Ventilation strategies for the deep energy retrofit of a kindergarten

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ABSTRACT

The scientific literature often reports example of educational buildings with extremely poor ventilation performance. An in-field investigation for the environmental and energy assessment of a kindergarten in Milano, confirmed that operable windows were not operated when the average daily temperature dropped below 14 °C, jeopardizing indoor air quality and kids learning performance. Seven different ventilation strategies were therefore simulated, in order to evaluate the one that better fitted a general project of deep energy retrofit of the building, including building envelope and systems. The best scenario resulted to be the one using hybrid ventilation at nighttime and mechanical ventilation at daytime. Both energy and thermal comfort conditions were evaluated and a tradeoff between them was established. Nighttime ventilation showed to be extremely effective in improving thermal comfort conditions, during the cooling season. It resulted much better than mechanical ventilation in the simulated case study. Simulations show that under moderate weather conditions and if the building is properly operated (ventilation, lighting and solar screening systems) the retrofitted building may perform well also without additional active cooling.

KEYWORDS

Hybrid Ventilation, Mixed Mode, Mechanical Ventilation, Energy Retrofit

1 INTRODUCTION

The Italian educational buildings stock consists of 52 000 buildings for a total covered surface of 73.3 million square meters; around 63% of them constructed more than 40 years ago (CRESME, 2014). The large majority of these buildings are not equipped with mechanical ventilation and thus rely completely on manual opening of windows to provide ventilation air change (Legambiente, 2014). Similar scenarios are shared by many other countries (Daisey et al., 2003; Santamouris et al., 2008; Wyon et al., 2010). The analysis of CRESME (2014) shows also that the Italian school building stock could achieve energy savings of about 48.3 % and shift from a current energy consumption rate of 9.6 TWh/a to a target value of 5.0 TWh/yr. These results may be obtained improving opaque and transparent envelope performance, enhancing building systems efficiency and optimizing building management and control. A typical consequence of this kind of intervention is the drastic drop of air infiltrations, substantially enhancing the building's airtightness. This is very good from an energy point of view but it may have drawbacks in terms of indoor air quality (IAQ), which is typically already very bad in existing educational buildings. The problem of insufficient ventilation in schools appears, in fact, to be quite common (Daisey et al., 2003; Santamouris et al., 2008; Wyon et al., 2010). In many school buildings, the CO_2 concentration reached very high values, quite above what is suggested in relevant standards and building codes (Brelih, 2012; Danish Building

Regulations, 2010; Dimitroulopoulou, 2012; Hasegawa et al., 2012). Insufficient ventilation in schools has been linked with respiratory and general symptoms, infectious diseases and impaired learning outcomes. Poor ventilation is also associated with higher levels of chemical pollutants, and problems with mold and dampness (WHO, 2011). The present paper investigates the possibility to include a dedicated ventilation strategy in the deep energy retrofit of a kindergarten, in order to improve the IAQ of the building while controlling energy requirements for ventilation. A decentralized ventilation system is studied, included in prefabricated modules for the renovation of transparent and opaque envelope components and solar screening. Different ventilation options are compared in terms of energy and thermal comfort performance in order to define a trade-off between occupants' needs and retrofit aims.

2 BUILDING DESCRIPTION

The analyzed building is a kindergarten built in the 80s. The one-story building has a length of 44 m (south-west and north-east façades) and a depth of 23 m (south-east and north-west façades). Around 35 % of the ground floor is dedicated to children activities and the rest to the staff and service areas. The building has a gross floor area of 944 m^2, a net floor area of 855 m^2 and a gross volume of 3 422 m^3 (S/V ratio equal to 0.77 m^2/m^3).

Figure 1: (left) Picture of the southwest façade; (right) kindergarten plan view including the five monitored rooms.

Walls description: the existing building is a typical heavy-prefabricated building made of precast concrete panels including a thin polystyrene layer. The U-value of the walls before retrofit is estimated to be 1.0 W/(m^2 K).
After the retrofit the façade will be covered with prefabricated modules including mechanical ventilation and automated solar shading system. The U-value of the walls after retrofit will be 0.1 W/(m^2 K).
Roof description: the existing roof is a pitched metallic plate with no insulation, placed upon a horizontal concrete slab (Predal system). The U-value of the roof before retrofit is estimated around 0.9 W/(m^2 K). The metallic plate will be removed and a new insulation layer will be laid on the existing slab (approximately 38-40 cm of mineral wool). After the retrofit the U-value of the roof will be 0.1 W/(m^2 K).
Windows description: the existing windows are single pane windows with aluminum frames. In addition to the low thermal performance, the low airtightness of the existing windows cause a high infiltration loss. The U-value of the windows before retrofit is estimated to be 5.85 W/(m^2 K). The post retrofit triple glazing windows will be integrated in the prefabricated façade modules. The U-value of windows will be 0.73 W/(m^2 K).
Heating system: a natural gas boiler for heating is currently installed in the kindergarten in combination with metal radiators, whereas a connection to the local district heating system will be provided after the retrofit.
Ventilation system: currently, no mechanical system is available in the building and the ventilation is accomplished by manual operation of the windows. A new decentralized

