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A simple method for the comparison of bioclimatic design strategies based on dynamic indoor thermal comfort assessment for school buildings

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Abstract

Bioclimatic design strategies have been proposed for decades, on a qualitative basis, because a quantitative approach, ineludibly based on dynamic measurements or simulations, was too expansive and complex. If simulation considerably evolved, in the last years, in terms of speed, cost and diffusion of available tools, their utilization is still complicated by the managing a huge amount of hourly data. The passive behavior of a building, moreover, is not effortlessly synthetized: conditioned buildings may be easily compared just summing the hourly consumption of primary energy, while buildings with no thermal plant need more sophisticated statistical analyses because in these kind of buildings, it is particularly difficult to assess the effect thermal inertia. The existing school buildings stock has a strong need of energy renovation in accordance with Government vision of a community 24 hours a day use and consequently increasing the requirement of comfort conditions and energy consumption. Hence, a current school building heated and not cooled is considered as application field of the novel methodology and a classroom is used to test different energy retrofit solutions compared against a base-line, in terms of capacity to decrease the indoor air temperature variation. The analyzed simulations have been thus compared with ideal comfort conditions by an original analysis approach based on a visual tool as a support for designers in choices comparison to simply assess and visualize the performance of building technologies.

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Keywords: Thermal comfort; thermal inertia; school building; bioclimatic architecture; energy performance and data analysis

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1. Introduction

The attention to existing school buildings in Italy is increasing due to National strategies targeting at improve the conditions of the more than 42,000 schools composing the educational building stock which in the 35% of the cases are in need of maintenance and heavy refurbishment to achieve levels of environmental well-being, health, attractiveness and cost-effectiveness. Energy efficiency is a main driver of the Government actions [1] which focus not only on the control of the running costs, but moreover in enhance pupils' awareness on environmental problems, general wellbeing and learning performance through the accurate design and renovation of schools' spaces [2]. Extensive studies [3][4] show that improving indoor conditions and spaces quality promote to increment of the learning performance of the pupils until a 16% [8] and controlled thermos-physical and indoor air quality parameters (e.g. ventilation [5], lighting [6], acoustic [7], CO_2 and VOC) affect significantly the upgrading at classroom level by 50% [9]. The strong correlation between user and built environment defines comfort levels and proficiency of workers [10] and students [11][12] and health and safety of the indoor spaces is nowadays a core topic. An additional and correlated issue is related to the characterization of occupancy profiles [13] in the school buildings aiming at optimize the space organization strategies and identify in a proper way the effects in term of energy consumption [14] in order to predict the variability of the energy performance owing to users' behaviors and fluxes [15]. Even so, energy saving measures results in significant costs and extended payback time and often the cost related to envelope refurbishments are harshly higher than replacement of thermal plants or addition of smart control devices. However, the bioclimatic approach entail undeniable benefits (i.e. affordability and easiness of implantation) pursued by passive regulation of the heat gains and indoor comfort conditions through the thermal mass. Educational buildings are mainly equipped with heating systems for winter use nevertheless, the climate change and the extended use of the buildings reveal the need of mitigation measures for overheating in the middle and summer periods. The concept is to avoid the installation of a cooling system to accomplish with thermal comfort in the extended periods but to manage adaptive comfort conditions by thermal inertia.

