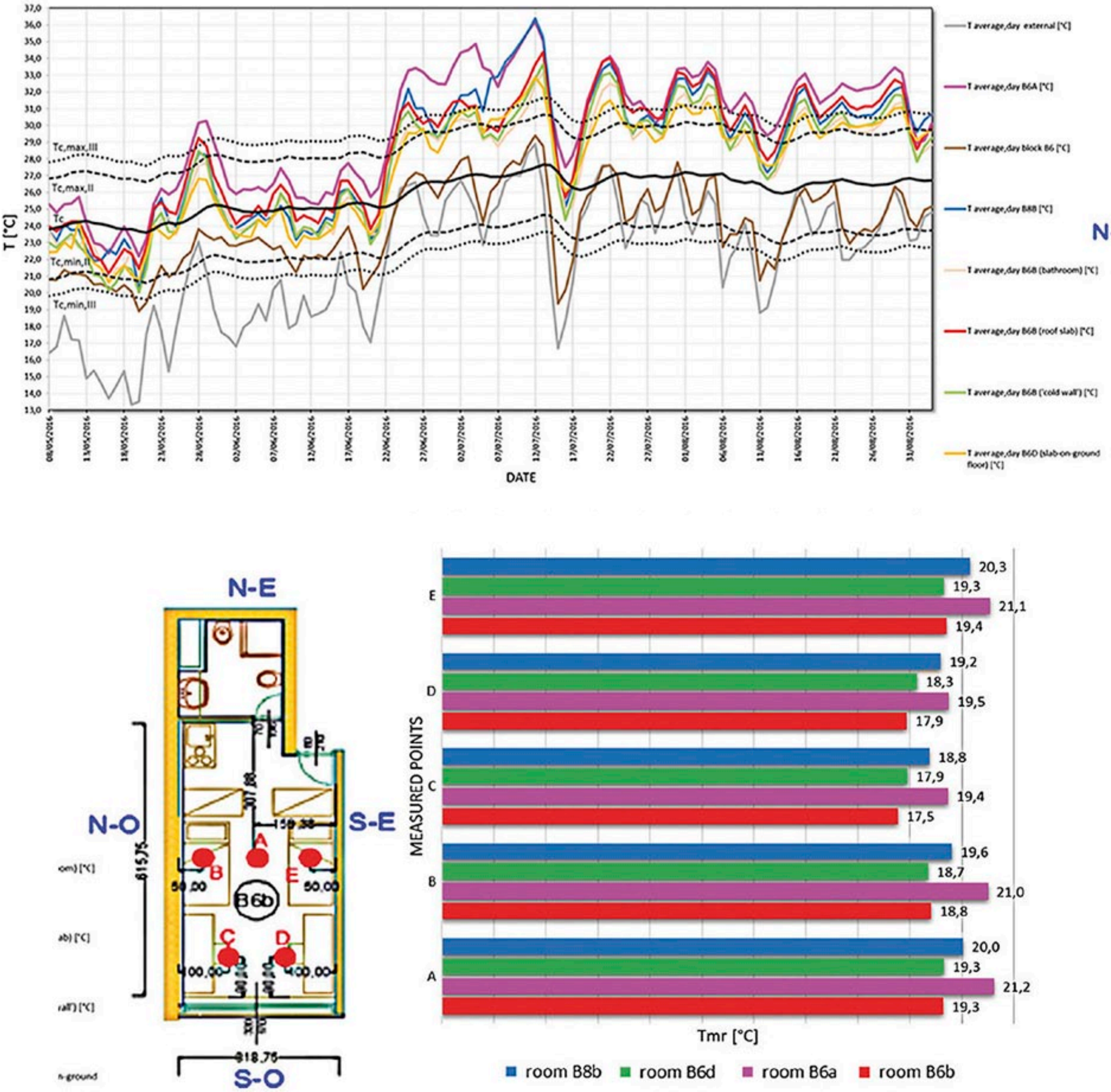


Figure 4. (See a close-up of this figure on the next page). Left: daily average air temperatures. Acceptance bands according to the adaptive method (8.5–31.8.2016). Right: mean radiant temperatures in the monitored rooms when the heating system is on.



(Figure 4. A close-up from the previous page)

Left (= above in this close-up): daily average air temperatures. Acceptance bands according to the adaptive method (8.5–31.8.2016). Right (= below in this close-up): mean radiant temperatures in the monitored rooms when the heating system is on.

