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Simulation of historical buildings and plant system. *La Montagnola* primary school in Florence

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ABSTRACT

Any operation addressing historical buildings refurbishment and plant system retrofitting is a complex task. Here we propose a methodological approach for achieving efficient, sustainable energy solutions guarantying objectives of conservation and preventive protection of the Cultural Heritage as well as Indoor Air Quality (IAQ) and thermal comfort for the users. As a consequence, all the related operations should be efficient and effective, in compliance with required indoor thermo-hygrometric conditions, ventilation, air quality and user wellbeing. *La Montagnola* primary school in Florence, designed by the architect Francesco Tiezzi and built between 1958 and 1963 is the case study. Dynamic simulations specifically addressed to control and adaptive proportional regulation of the building-plant system. Results showed that refurbishment and retrofitting operations on the plant system led to more significant energy saving in comparison with that obtained only with interventions on building envelope, mainly under constraints imposed by the National Heritage Protection Offices (*Soprintendenza*). Results assessment highlighted the fact that the use of dynamic simulation and CFD techniques, and consideration of thermal comfort at an early design stage, allowed the identification of design solutions combining energy saving with internal comfort, health and safety during throughout the school year.

1. INTRODUCTION

In Italy, public buildings are responsible for around 10% of national thermal energy demand, of which 75% is due to school building stock [1]. Almost 90% of the buildings dated from before 1990, when there were no standards about building energy performance [2], and about 40% belong to a period between 1940 and 1970, when the need of new schools combined with limited resources led to low quality requirements. Envelopes generally have no thermal insulation, causing insufficient thermo-physical and energy performance. The use of poor building materials and exposed concrete causes problems such as interstitial condensation or mildew formation, besides the need for frequent maintenance [3-4]. In most cases, thermal plants only provide sensible heating, and the absence of a controlled air change often leads to unsatisfactory IAQ. Energy waste, connected with the age and the quality of structures, is high, and average energy consumption is quantifiable between 130 and 160 kWh/m^2 year [5]. In the last ten years, widespread interest in institutions for school building heritage led to considerable fund assignments, employed in over 27,000 operations for maintenance, structural and energy refurbishment in addition to new buildings. In particular, 3,600 projects regarding energy consumption reduction and renewable energy utilization have been carried out since 2007 [6], representing only a small part of the overall stock of school premises, consisting of almost 45,000 buildings the majority of which are characterized by low performance in energy saving and comfort. Refurbishment proposals concerning school buildings must take into consideration some important aspects:

(1) students spend from 4 to 8 daily hours in school buildings, for at least 10 years;

(2) children are more sensible to air pollution than adults, thus IAQ for educational buildings is a fundamental issue, especially for kindergartens and primary schools;

(3) quality of internal environment can help children in the development of skills and potentialities, avoiding thermal, visual and sound stress and favouring communication among classmates and between students and teachers;

(4) school is a workplace, that employs about 10,000,000 people, approximately 15% of Italian population, including both students and teachers [7].

It is clear that the achievement of health and comfort conditions should be the primary objective of any design process, prior to energy saving. Sometimes retrofitting, although efficient in global consumption reduction, can produce uncomfortable, unhealthy conditions if it is not properly correlated to pre-existing building. Several items in the literature on school buildings in Italy [8-9] show that dynamic energy simulation allows an accurate prediction of thermal building behaviour, and the identification of efficient design and control strategies. Significant results are accomplished when the need for preserving the original architectural features becomes a primary requirement [10]. Some authors have highlighted that for historical building refurbishment and retrofitting, insulation position depends on formal architectural and historical constraint aspects, but mainly on climate, destination and period of use. For intermittently heated spaces and for no heating conditions, the better position of insulation material for energy consumption reduction and indoor thermal comfort is on the interior wall surface [11]. It has been widely demonstrated that plant and regulation system retrofitting interventions are preferable because they are effective and with much lower overall costs than any intervention on the building envelope, especially if the building belongs to historical heritage [11-12]. Other studies show that the use of PMV as a parameter for the control strategy of a plant system leads to a considerable energy saving in comparison with the use of a fixed set-point range of indoor air temperature [13]. In particular, a recent study is finalized to the identification of the optimal HVAC plant solution for school buildings in Mediterranean climate that can guarantee better comfort and IAQ indoor conditions but also minimum costs [14].

Some research on CFD simulation demonstrated that this kind of analysis is able to produce reliable data, to detail temperature and velocity in the control volume, and it is also efficient for different ventilation layout comparisons [15-16]. A coupled numerical approach combining Building Energy Performance Simulation with Computational Fluid Dynamics is therefore suitable for obtaining high level building and plant system control [17]; the considerable growth of simulation techniques and instruments and the availability of a large amount of research and validation procedures allow the use of this type of methodological approach [18]. Our study proposes a simple method for an efficient and energy sustainable design of building-plant systems, especially historical ones, using dynamic thermal simulation and CFD analysis in an early design stage. This can prove to be a useful tool to define strategies aimed at optimal plant system regulation that is minimally invasive, reversible and oriented to energy efficiency. A schematic diagram of the proposed methodological approach is shown in Figure 1 as a flow chart representation.