1.1. Energy performance of the National school building stock

The 75% of Italian schools dates before energy laws and the distribution in the territory from north to south does not change. The 33% of the school buildings dates before L. 373/76 [16] and about the 50% has been realized after the law nonetheless, the energy quality did not improve dramatically. The 25% of the school building dates after '80s and thus towards the L.10/91 [17] (Fig. 1). Moreover, the progressive ageing of the schools means a crucial need of improvement and performance to accomplish current standards [18] and EU Directives [19]. The school building stock counts over 62,000 schools of which about 45,000 public, largely overtake the public housing sector with about 1 million TEP of energy consumption per year of which 70% of heating and 30% of electricity. The potential of reduction, with effects on energy, environment and social aspects is impressive. A first step towards energy efficiency can be implemented by promoting energy behavioral awareness with low cost actions and a 20% of estimated effectiveness [20]. Energy saving measures focusing on envelope and thermal plants can decrease strongly the consumption with additional costs however about 40% of the school buildings are in need of maintenance and the retrofit measures could be included inside this cost item. The cost percentage of energy retrofit measures in school buildings show that the control and upgrading of lighting and thermal systems have low costs in comparison with envelope solutions such as insulation of the vertical and horizontal opaque portions or thermal enhancement of transparent surfaces [21]. The cost of measures focusing on the envelope can affect by 10% to 46% the refurbishment interventions (Fig.2). Furthermore, the age of the school building stock, defines the typologies of envelope and the associated thermal plant. In fact the 70% of the national school buildings is realized with reinforced concrete frame structure with brick infill walls and it is equipped with a gas boiler heating system (efficiency η=0.9). In any case, for buildings realized after the 1976 a thin insulation layer in the opaque envelope can be expected [24] (Table 1). The average heating energy consumption for public schools is about 180 kWh/m^2year whereas the requirement for new construction is about 30-40 kWh/m^2year. Thus, it is not appropriate supplement with an additional cooling need this amount of energy inasmuch cooling systems diffusion had a dramatic growth in the last 15 year in the housing sector. The requirement of comfort is however pushing and the capacity of the envelope to reduce and manage the heat gains [22] with dynamic thermal properties has been introduced in the national regulations since 2009 [23].

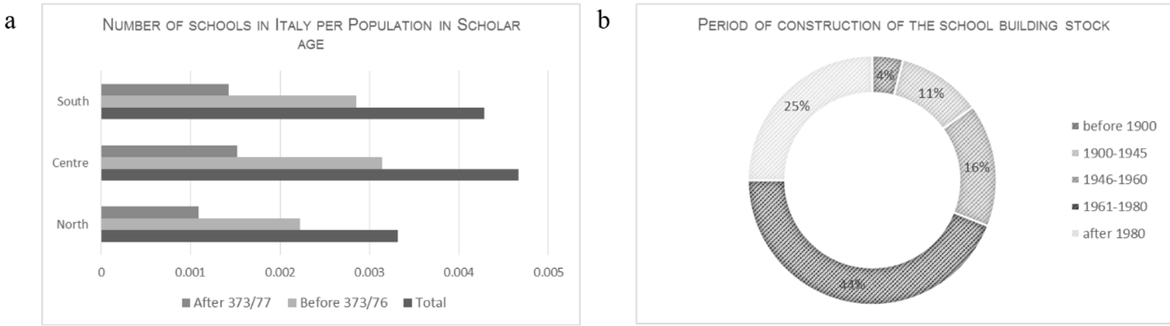


Fig. 1 (a) Distribution of schools in the Italian territory and age (Energy law 373/76); (b) Year of construction of the Italian school buildings.

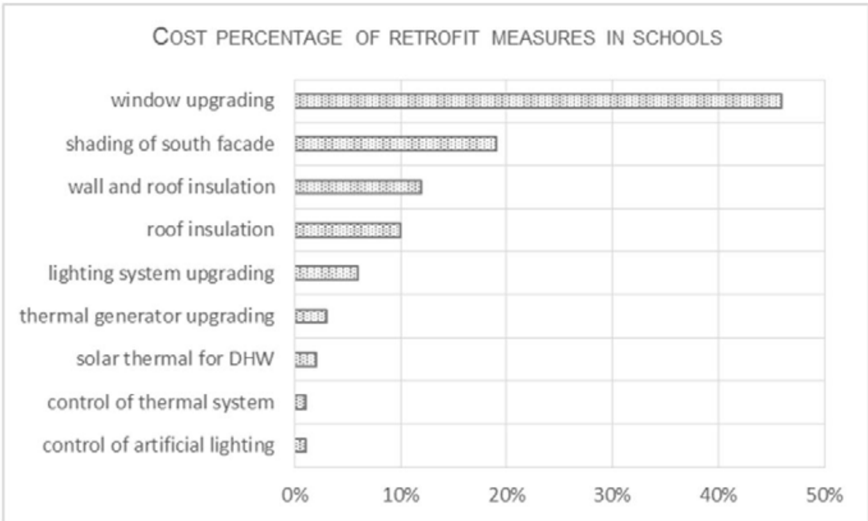
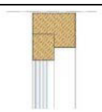
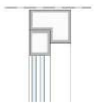