An average of 20 °C was measured in all the bedrooms, although near the dispersant wall in room B6B, air temperature was < 20 °C for the 54 % of the days. This situation highlights a possible local discomfort. The hygrothermal comfort was then analyzed through the air operating temperature, which includes the linear average radiation temperature. In fact, a complete analysis must consider both the air temperature, and the local thermal discomfort.

The mean radiant temperature is obtained from five different points located in four rooms, through the calculation of the view factors (Figure 4b, left-side graph). We analyzed the most critical situation in winter conditions. We considered the air temperatures measured by all the sensors during the coldest weeks (01/12/2015–24/01/2016), making a distinction between the averages registered when the heating system was in operation (from 8 am to 10 pm) and the averages registered when the heating system was turned off (from 11 pm to 7 am). The air temperature in room B6B is 20.6 °C while the linear radiating temperature next to the dispersant wall (point C) is 17.5 °C, thus resulting in a 3.0 °C difference. During the nights, when the heating system is not operating, the temperature falls to 16.3 °C. Considering the average of the two, an operating temperature of 19.1 °C is obtained, thus resulting in discomfort by 1.5 °C. The discomfort was higher in proximity to the walls and to the windows characterized by poor thermal transmittance (5522 W/(m K)).

The local thermal comfort indices PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) were calculated in a couple of critical points [3] by means of a software based on UNI EN ISO 7730:2006. The clothing thermal resistance was set to 1 clo (1 clo = 0.155 m^2•K/W), as estimated for men's standard winter home clothing. The metabolic rate corresponding to the metabolic activity of a person sitting in an office (point C) is 1.1 met (1 met = 58.2 W/m^2), while the established rate for a person sleeping (point B) is 0.8 met. Point C is the most uncomfortable when the heating system is on. Considering the case of a student sitting at a desk by the window during the day, the PMV is -0.99, thus exceeding the limits of acceptability by ± 0.5 according to UNI EN ISO 7730 and it thus corresponds to class C. The PPD expressing the feeling "very cold" results in 25.6 %. If we consider a student lying down on the bed at night (point B), the PMV is –2.85, which corresponds to a condition of absolute thermal discomfort. The PPD expressing the feeling "very cold" results in 98.2 %.

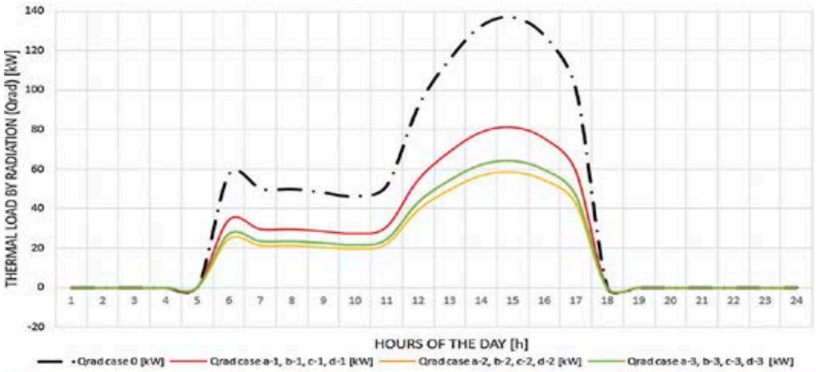
Thermography confirmed the thermal discomfort nearby the outer dispersant walls. The connection between the wall and the roof slab (17.5 °C < 20.8 °C) originates a thermal bridge, where temperature is 16.2 °C. Similar discomforts were detected in the "Colle" building, where a wall temperature of 12 °C was measured (room 83, March 25th at 10 a.m.). The air temperature near an outer wall (B6b, 23.5 °C) is lower than an inner room (B6a, 25.5 °C). Nearby the cold wall, a low air temperature results in a rise of specific humidity, due to the evaporation of leaked water. The same rooms were analyzed during summer, when the temperature of the inner side of the roof is 35 °C. Results also confirm the poor performance of the windows, which is a major issue to obtain stable conditions.