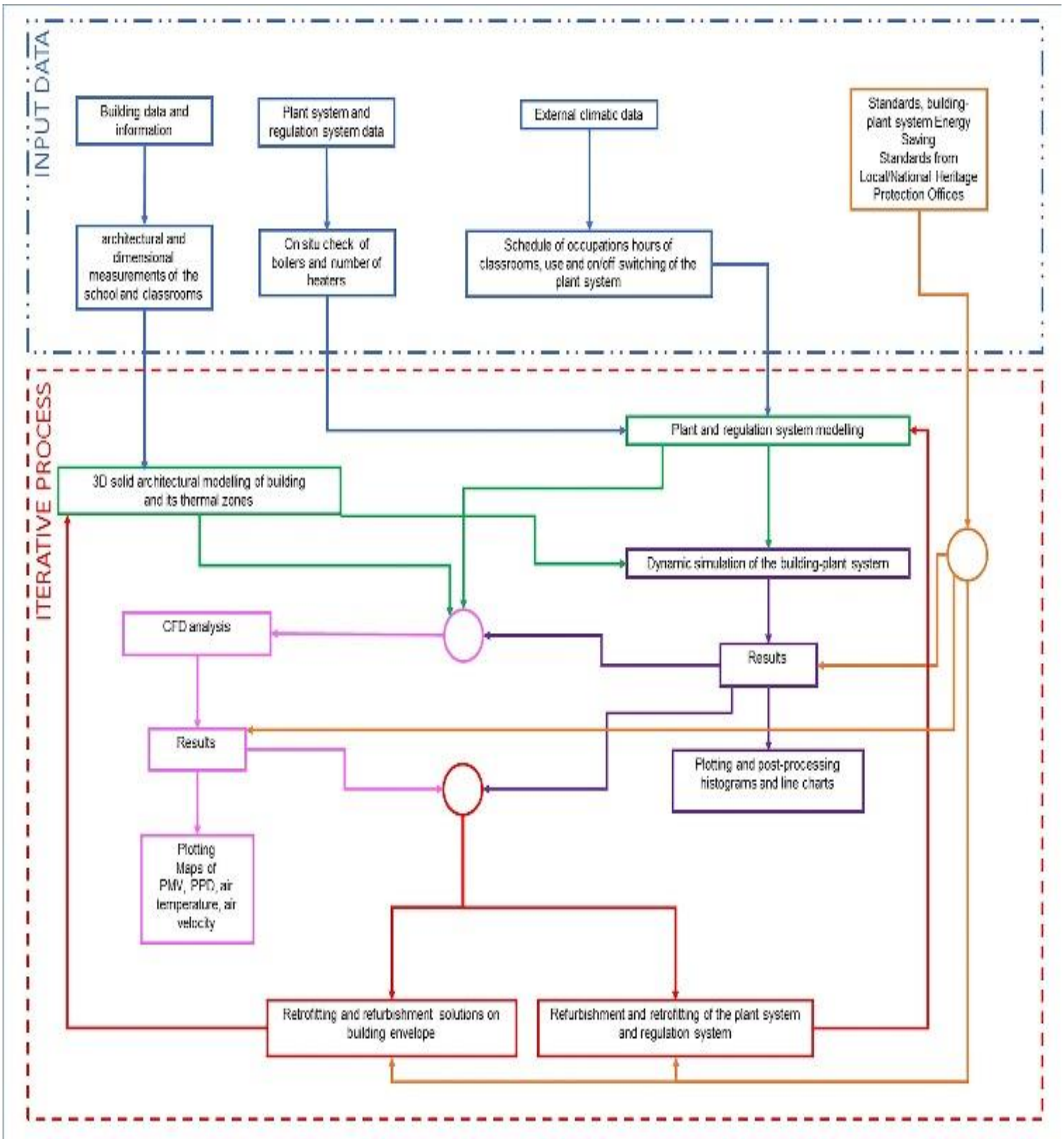

Figure 1. Flow chart representation of the methodology

2. MATERIALS AND METHODS

Building geometry, envelope stratigraphy and plant layouts, useful for model definition, were determined with reference to design documentation, validated by in situ checks, direct surveys, measurements and trials. Following the procedure illustrated in Figure 1, dynamic simulation was performed on the three dimensional model of the building in its present condition, referring to the heating and cooling season, when the present heating system is working and when it is not. The distribution of the hourly indoor air temperature values was obtained by transient simulations in order to identify discomfort hours for users during occupation time and then quantify potential cooling needs. Sub-hourly time trends for indoor air temperatures (i.e. air, mean radiant and operative temperature), heat gain and thermal losses, were evaluated referring to four representative weeks for winter, summer and mid-seasons. In particular, the comfort indexes Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) were evaluated referring to UNI EN ISO 7730-2008 [19]. Total heat and mass transfer through the building envelope, daily, monthly and annual heating and cooling demand for the present state were assessed by building-plant system dynamic simulation. Results analysis suggested specific refurbishment solutions, for guarantying thermal comfort, indoor air quality and healthy conditions combined with energy saving, low environmental impact and preventive conservation. An effective mechanical ventilation system was proposed for each classroom in compliance with current Standards, ensuring appropriate thermo-physical performances and minimum fresh air ratio [20]. Plant regulation was determined by simulating dynamic control over PMV, where a comfort range between -0.5 and +0.5 was imposed for all the occupation hours of the school year. A minimum operative temperature corresponding to PMV lower limit was identified and used as the effective design plant regulation set-point. Results concerning energy consumption and comfort condition improvement, due to building envelope refurbishment and plant system retrofitting, were obtained. A simplified Computational Fluid Dynamics (CFD) analysis of a classroom, used as a representative and test room, was performed for possible airflow scheme comparison. Different design configurations were compared based on operative temperature, velocity and PMV distribution inside the control volume. The optimum solution was identified by the comparison between PMV spatial maps, looking for a configuration able to guarantee thermal neutrality and uniformity in the occupied zone, in addition to minimum impact and interference with the existing structure.

3. THE CASE STUDY

La Montagnola primary school in Florence, designed by the architect Francesco Tiezzi and built between 1958 and 1963, is the case study. We limited the present study to "block C", built up on two floors. The basement, shown in Figure 2, includes a refectory, east oriented, where an exposed concrete pillar and beam structure filled with bricks and aluminium frame with single glass windows, are present.

On the ground floor, in Figure 3, the building block shows three rectangular aggregates with alternated brick and stone vertical structure and a single gable roof, containing classrooms and bathrooms. The rest of the space, covered with a flat roof, contains several corridors and one laboratory. Windows are made of aluminium/PVC frame with double glazing.

A heating plant with radiators supplies the whole building block, while the refectory is additionally equipped with a Constant Air Volume (CAV) air change system. The heat generator is a gas-fired boiler supplying all the thermal zones of the school. Neither cooling plant nor HVAC system are installed.