Fig. 2 Percentage of cost of energy retrofit measures for schools [21].

1.2. Envelope definition and thermal inertia

Thermal inertia is a fundamental parameter to improve comfort conditions and promote energy saving in buildings in mild and hot climates. Extensive studies specify the energy saving potential associated with the use of a suitable level of inertia. The weight of inertia in the thermal behavior of the buildings reported by the different estimations vary from a few percentages to more than 80%. Different calculation systems are reported from standard algorithm implemented in dynamic simulation software [24] to dynamic multi-nodal capacitive lumped non-linear model to describe the building [26]. Moreover, simplified tools to investigate the influence of thermal mass on building performance by conceptual one-dimensional models have been created to show in three-dimensional graphs the different output variables as functions of volumetric heat capacity and thermal conductivity of the material in the heavy construction part [27]. Thermal inertia reveals advantages in semi-humid climates [28] however, in buildings with high internal load the influence can be extensively relevant. Researches on the school buildings, with high internal loads, show that active thermal inertia is affected by solar heat gains. In old school buildings where the transparent/opaque envelope surface ratio is low, the effect of the parameter decreases while air change rate and permeable coverings interact more efficiently with time constants and energy saving [29]. Thresholds of suitable internal areal heat capacity related to periodic thermal transmittance (Y_{ie}) have also been defined for school buildings envelopes ranging between 50 kJ/m^{2}K for $Y_{ie} \leq 0.04$ to 70 kJ/m^{2}K for $0.04 \leq Y_{ie} \leq 0.08$ and 90 kJ/m^{2}K for $0.08 \leq Y_{ie} \leq 0.12$ [30]. In the following table 1, the thermal properties of the most diffused technological solutions used in school buildings in Italy are reported.

Table 1. Typology of envelope for the Italian school building stock frequently adopted and used in the case study.

Component	Layers	Description	Period from to		Thermal transmittance U [W/m^{2}K]	Periodic thermal transmittance Y_{ie} [W/m^{2}K]
Roof		Flat roof with reinforced brick-concrete slab, low insulation	1976	1990	1.01	0.19
Wall		Hollow brick masonry, low insulation (25 cm)	1976	1990	0.80	0.19
		Hollow brick masonry, low insulation (40 cm)	1976	1990	0.76	0.06
Floor		Floor with reinforced brick-concrete slab, low insulation	1976	1990	0.98	0.19
		Concrete floor on soil, low insulation	1976	1990	1.24	0.11
Component	Layers	Description	Period from to		Thermal transmittance U [W/m^{2}K]	Solar Heat gain Coefficient SHGC [-]
Window		Double glass, air filled, wood frame	1976	2005	2.8	0.75
		Double glass, air filled, metal frame without thermal break	1976	2005	3.7	0.75

2. Case study definition

The proposed methodology, described in detail in section 3, has been applied to a simple case study which is standard classroom space (dimensions 8700x7600, height 3000mm) equipped with three south oriented windows (1250x2500mm) on a single outdoor exposed side. The space is conceived as included in a main school building with two/three floors and accordingly the roof, floor and the other walls collaborate in the thermal inertia of the space (Fig.3).