As regards to the summer season, (08/05/2016 – 15/10/2016) it must be considered that the building has no cooling system. A thermal adaptive comfort model (UNI EN 15251:2008) was therefore used to analyze the summer period. The adaptive model correlates the thermal sensation with the main climatic variables, thus taking into account the psychological wellbeing and the users' perception of the environment. The acceptability interval Class II represents a normal level of expectation and should be used for new buildings and renovations. The acceptability interval Class III represents an acceptable, moderate level of expectation and may be used for existing buildings. Both Class II and Class III have been verified. Figure 4, left-side graph shows the trends of daily average temperatures measured by all the sensors and the acceptance bands calculated according to the adaptive method. The thick black line represents the comfort temperature. The dashed black lines mark the Class II comfort range. The black dotted lines delimit the Class III comfort range. As a result, all bedrooms are overheated especially room B6a (magenta). The roof slab also gets overheated during summer because of solar radiation. The indoor air temperature is consequently very high, with a maximum (12/07/2016) of 41.3 °C in B8b room (blue), 39.6 °C in B6a (magenta) and 39.0 °C in B6b (red). High temperatures are also due to the poor insulation of the windows and to the lack of solar shading since the only shelter provided consists of indoor cotton curtains. These rooms are warm and dry, and such features affect the users' comfort (RH < 30 % for the 66 % of the days in room B6a).

3. ENERGY RETROFITTING

The building-HVAC system was studied by means of "MasterClima MC 11300 PRO" energy simulation software by AERMEC. Two blocks of rooms in the "Aquilone" building were analyzed, including bathrooms and common lounges (gross volumes of 14,143.70 m^3, usable area of 3944.00 m^2). The "Aquilone" building was used as a pilot site to test the building before and after the intervention. The model was validated by comparing the real consumption of methane with the temperature measured by the sensors. The simulation model applied to the original configuration allowed to calculate the thermal load in winter (585.85 kW) and summer conditions (377.66 kW). This early analysis highlighted the need of minimizing thermal bridges by means of insulating the walls and slabs, and of improving the performances of the windows, even considering a possible substitution. The roof slab resulted to be responsible for 12.3 % of the total dispersion and it thus needs to be improved, also considering the widespread problems related to water infiltrations.

Four scenarios for the insulation of walls and slabs were combined with three scenarios for the improvement of the windows, resulting in twelve scenarios to be compared (Figs. 5 and 6). The energy performance indexes, thermal and primary energy requirements and natural gas consumption were calculated for each scenario, together with the variations of thermal loads in winter and summer conditions. The best choice was made considering the combination of the winter and summer season, and taking into account the data obtained from the energy simulations and the indoor climate monitoring. Due to the architectural relevance of the buildings, all the options were discussed among the different members of the project team, and especially among those responsible for the retrofitting design, and those in charge of the building maintenance and management. The aim of the team was to balance conservation issues, energy efficiency and



TYPOLOGY OF GLASS TO SOLAR CONTROL: DOUBLE-GLAZED WINDOW WITH	g [-]	ε_{ext} [-]	ε_{ext} [-]	selectivity
CASE 1: STRATIFIED LOW-EMISSIVITY GLASS	0,43	0,04	0,29	1,56
CASE 2: STRATIFIED SELECTIVE GLASS	0,31	0,02	0,46	1,90
CASE 3: TEMPERED SELECTIVE GLASS	0,34	0,04	0,41	1,68

Figure 5. Thermal load by radiation in the windows before/after substituting the glass.