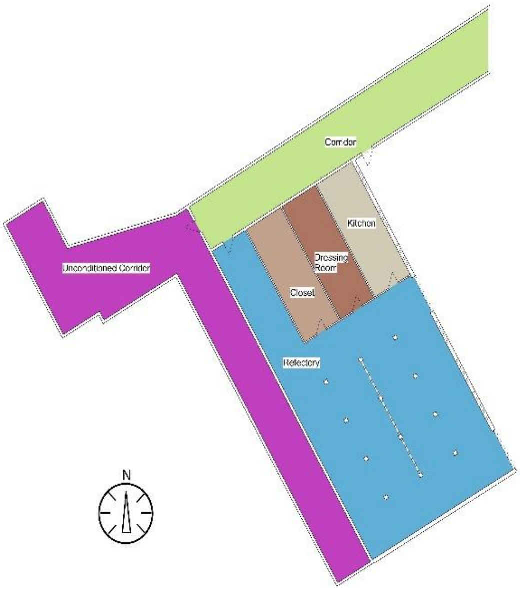

Figure 2. Block C, basement floor plan. Thermal zones are identified by different colours

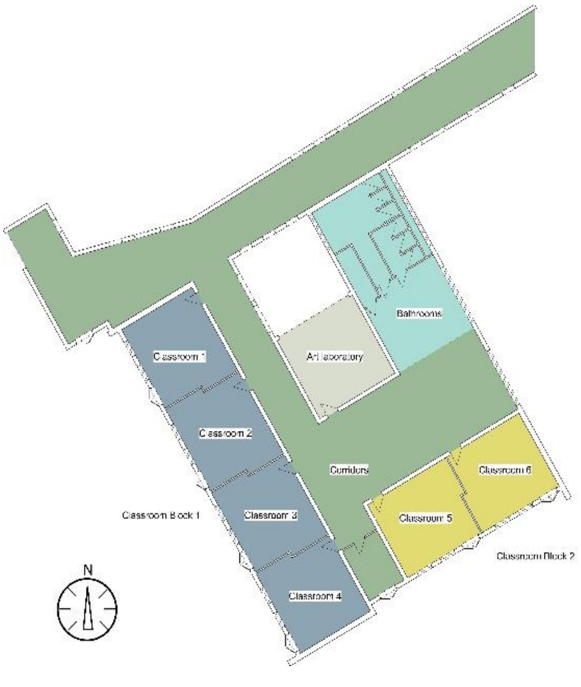

Figure 3. Block C, ground floor plan. Blocks are identified by different colours, while thermal zones are identified by labels

4. SOLID ARCHITECTURAL MODELLING

The solid modelling follows a B.I.M. architectural and structural model, made by a commercial software [21]. A "base model" on which multiple analyses were conducted means of specific tools, was built up, due to the necessity of the assessment of a complex refurbishment intervention concerning architectural, structural and energy aspects. Although B.I.M. data provides considerable "intelligence" in comparison with basic CAD data, it does not contain the volumetric/zonal parameters required by the software and tools generally and widely used for building performance analysis. Therefore, these parameters must be superimposed identifying the different thermal zones coinciding with the connected classrooms and different ambients. After this procedure, the model moved to the energy analysis software [22], automatically changing rooms into blocks and thermal zones. In this phase, some adjustments were made in order to reach a correct model transposition. Discrepancies in height and volume definition were adjusted to obtain a complete match, checking the results obtained by double software used for different rooms, thermal zones and volumes. Building orientation was determined by the application of free online software [23] and all the building blocks of the remaining parts of the school were added. These component blocks are solid objects not included in the simulation domain, but useful to evaluate solar shading on building external opaque and transparent components. An energy analysis model was used for different building blocks and thermal zones referring to plant equipment, building orientation and different use conditions. Basement floor, coincident with a single block, divided into six zones, and including an unconditioned space is shown in Figure 2. On the ground floor, four blocks were identified, as shown in Figure 3. The first, characterized by a flat roof, contains corridors and a laboratory; the other three blocks correspond to gabled roof areas for different orientations, with classrooms and toilets. A total amount of nine different thermal zones was identified.

5. BUILDING PLANT SYSTEM DYNAMICS SIMULATION

Energy and comfort analyses were carried out using EnergyPlus [24], a simulation-calculation commercial software for dynamic analysis of building-plant systems, that allows taking into account both resistive and massive characteristics of a building envelope. The software contains a CFD module, useful to produce detailed temperature, air velocity and comfort index distribution maps inside the control volume. Climatic parameters were provided by a weather file from EnergyPlus, referring to Firenze Peretola weather station, about 3 km from the school. Physical parameters were collected and assigned to different materials and components referring to the survey results, literature and experimental evidence. Information from Italian standards [25] and literature [26] was compared with some database values used, choosing the most reliable parameters. Occupation default schedules were edited to obtain a realistic simulation of internal gains, according to [27]. The opening and closing times of the school were given on the basis of the Italian school year [28], that begins in mid-September and ends in mid-June, thus excluding the hottest summer period; during holidays and weekends, all the plant systems were considered shut off and occupant thermal contributions absent. Then, a daily occupation schedule was set, distinguishing between classrooms and the refectory. In the first case, 25 people for each classroom were assumed during lesson time, from 8.30 to 13.00 and from 14.30 to 16.30. In the second, 100 occupants were considered during refection (13.00-14.00). Internal gains were quantified with 108 W per person, corresponding to light activity [29]. Clothing thermal resistance was assumed at 1.0 clo during the heating season and 0.5 clo for the rest of the year. The conditioning plant was modelled with reference to the results obtained by the in-site inspections and available documentation.

Heating powers of radiators were evaluated according to Italian regulations [30], while the generator was auto-sized, with a global efficiency of 75%, according to the survey results. Heating plant activation schedule was set from November 1st to April 15th [31], from 7.30 to 17.30 excluding weekends and holidays. In the refectory, the air change system was also modelled, and an air exchange volume of 4000 m3/h was directly obtained by fan documentation, following an activity schedule from 12.30 to 14.30. Since all the classrooms have no air change system, it was supposed that ventilation could be regulated by infiltration and user behaviour. When internal temperature exceeds a threshold value fixed at 24°C for the heating season and 26°C for summer, simulation concerns only natural ventilation technique (with opening windows for lateral and cross ventilation), based on wind pressure and direction provided by the weather file.