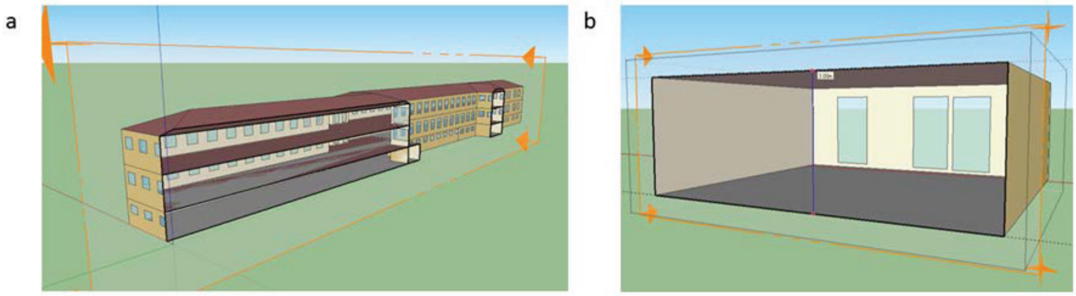


Fig.3. (a) Model of an existing primary school in northern Italy organized with a main corridor and two sides of classrooms; (b) single classroom space adopted for the simulations.

2.1. Base case envelope and measures

The classroom space is assumed in an existing base case version and five improved cases assuming energy retrofit strategies focused on the envelope characteristics to reduce the energy consumption and increase the comfort band in the indoor space. The measures of insulation of the opaque envelope and the replacement of transparent surfaces in the existing school buildings are the most expensive however the potential of energy saving is high. The combination of the energy saving measures to improve the energy performance of the case study aims at simulating possible strategies of investment in the envelope enhancing. The base case adopts thermal characteristics aligned with the ones described in Table 1. The main thermal characteristics of the opaque envelope surfaces for the base case and the improved cases are listed in Table 2.

Table 2. Description of the envelope components used as existing situation and new features.

	Thickness [m]	Thermal transmittance U [W/m^{2}K]	Surface mass M_s [kg/m^2]	Time lag [h]	Decrement factor [-]	Periodic thermal transmittance Y_{ie} [W/m^{2}K]
Opaque existing component						
Roof	0.34	1.09	303.2	9.25	0.233	0.254
Wall	0.40	0.64	366.2	14.70	0.102	0.065
Floor	0.34	0.91	288.2	9.37	0.215	0.196
Opaque improved component						
Roof	0.43	0.31	305.0	10.44	0.144	0.045
Wall	0.49	0.26	368.0	15.30	0.047	0.012
Floor	0.43	0.29	290.0	1055	0.142	0.041

For the windows, the following parameters are considered:

- Existing window: U_w=2.8 W/m^{2}K, $g_{gl,n}$=0.75;
- U_w Improved case: U_w=1.0 W/m^{2}K, $g_{gl,n}$=0.50;
- SHGC Improved case: U_w=1.0 W/m^{2}K, $g_{gl,n}$=0.35.

The core of the analysis is thus the use of new windows in accordance with the current performance requirement [30] whereas the insulation is considered just on the exposed façade and with a thickness (i.e. 10 cm) capable to rise the energy performance in winter period however for the summer period the thermal performance gets worse.

The base case, using the opaque existing components and the existing window as defined previously, is compared with solution in which only the windows replacement or the insulation are improved to verify the changing of the energy performance. Anyway, the progressive combination of improved windows and opaque envelope is compared to the base case to define the percentage of energy saving.

2.2. Thermal zone setting

The thermal zone setting considers the parameters described in Table 3. The hypothesis promotes an intense rate of occupancy according with a more efficient exploitation of the spaces referred to MIUR guidelines [1].

2.3. Improved cases

The list of the tested cases with the identification numbers used in the results diagrams to enable the comparison of the different solutions is reported in Table 4. The average opaque envelope thermal transmittance used in each test is summarized.

Table 3. Description of the envelope components used as existing situation and new features.