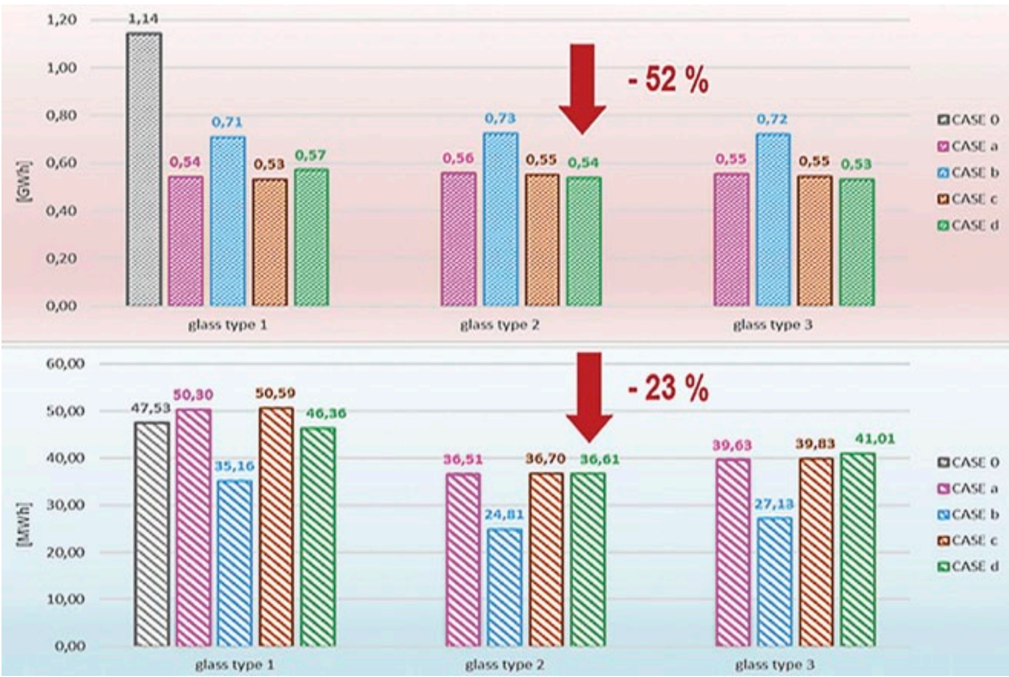


Figure 6. Energy demand for heating (top) and cooling (bottom). Present state vs 12 scenarios of retrofitting.

effectiveness in practical application. Any proposal had thus to cope with the architectural value of the Collegi. Insulating by external coating was therefore unacceptable, even if it would have contributed to solve several energy issues. Filling the wall with insulating materials was also not an option, since there is no cavity. As for the walls, internal insulation was thus considered the best choice.

A pilot site (12/2016–1/2017) implemented the best combination: scenario D (wall and roof slab) + scenario 2 (windows) in rooms B6a and B6b (Figure 7). However, during the pilot site some decisions were reconsidered. The concrete parapet on the top of the building could not be raised up and consequently, for safety reasons, the new slab insulation could not be thicker than 8 cm. An insulating panel was applied to the inner side of the perimeter wall but the panels had to be cut 20 cm before the window, in order to not have them visible from the outside. These limitations clearly resulted into weaknesses in terms of energy efficiency (Figure 8).

4 x 3 INSULATION SCENARIOS

WALL/SLAB/ROOF		
A	FLAT ROOF: extrados layer (extruded polystyrene foam) - 8 cm	
	PARAPET: indoor panel (mineral wool inside gypsum board) - 5 cm	
	EXTERNAL WALL: indoor panel (mineral wool inside gypsum board) - 5 cm	
B	FLAT ROOF: extrados layer (extruded polystyrene foam) - 8 cm	
	PARAPET: indoor panel (mineral wool inside gypsum board) - 5 cm	
	EXTERNAL WALL: not insulated	
C	FLAT ROOF: extrados layer (extruded polystyrene foam) - 12 cm	
	PARAPET: indoor panel (mineral wool inside gypsum board) - 5 cm	
	EXTERNAL WALL: indoor panel (mineral wool inside gypsum board) - 5 cm	
D	FLAT ROOF: inverted roof extrados layer (extruded polystyrene foam) - 12 cm	8 cm instead than 12 cm
	PARAPET: indoor panel (mineral wool inside gypsum board) - 5 cm	
	EXTERNAL WALL: indoor panel (mineral wool inside gypsum board) - 5 cm	Insulation ends 20 cm before the window

WINDOW	
1	SLIDING ALUMINIUM WINDOW FRAME DOUBLE GLAZING STRATIFIED + LOW-EMISSIVITY GLASS
	ALUMINUM BATHROOM SKYLIGHT DOUBLE GLAZING STRATIFIED - LAMINATED + LOW-EMISSIVITY GLASS
2	SLIDING ALUMINIUM WINDOW DOUBLE GLAZING STRATIFIED + SELECTIVE LAMINATED GLASS
	ALUMINUM BATHROOM SKYLIGHT DOUBLE GLAZING STRATIFIED + SELECTIVE LAMINATED GLASS
3	SLIDING ALUMINIUM WINDOW DOUBLE GLAZING + SELECTIVE TEMPERED GLASS
	ALUMINUM BATHROOM SKYLIGHT DOUBLE GLAZING + SELECTIVE TEMPERED GLASS

DISCARDED SOLUTION (white)
ADOPTED SOLUTION (green)
PILOT SITE CHANGES (yellow)

Figure 7. Different scenarios for the insulation of wall, slab, roof and windows.