6. RESULTS AND DISCUSSION

Basic considerations of the present state building-plant system started with the result analysis of dynamic simulation of the envelope performance without the support of a conditioning plant. Internal air temperature distribution was obtained, and discomfort periods were quantified, assuming an air temperature range of $19°C \leq Tair \leq 27°C$ [32]. Since the block is closed during the hottest summer months, results shown in Table 1 highlighted the fact that cooling demand is absent, correspondent to a quite negligible percentage of "hot" occupied hours (Tair>27°C) for classrooms, falling to zero in the case of the refectory space. On the other hand, "cold" periods (Tair<19°C) represent a higher percentage of total amount, particularly for the refectory, accounting for 15% of total occupied period, and highlighting a heating need for specific periods during the cooling season.

Table 1. Discomfort period for classrooms and refectory during cooling season, with no conditioning plant. No summer activities scenario

	CL. BLOCK 1		CL. BLOCK 2		REFECTORY	
	h	%	h	%	h	%
T < 19 °C	128,9	4,2	54,0	3,5	40,2	14,4
T 19-27 °C	2888,8	93,8	1456,4	94,6	239,8	85,6
T > 27 °C	62,3	2,0	29,6	1,9	0,0	0,0

The above considerations drastically change when considering a different utilization scenario, where the school was considered "used" also during the hottest summer months with the same occupation profile: results provided in Table 2 confirmed that, in this case, a cooling plant is really needed, to the point where the "hot" periods accounted for 17-18% of the total.

Indoor air temperature, ventilation and PMV trend over time, for typical weeks during winter, summer and mid-season were evaluated. Results were provided with the corresponding graphs referring to classroom 1, representative of all the classrooms behaviour. Winter analysis (Figures 4 and 5) showed serious failings due to low ventilation rate and poor internal comfort (PMV lower than -0.5).

Table 2. Discomfort period for classrooms and refectory during cooling season, with no conditioning plant. Summer activities scenario

	CL. BLOCK 1		CL. BLOCK 2		REFECTORY	
	h	%	h	%	h	%
T < 19 °C	160,8	2,6	68,9	2,2	45,0	8,0
T 19-27 °C	4932,5	80,1	2449,3	79,5	409,6	73,1
T > 27 °C	1066,7	17,3	561,8	18,2	105,4	18,8

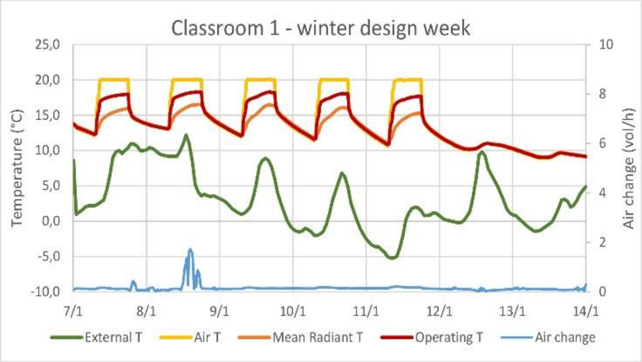

Figure 4. Evolution of internal temperatures and air change rate for classroom 1, winter design week, actual configuration. Calculated natural ventilation

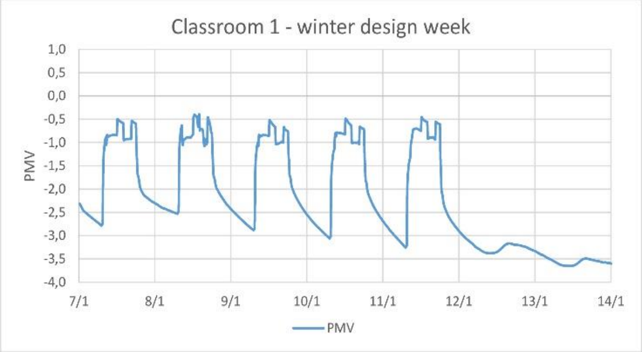

Figure 5. Evolution of PMV for classroom 1, winter design week, actual configuration. Calculated natural ventilation

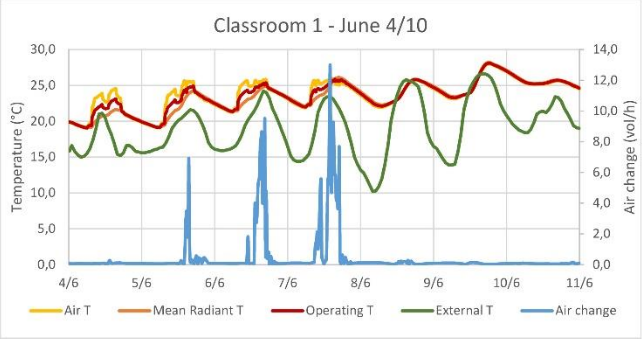

Figure 6. Evolution of internal temperatures and air change rate for classroom 1, June 4/10, actual configuration. Calculated natural ventilation

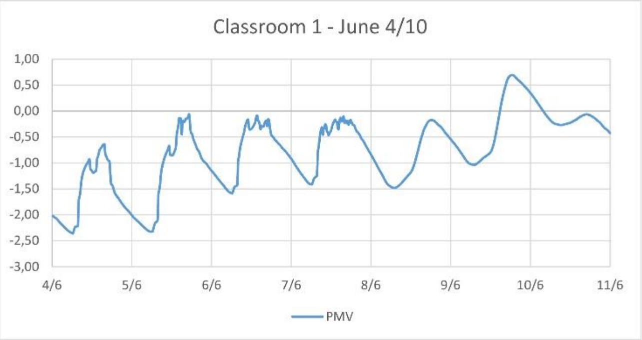

Figure 7. Evolution of PMV for classroom 1, June 4/10, actual configuration. Calculated natural ventilation

The hottest week analysis was conducted considering two different scenarios. In the first scenario, an air change rate depending on internal temperature was considered as described above, confirming an absence of cooling demand; this condition involves Tair ≤ 27°C and PMV ≤ 0.5 for the whole occupied period (Figures 6 and 7); opening windows ensures a large air change rate but opens up to possible outdoor noise.

In the second configuration, no ventilation is considered except for air infiltration: an important thermal discomfort due to high internal temperature and humidity is then caused, as confirmed by the diagram in Figure 8.