Parameter	Symbol	Unit	Value
Occupancy density index	i_s	person/m^2	0.5
Internal gains	q_i	W/m^2	4
Ventilation rate	n	h^{-1}	2.8
Occupancy schedule weekdays	-	h	7:00-19:00

Table 4. Tested combinations of energy saving measures.

n.	Tested cases	Opaque envelope	Transparent envelope
(1)	Base case	U_{av}=0.96 W/m^{2}K	U_w=2.8 W/m^{2}K, $g_{gl,n}$=0.75
(2)	U_w improved case	U_{av}=0.96 W/m^{2}K	U_w=1.0 W/m^{2}K, $g_{gl,n}$=0.50
(3)	SGHC improved case	U_{av}=0.96 W/m^{2}K	U_w=1.0 W/m^{2}K, $g_{gl,n}$=0.35
(4)	Insulated base case	U_{av}=0.29 W/m^{2}K	U_w=2.8 W/m^{2}K, $g_{gl,n}$=0.75
(5)	Insulated and U_w improved case	U_{av}=0.29 W/m^{2}K	U_w=1.0 W/m^{2}K, $g_{gl,n}$=0.50
(6)	Best case	U_{av}=0.29 W/m^{2}K	U_w=1.0 W/m^{2}K, $g_{gl,n}$=0.35

3. Methodology

The proposed methodological approach aims at easing in identifying the capability of the envelope to foster indoor comfort condition in free floating. The indoor temperature inside the classroom thermal zone (T_{zone}) is calculated through dynamic simulation with the hourly climate data of Milan, Italy (IWEC). Thus, the evaluation is visualized in a cloud diagram in which the following quantities are related:

$$y = T_{zone} - T_{24} \quad (1)$$

where T_{24} is the moving average of the indoor air temperature inside the thermal zone, and:

$$x = T_{24} - T_{comfort} \quad (2)$$

where the comfort temperature $T_{comfort}$ is fixed in winter to the set-point room temperature and considering the heating period going from 04/15 to 10/15 to:

$$T_{comfort,winter} = 20°C \quad (3)$$

while in summer period it is evaluated in accordance with the adaptive comfort model and with T_{air} as the outdoor air temperature:

$$T_{comfort,summer} = 17.6 + 0.31 * T_{air} \quad (4)$$

The origin of the diagram (the point x=0 and y=0) has been considered , both for summer and winter, as an optimal comfort condition reference state in accordance with (1), (2) because of the coincidence with the air zone temperature to the comfort zone temperature and for the persistence of the temperature during the hours of the day.The graph values are then plotted in Mathematica [31] for every x,y couple using a color scale obtained from a hue color function referring to the following condition:

$$hue\left(\frac{d}{dmax}, 1, 1\right) \quad (6)$$

where *d* is a measure of the hourly comfort conditions defined as:

$$d = |x| + |y| \quad (5)$$

4. Results

As stated in the previous paragraphs we evaluated the performances of the six building envelope alternatives, both opaque and transparent, assessing the hourly indoor air temperature as a comfort parameter under free-floating conditions. The effectiveness of the proposed refurbishment alternatives can be appreciated in Fig. 4 in accordance with the proposed methodology.

4.1. Thermal comfort assessment

The diagrams show the results of four relevant tests: the base case (Case 1), the simple replacement of the window with improved SHGC (Case 3), the improved thermal transmittance of the opaque envelope (case 4) and the best case (Case 6) in which both wall insulation and window replacement take place.

The average dimension of the cloud of points in Fig. 4 and their location related to the diagram axes are key elements to evaluate the effects of the refurbishment strategies of the façade components on the building comfort performances.

In winter the more the point distribution is compact and centered around the graph origin (i.e. Case 6), the more the refurbishment strategy avoid over-heated and under-heated hours.