Figure 8. After the pilot site, from left to right: new window, “cold wall” insulation, slab cover.

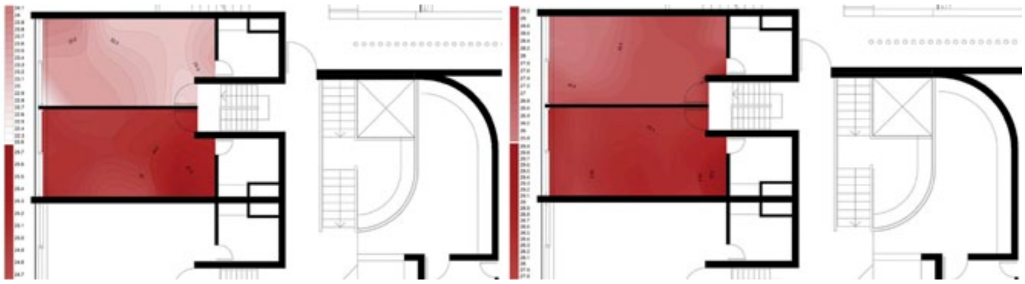


Figure 9. Temperature distribution before (left, 30.11.2015) and after (right, 22.2.2017) the pilot site.

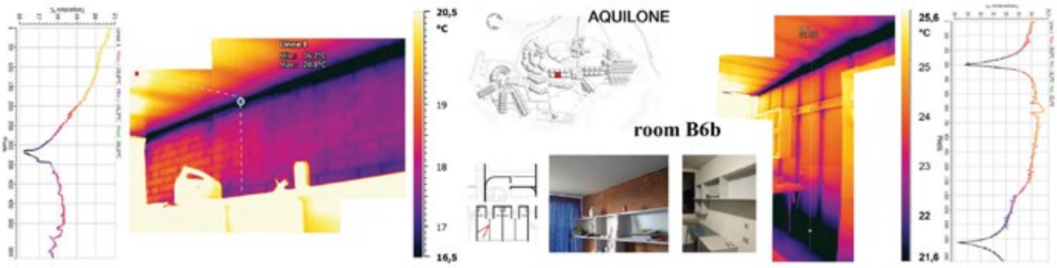


Figure 10. Room B6b before (30.11.2015) and after (9.2.2017) the pilot site. Heat losses are near the concrete structure.

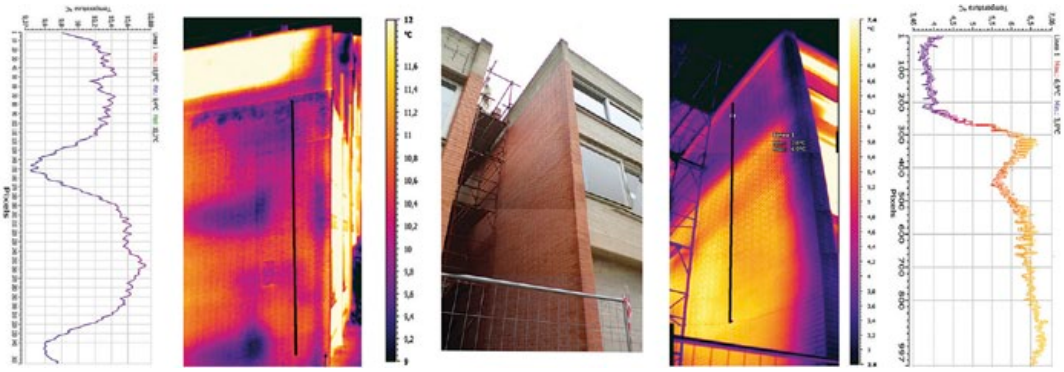


Figure 11. Pilot site: before 30.11.2015 and after 9.2.2017. Improved performance of the insulated wall.