ventilation system will be installed inside the prefabricated facade with high-efficiency heat recovery units with a nominal sensible recovery efficiency of $\eta = 0.80$.
The indoor environmental conditions were monitored in the building from July 2014 to May 2015. Figure 2 – left, shows the measured operative temperature in room 5. It is possible to check discomfort conditions against category I boundaries according to standard EN 15251 (CEN, 2007). Constant Fanger's boundaries are plotted from 15th October to 15th April (heating season) following Table A.3, Annex A, of EN 15251 for kindergartens. According to EN 15251 specifications, the adaptive model limits are applied during the free running period only, when no mechanical system is operating. Both Fanger's and adaptive comfort models were developed for grown up persons and mostly for office spaces, however the comfort boundaries provided by EN 15251 for category I, i.e. for very sensitive persons, may be considered quite restrictive and adequate for a kindergarten, while waiting for a dedicated future comfort models for kids. It is quite evident that indoor temperature drops down during Christmas holiday, when the heating system is off, and similar, though less dramatic, patterns are clear during winter weekends and at nighttime. This is evidence of the poor thermal behaviour of the building envelope.

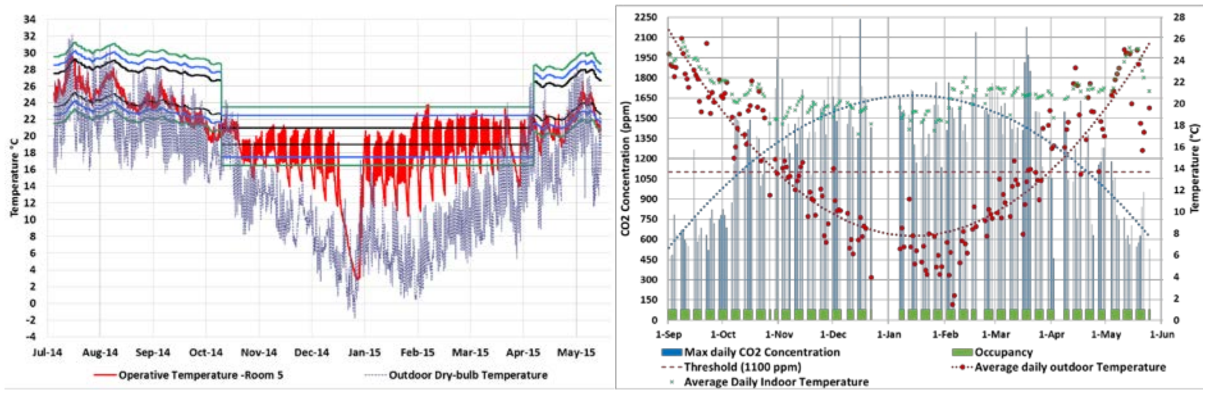

Figure 2: (left) Operative temperature in room 5, and outdoor dry-bulb temperature (DBT) between 8/7/2014 and 25/05/2015 compared to EN 15251 comfort limits (black, blue and green lines corresponding to the limits for categories I, II and III, respectively – (right) Maximum daily CO_2 concentration in room 4 versus average indoor and outdoor air temprerature over occupided period

CO_2 concentration was monitored in room 4 (Figure 2 - right), which is the common space where children play and spend a large part of their time. During August the building is unoccupied therefore the recorded average value of 400 ppm may be considered as the average background outdoor level. After September, noticeable picks are recorded in the room, with values that substantially exceed the reference value of 700 ppm above the background level (ANSI/ASHRAE, 2013), i.e. beyond 1100 ppm. This evaluation should be made under steady-state conditions, however, the recorder picks go far beyond the threshold, showing that the building needs a better ventilation strategy. During September and May, when outdoor temperature is quite mild, indoor CO_2 concentration is relatively low, as consequence of windows opening, whereas during all the winter months CO_2 levels leap above the recommended threshold, showing that manual windows opening is driven by outdoor temperature and not by indoor air quality perception (Wargocki and Da Silva. 2015). Figure 2 shows that windows start to be effectively operated, and thus CO_2 concentration decreases, when outdoor average daily temperature is in the range between 14 and 18 °C, and they keep being operated for higher temperatures, whereas they are closed for lower ones (Causone, 2015).
Energy bills for year 2011 to 2013 report an average value of 142 kWh/m^2 for heating and domestic hot water and 35 kWh/m^2 for electricity. Space heating data, normalized according to

heating degree-days (HDD), i.e. winter severity correspond to 202 kWh/m^2 using the weather data used for the following energy simulations.
The building measurements show clear evidence of poor indoor air quality, low performance of the existing envelope and inefficient heating and lighting systems.
The energy retrofit strategy was therefore defined targeting the goals reported in Table 1.