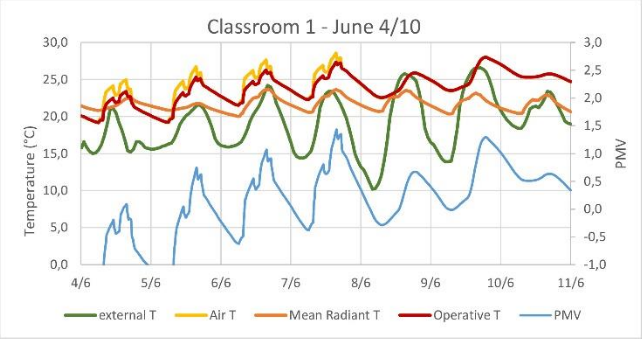

Figure 8. Evolution of internal temperatures and PMV for classroom 1, June 4/10, actual configuration. Natural ventilation is absent except for infiltration

Mid-season results highlighted the fact that a discontinuous ventilation ratio and a thermal sensation moving from neutral to slightly cold. The PMV distribution assessment of the refectory environment showed a general cold sensation during occupation time, both for the typical winter design week and the hottest week, while for the mid-season this trend provides neutral ambient conditions. Monthly and annual energy consumptions were evaluated; in particular, a total thermal energy need of 61.4 kWh/m^2 year from gas boiler in addition to a 0.8 kWh/m^2 year electric consumption was obtained. Refurbishment and retrofitting solutions were identified combining standard requirements, energy saving objectives, comfort instances and preventive conservation constraints. A thermal insulation of the external walls and roofs was imposed to obtain thermal transmittance and thermal lag in compliance with the current Italian regulation standard [22, 32] as described in Table 3.

As a fundamental result, heating power peak demand conspicuously decreased between 22% and 42% for all the classrooms, while the same effects for the refectory environment were limited to 5%; moreover, during summer and mid-season the effect is negligible as the growth of “hot” hours was lower than 1%. Since no appreciable cooling demand was detected either for classrooms or for the refectory zone, the plant refurbishment intervention was identified as follows:

(1) maintenance of the existing hot water plant for sensible heating;

(2) substitution of the present heat generator with a condensing boiler, using the lowering of the thermal power needed by the heated spaces due to the thermal insulation to decrease the temperature of the supply water at the present radiator increasing hot water plant efficiency;

(3) installation of a new Variable Air Volume (VAV) system with heat recovery for all the classrooms, in order to ensure a minimum air change ratio during all the occupation hours during the year, save heating energy and adopt free cooling strategies;

(4) integration of the refectory Constant Air Volume (CAV) air loop with air-to-air heat recovery systems for energy saving for the winter system configuration, and for guarantying a free heating for “cold” periods during cooling season.

Table 3. Thermo-hygrometric characteristics for actual and modified opaque envelope

Element	insulation (mm)	ACTUAL U (W/m²K)	ACTUAL ϕ (h)	DESIGN U (W/m²K)	DESIGN ϕ (h)
brick wall	70	1,72	9,6	0,28	12,1
stone wall	70	2,43	8,7	0,29	10,0
concrete wall	70	2,51	7,6	0,29	10,5
flat roof	70	1,25	10,1	0,26	12,1
gabled roof	70	1,41	5,9	0,25	7,2

Operational control criteria were set and assessed in order to ensure a proper internal comfort level. A comfort range between -0.5 and 0.5 in PMV was used as a target for the control system of heating and ventilation plants in the sub-hourly time energy simulations for winter design week. Trends revealed a correspondence between minimum PMV value for neutral band and an operative temperature (OT) of 21°C. Starting from these results, a heating control based on operative temperature was proposed for the plant system; internal OT was set to a minimum of 21°C, as long as external air temperature is lower, and contemporary ventilation was set to the minimum standard air change ratio. Simulation results obtained for design configuration during winter design week (Figures 9 and 10) showed a thermal comfort improvement, combined with a proper scheduled air change.

On the other hand, during the cooling season the conditioning plant works on an adaptive control.

When external temperature is lower than 21°C, the air system works as described earlier, if necessary employing heat recovery, while radiators are shut off; otherwise, ventilation can be increased up to 1.5 times the minimum value, and free cooling strategies are adopted, to align external and internal temperatures.

An upper limit to internal OT is set to 26°C, in order to guarantee a PMV value lower than +0.5 without need to open windows. The analysis of the results shown in Figures 11 and 12, obtained for the hottest week, showed an increase of PMV value, remaining anyway lower than +0.5, corresponding to a controlled air exchange.

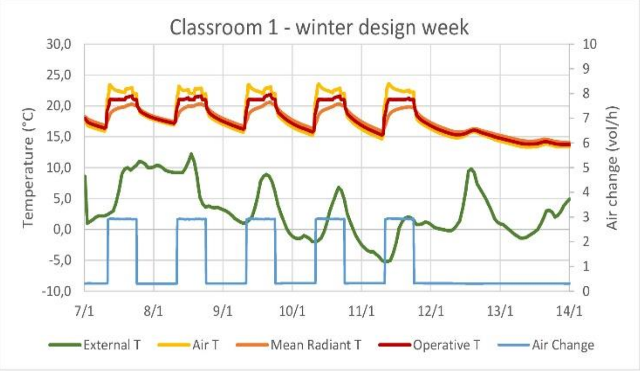

Figure 9. Evolution of internal temperatures and air change rate for classroom 1, winter design week, design configuration

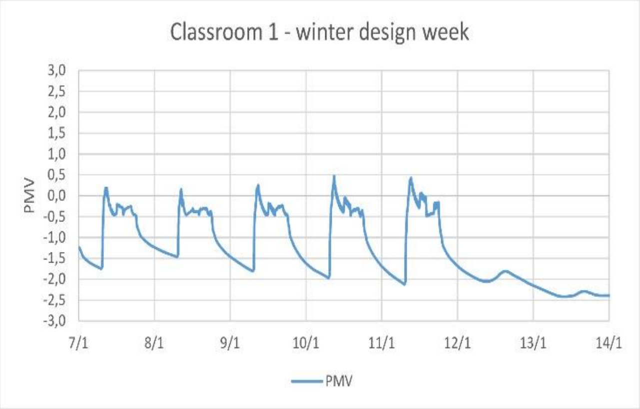

Figure 10. Evolution of PMV for classroom 1, winter design week, design configuration