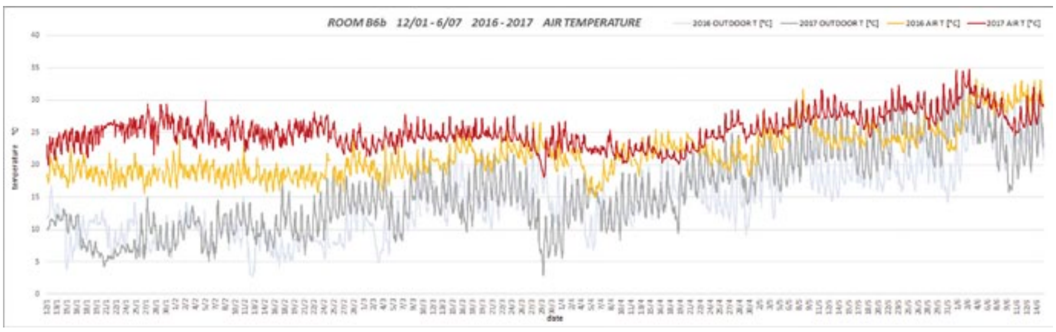


Figure 12. Room B6b temperature trend February – July. 2016 (yellow) vs. 2017 (red).

The on-field analyses have been repeated after the pilot site. Thanks to the application of the inner insulation on the external brick wall, the differences and the imbalances between the two rooms were considerably lowered. Thermal images confirm that surface temperature has increased after the application of the insulation layer, thus resulting in more comfortable conditions, especially for the students sleeping close to the wall. Unluckily, the exposed concrete structures resulted in thermal bridges, even after the energy retrofit (Figures 9, 10 and 11). The graph in Figure 12 draws a comparison between the data recorded before (yellow) and after (red) the pilot site. In room B6b, the external wall and roof slab have been insulated, and a new window has been installed. The winter temperatures measured after the pilot site are higher than the ones detected in winter 2016, and during the period February–April, average temperature resulted in an increase of +5.5 °C in comparison to the previous year (from 19.4 °C to 24.9 °C). Similar results have been achieved in room B6a, where insulation was applied only onto the roof slab and windows were substituted. Also in this case, insulation proved to be effective, as the average temperature in winter has risen by +4.4 °C, comparing to 2016. Nevertheless, such improved performances of the envelope might result into overheating both in winter and summertime. In fact, average temperature has increased from 22.4 °C to 26.8 °C and on sunny days 30 °C may be exceeded due to a greenhouse effect. The retrofitting of the building envelope should thus be integrated with a better and possibly local regulation of the heating system.

4. CONCLUSIONS

Improving the energy efficiency of a historic building is a critical issue as it is controversial to modify the original design and the material integrity of the building. The case of the Urbino University Colleges confirms the relevance of this topic even in 20th century architecture, where the need of adding insulation layers often leads to substantial alterations of the aesthetics of such buildings. To further improve the energy efficiency of such a large complex, alongside efforts towards the energy performance of the building envelope, the regulation of the heating system will also need to be improved. In general, the better a control system is linked to the measurement of local imbalances, the more manageable and effective it is. On the contrary, in such large centralized heating systems, it is not easy to define an effective correlation between the central set-points and the improvement of the local thermal conditions. This issue will have to be addressed in the near future.

Moreover, beside the actions towards the building insulation and the heating system regulation, it is worth involving the users in matching energy and conservation goals [4]. In fact, while optimal energy performances rely on detailed information and data about the indoor microclimate, they could also benefit from the users' attitude and their awareness towards these issues.

Interest towards smart home systems has recently increased, as they may be a way to improve indoor climate control by stimulating users to get involved in this task. T, RH and CO_2 thresholds may be used to control the heating system and to activate ventilation and de-/humidification when needed. Moreover, an early alert could guide users in taking simple measures such as opening the windows when CO_2 concentration is too high. Even little adjustments to users' daily routine may have positive impacts on energy saving, and this would especially reflect on the domestic energy demand. An adequate or comfortable indoor environment relies onto the calibration of the heating system, even locally. The Urbino University Colleges are fully in use and have a homogenous population (hours, age, habits). This would allow to design specific actions on capacity building and soft skills, involving the users within a sustainable conservation strategy. Students' awareness of the good climate of the Colleges and their energy demand may be improved, together with the economic impact. This would lead towards a process of individual involvement and responsibility, where the behaviour of each student may result in lower energy consumption and money saving, which is a concrete approach to energy sustainability in architectural conservation and use.

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