In Case 3 the use of a window component with a low SHGC value permits to completely reduce the over heated period, as stated by the movement of the points from the in the right side of the diagram to the center. Improving window SHGC, especially using films, could be a lean alternative to improve energy behavior of a building [32].On the other side, the increase in under heated hours probably refers to the solar gains reduction due to the decreased solar heat gain coefficient of the glazed components. Solar gains control through transparent surfaces is an effective refurbishment strategy rather than improving thermal wall insulation, especially considering the summer period (case 4). As the movement of the cloud along the x-axis assess the effectiveness in achieving thermal comfort indoor air temperature, the span between the cloud extremes along the y-axis, define the responsiveness of the envelope in mitigate temperature fluctuation and thus thermal inertia efficacy. In Fig. 4 for summer and Case 1, comfort conditions are far from adaptive comfort optimal temperatures, resulting as an over-heated condition during all the season. The improvement of the building envelope Case 6, going through the other alternatives allows to reduce the overheating period, despite of a greater responsiveness of the fluctuation of the room air temperature due to internal and solar gains.

4.2. Discomfort frequency

The diagrams in Fig. 5 synthetically present the effectiveness of every scenario plotting on the Y axis the number of hours when *d* is bigger than 2 divided by the total number of hours of each simulation, hear called discomfort frequency, and on the X axis the mean of the differences between T_{24} and $T_{comfort}$.for each point cloud, The values are represented by the cross mark in the center of every circumferences which radius value represents the average measure *d* of the point cloud. For both, summer and winter scenario, circumferences (i.e. retrofit strategies) can be compared by X value (i.e. mean difference between T_{24} and $T_{comfort}$), by Y axes value (i.e. in a limited number of time during the simulation the room is in discomfort zone) and by the radius (i.e. the average dispersion of the point cloud). The smaller are the circumferences and the closer they are to the origin of the axis the better is the retrofit strategy.