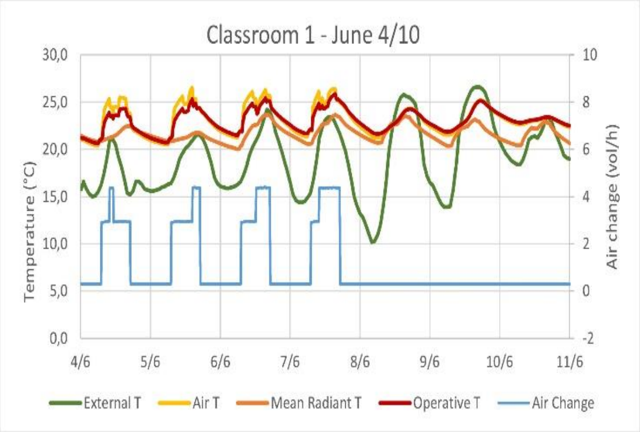

Figure 11. Evolution of internal temperatures and air change rate for classroom 1, June 4/10, design configuration

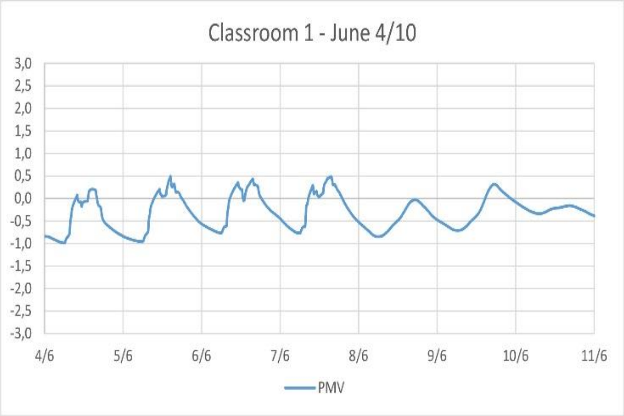

Figure 12. Evolution of PMV for classroom 1, June 4/10, design configuration

Refectory comfort conditions were also improved since PMV was generally set in the neutral band during the occupation hours. Total thermal energy consumption was significantly reduced to 21.2 kWh/m^{2}year (-65%), while electric need increased up to 6.6 kWh/m2year due to the introduction of a new air change system. Furthermore, an appropriate air delivery system was chosen based on the CFD results analysis performed for the typical (test) classroom, i.e. Classroom 1. The first solution consisted of an air inlet diffuser from behind the teaching post and a wall retake; the second solution suggested a commercial "conditioning beam" with integrated air inlet and air recovery (outlet) diffusers. Operative temperature, velocity and PMV distribution maps (which provide the stratigraphic and altimetric distribution of the connected values) were carried out, including vertical cross sections and horizontal sections. Contour conditions were determined by sub hourly dynamic analysis, referring to the winter and summer scenario chosen. For the first scenario, January 11th at 11.00 h was chosen, and constitutes the winter design day; for the second the day of June 7th at 15.00 h, corresponding to the highest outside temperature, was considered. For winter simulation a 450 m^3/h flow rate and an inlet air temperature of 21°C were taken into account, while the maximum flow rate of 675 m^3/h and the external temperature of 27°C were imposed for summer configuration. Figures from 13 to 16 provide the comparison between the two solutions for the operative temperature (OT) and mean air velocity, referring to winter configuration.

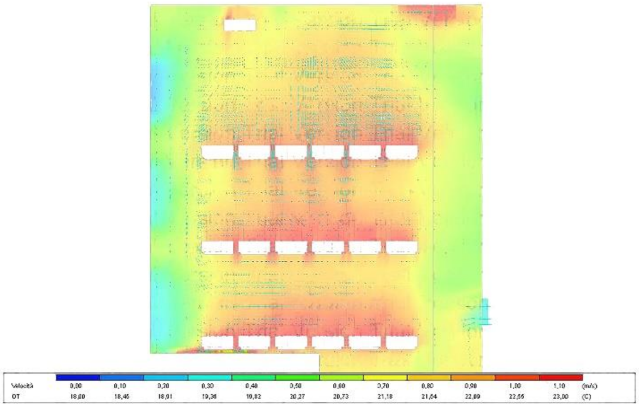

Figure 13. Diffusers intake and wall retake, winter scenario, OT and air velocity distribution, horizontal section at 90 cm height

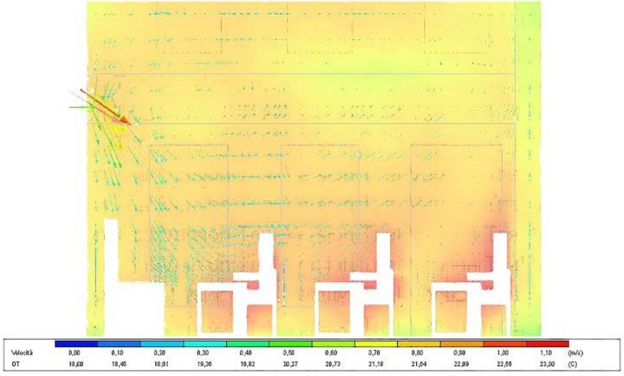

Figure 14. Diffusers intake and wall retake, winter scenario, OT and air velocity distribution, longitudinal section

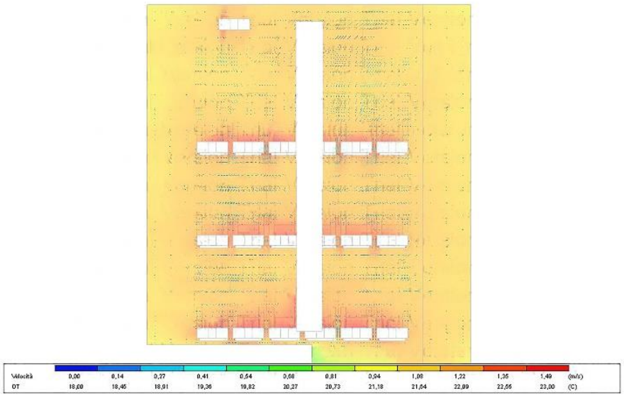

Figure 15. Integrated solution, winter scenario, OT and air velocity distribution, horizontal section at 90 cm height

The air flow scheme and location of air inlet and recovery diffusers show a lack of homogeneity both in cross sections and at person head level in terms of air velocity and OT; at the same time a reasonably uniform vertical and horizontal distribution corresponding to the conditioning beam system can be appreciated. The same trend can be found in PMV distribution on horizontal maps shown in Figures 17 and 18, together with the resulting slightly cold sensation at ground level due to the air flow scheme especially to the air inlet and extraction grids.