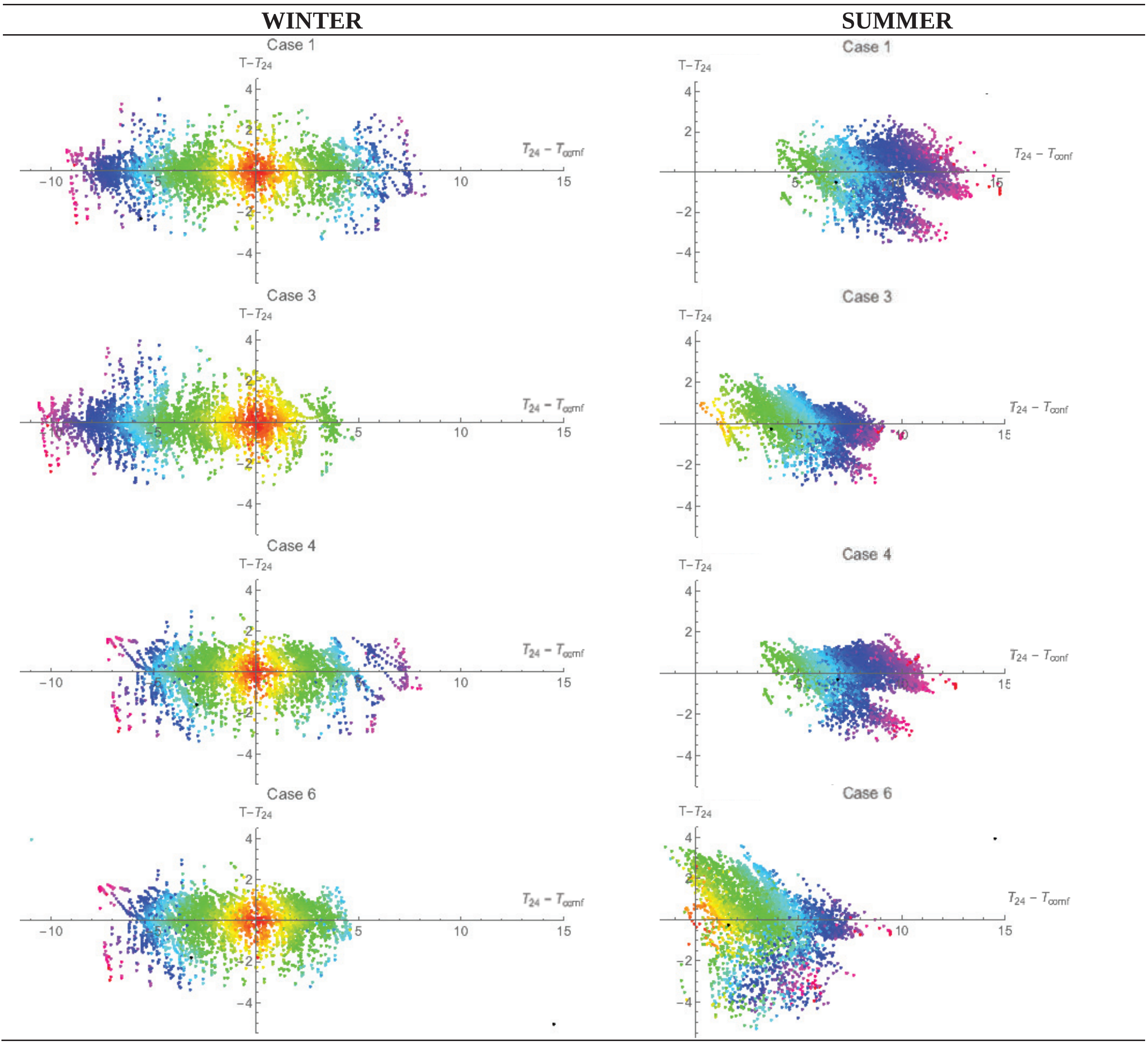


Fig. 4 Temperature difference plot [$(T_{zone}-T_{24})=f(T_{24}-T_{comfort})$] for winter (left) and summer conditions (right), considering refurbishment case 1,3,4 and 6. The Hue color plot in accordance with the measure of the hourly comfort conditions - equations (5) and (6).

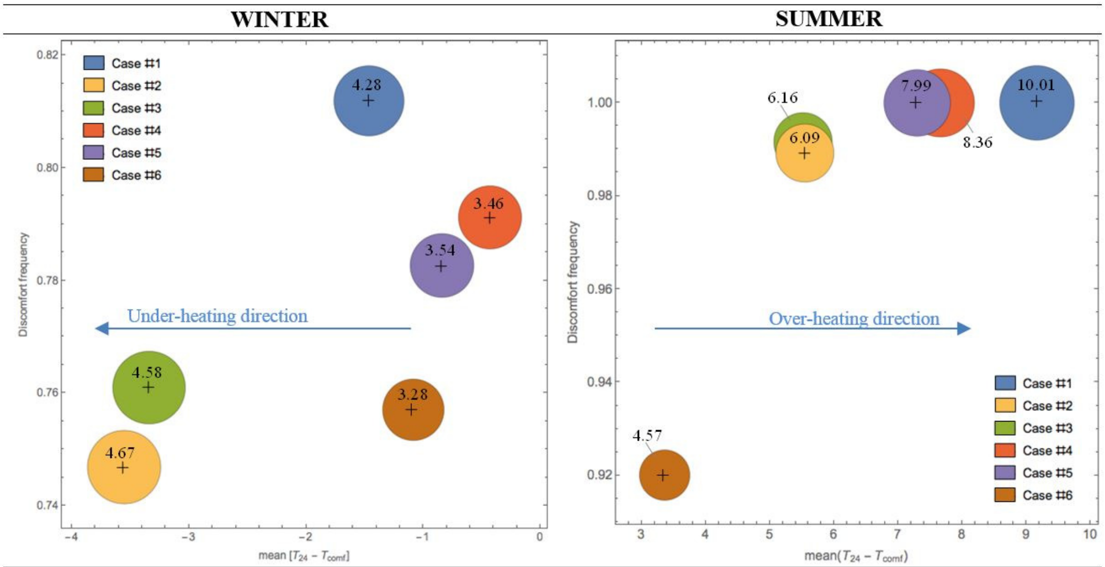


Fig. 5 Synthetic plot of comfort conditions. The diagram reports the discomfort frequency as a function of the mean (T_{24}-$T_{comfort}$) and the mean of measure *d* (radius).