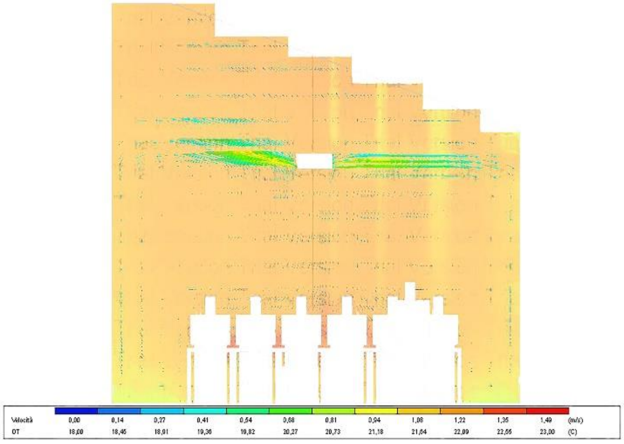

Figure 16. Integrated solution, winter scenario, OT and air velocity distribution, transversal section

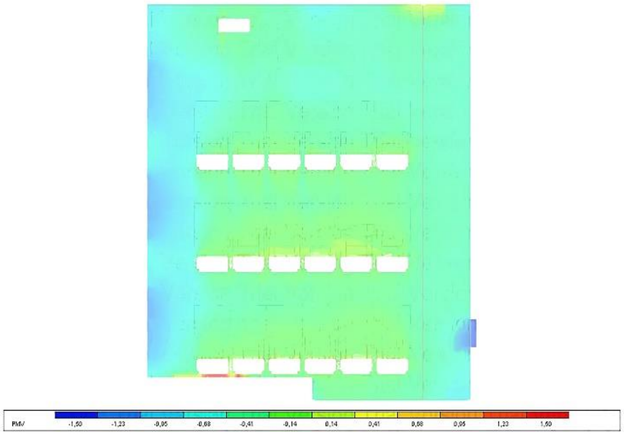

Figure 17. Diffusers intake and wall retake, winter scenario, PMV distribution, horizontal section at 90 cm height

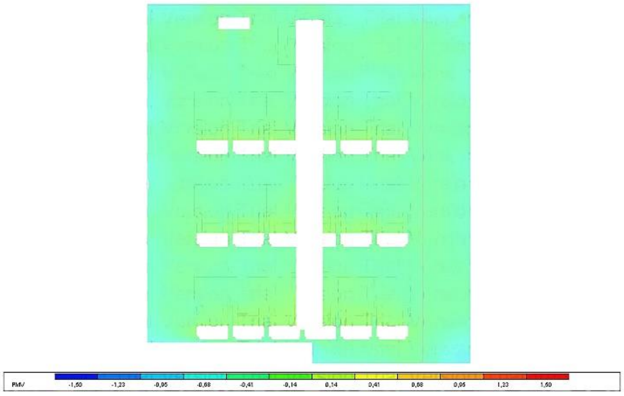

Figure 18. Integrated solution, winter scenario, PMV distribution, horizontal section at 90 cm height

Summer configuration maps in Figures 19-22 confirmed all the above considerations on the uniform and equally spatial variations of the mean air velocity and air temperature, although the suggested integrated solution provides a PMV>0.5 for specific zones at people head level (Figures 23 and 24), proving that global thermal comfort can be guaranteed, albeit any case improbable without local discomfort. On the other hand, result comparison shows that the airflow supported by air diffusers for the air inlet and recovery causes a cold sensation at feet level.

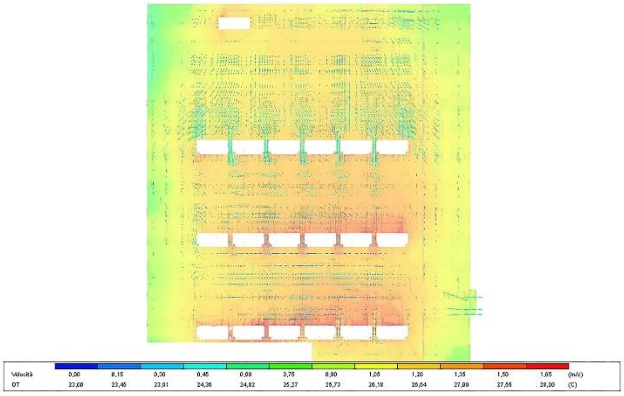

Figure 19. Diffusers intake and wall retake, summer scenario, OT and air velocity distribution, horizontal section at 90 cm height

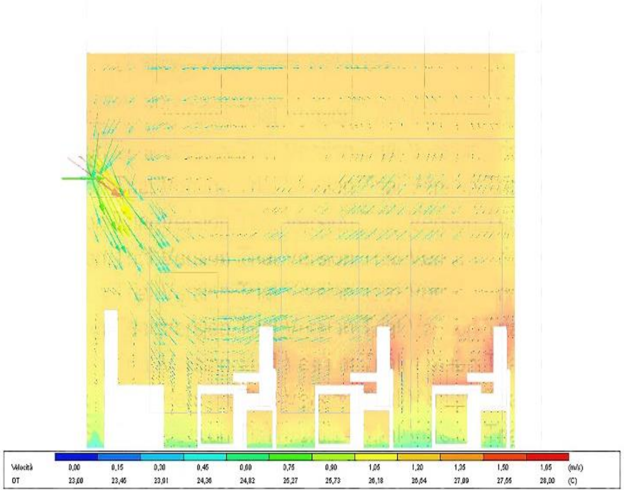

Figure 20. Diffusers intake and wall retake, summer scenario, OT and air velocity distribution, longitudinal section

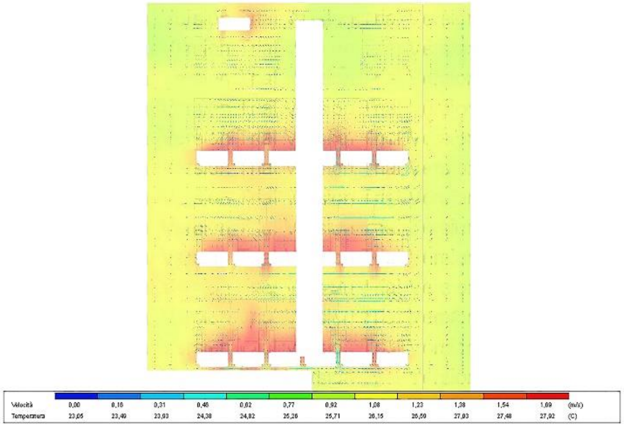

Figure 21. Integrated solution, summer scenario, OT and air velocity distribution, horizontal section at 90 cm height

The in depth result assessment shows that the integrated beam plant with inlet and air recovery system, represents a suitable configuration in order to maintain the optimal indoor comfort conditions over the whole year. This plant system solution also allows important benefits, such as a less complex and invasive construction site set-up, limited maintenance, and the possibility of inserting lighting systems and wirings.

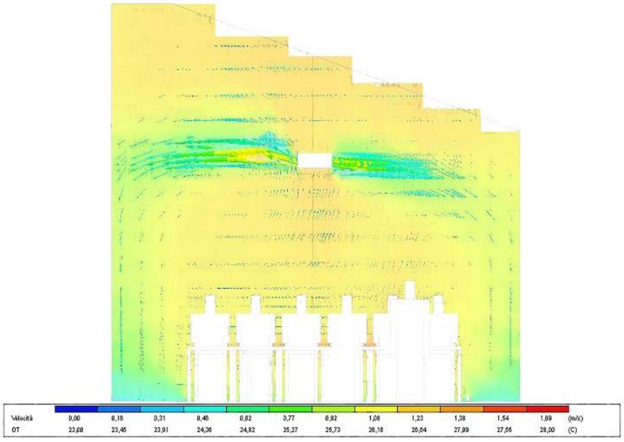

Figure 22. Integrated solution, summer scenario, OT and air velocity distribution, transversal section

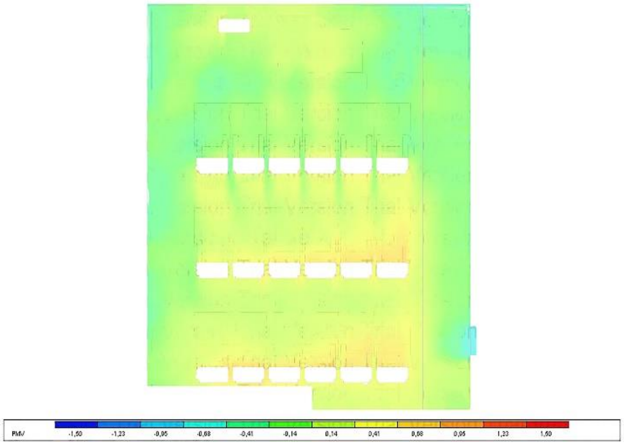

Figure 23. Diffusers intake and wall retake, summer scenario, PMV distribution, horizontal section at 90 cm height

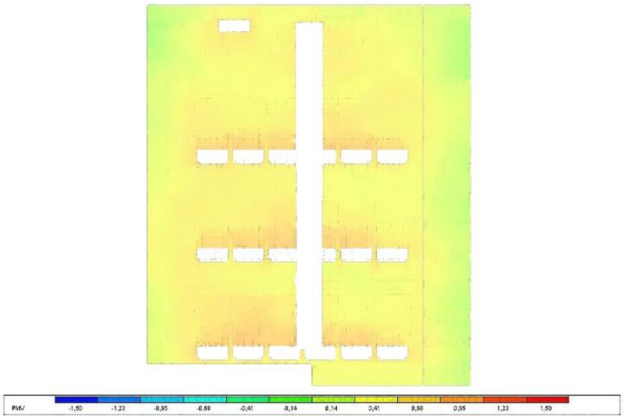

Figure 24. Integrated solution, summer scenario, PMV distribution, horizontal section at 90 cm height

7. CONCLUSIONS

Building plant system refurbishment and retrofitting of historical buildings is a complex task, where many different requirements such as energy saving, thermal comfort, correct ventilation and indoor air quality but also the guarantee of health conditions for the occupants must be considered and satisfied. Our research suggested an integrated methodological approach based on dynamic simulation of the building-plant system combined with Computational Fluid Dynamics analysis, thanks to the results assessment of which comfort indexes can be used for identifying the optimal control and regulation strategies that can be applied to the conditioning plant. The analysis of the system in present conditions suggested a design solution based on the present water heating plant retrofitting, integrated with an air change system allowing the utilization of heat recovery and free cooling strategies, without the need for a cooling system installation. Results showed that this design solution is efficient and effective in guarantying both energy saving, global thermal comfort and user health conditions for all the classrooms and the refectory during all the occupation hours throughout the school year. The comparison between different air delivery systems highlighted the fact that a conditioning beam solution with integrated air inlet and recovery diffusers system can be a very suitable solution for indoor ventilation and air quality, since it guarantees uniform distribution of the air temperature, velocity and PMV values in the occupied zone both for winter and summer conditions. In addition, the plant beam solution is less invasive, easily removable and reversible, allowing a strong integration of different systems and equipment such as lighting and electrical wirings. Therefore, it is the best solution that guarantees respect for the preventive protection of the historical, architectural and artistic value of the school building. This case study approach demonstrates that refurbishment and retrofitting solutions, with a lower cost and impact on the environment can be identified, and that in-depth assessment of the building physics and plant performance towards energy efficacy and sustainability can contribute to finding out the balance between energy saving, energy sustainability due to rational use of energy and quality of life especially for historical school buildings. Our methodological approach can be a useful tool for development and application of the analysis on the effectiveness of retrofit and refurbishment measures, to other similar case studies, especially historical school buildings.

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