5. Conclusion

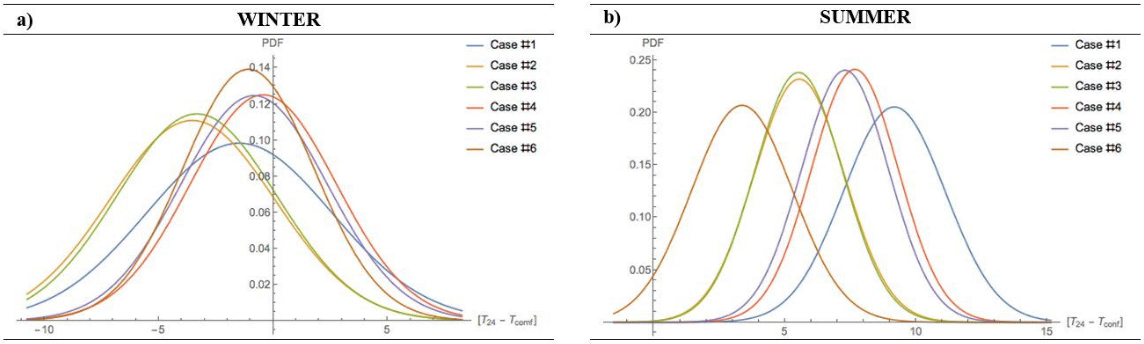
The assumption of a mechanical heating during the winter period and free-floating naturally cooled and ventilated condition during summer period is coherent with a traditional Italian school space. On the other hand, this assumption permits to split the reference year in two main seasons, considering two different indoor comfort temperatures: one, in winter, fixed and equal to the heating system set point temperature (20°C) and the other one, in summer, variable (centered in the range of 26-27°C), related to the adaptive comfort model. Data suggests that naturally conditioned buildings in summer were barely able to maintain thermal comfort for many hours of the day.

In Fig. 6 a statistical description of the obtained results is provided:

- for each case study a Gaussian distribution was fitted to the hourly values of T_{24}-$T_{comfort}$ calculated by dynamic simulations and plotted as Probability Density Function (PDF);
- the correlated table resumes moments of the same data.

The mean value gives the most probable difference between the moving average of the indoor air temperature and the comfort temperature (i.e. 0 means comfort conditions). The variance provides a measure of the variability around the mean. Skewness and Kurtosis measure data symmetry around the mean and similarity with a Gaussian distribution.

In summer period (Fig 6b) the best solution is case 6 as described by its very low mean value while the base case (case 1) has more than 9°C difference between T_{24} and $T_{comfort}$. Case 4 and 5, as expected, show that insulation can worsen indoor conditions when not coupled with an effective solar gains control. In winter period (Fig 6a) case 6 has a little expected difference from comfort conditions and a very low variance, i.e. the hours when the T_{24} is very much above or below the comfort temperature are fewer than in other cases. Moreover, the Skewness around zero means that there are almost the same number of hours when $T_{24} > T_{comfort}$ and $T_{24} < T_{comfort}$. The proposed method proved to be an innovative and valuable technique to compare retrofit strategies by means of robust mathematical models.



a)

Case	Mean	Variance	Skewness	Kurtosis
1	-1.46	16.26	0.22	2.11
2	-3.56	12.60	0.10	2.02
3	-3.34	12.07	0.08	2.04
4	-0.43	10.16	0.21	2.18
5	-0.84	10.17	0.22	2.19
6	-1.09	8.14	-0.04	1.91

b)

Case	Mean	Variance	Skewness	Kurtosis
1	9.17	3.73	0.05	2.57
2	5.55	2.94	-0.15	2.71
3	5.52	2.78	-0.15	2.69
4	7.66	2.69	-0.02	2.70
5	7.29	2.72	-0.02	2.70
6	3.36	3.67	0.21	2.42

Fig. 6 Gaussian distribution of (T_{24}-$T_{comfort}$) and main moments of hourly data for winter period (a) and summer period (b).

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