Table 1: Building retrofit strategies

Retrofit target	Strategies
Energy savings	• reducing energy needs for space heating; • reducing all the final energy uses by improving the efficiency of building systems; • adopting passive strategies whenever possible, while avoiding the installation of active cooling systems; • installing new generation systems using renewable energy sources; • reducing both construction time (to limit the disturbance or interruption of the educational service) and cost (to make the intervention feasible).
Indoor climate quality	• improving IAQ, by developing a ventilation strategy; • guaranteeing adequate thermal comfort condition all year long;

3 METHODOLOGY

The objective of this study is to evaluate the performance of different ventilation strategies in the process of energy retrofit of the existing kindergarten. Evaluations are made on the basis of primary energy, delivered energy and thermal comfort after retrofit. The analysis is developed following three steps. As a first step energy savings due to various ventilation scenarios are calculated. In this regard, two energy criteria were considered for each scenario. As a second step, a long-term evaluation of the thermal comfort conditions is performed using method A of Annex F of EN 15251. Based on this method, the percentage of time (occupied hours) outside the various comfort ranges for each scenario is calculated. In the end, the post-retrofit best scenario is selected and compared against the pre-retrofit situation. All the analyses are based on energy simulations.

3.1 Energy simulation

A numerical model of the building was developed to:
- optimize the selection of opaque and transparent envelope thermal insulation;
- optimize the ventilation strategy;
- define a solar control strategy;
- check energy needs and uses to implement a zero-energy approach;
- check indoor environmental conditions.

In this paper we will focus on the optimization of the ventilation strategy only. The energy simulation of the building was performed using the building performance simulation tool EnergyPlus (Crawley, 2001), version 8.1.0. The physical models and algorithms for calculating heat exchanges have been selected with a trade-off between precision and computation time. The heat conduction through the opaque envelope was calculated via the conduction transfer function method with four time steps per hour. Natural ventilation in the classrooms and corridors through dedicated window openings was simulated using the airflow network model. The minimum outdoor ventilation rate was set according to the national standard (UNI, 1995). School working schedule, number of occupants, equipment and lighting were based on interviews with teachers and building managers. The metabolic activity rates were calculated according to the definition of a “standard kid” (Fabbri, 2013).

Seven different scenarios, including a purely mechanical condition, were modeled and compared on the basis of energy and thermal comfort results (Table 2).

Table 2: Ventilation scenarios considered for simulation

Scenario Code			Winter			Summer		
			Heating System	Ventilation		Cooling System	Ventilation	
				Mechanical	Natural		Mechanical	Natural
A		Day	✓	✓	-	✓	✓	-
		Night	-	-	-	-	-	-
B	1	Day	✓	✓	-	✓	✓	-
		Night	-	-	-	-	-	✓
	2	Day	✓	✓	-	✓	✓	✓
		Night	-	-	-	-	-	✓
	3	Day	✓	✓	-	✓	✓	✓
		Night	-	-	-	-	✓	-
C	1	Day	✓	✓	-	-	✓	-
		Night	-	-	-	-	-	✓
	2	Day	✓	✓	-	-	✓	✓
		Night	-	-	-	-	-	✓
	3	Day	✓	✓	-	-	✓	✓
		Night	-	-	-	-	✓	-

The target of ventilation strategies is to provide adequate indoor climate conditions while reducing energy use directly (electricity) or indirectly (heating, cooling) connected to the ventilation.

Scenario A:

In this scenario an active system is applied for both the heating and the cooling period. The set-point temperature is 24 °C and 20 °C for cooling and for heating respectively. Minimum renovation air change rates, as defined by the national standard (UNI, 1995), are provided by a decentralized mechanical ventilation system with a high-efficiency sensible heat recovery unit. Ventilation is provided according to occupation schedules. This system is working all year long and it should guarantee stable environmental conditions during the entire occupation time.

Scenario B:

The active heating and cooling systems are set as for scenario A, whereas three different ventilation strategies are studied, adopting various mixed mode (or hybrid) settings. This system follows the logic presented in Figure 3. When the defined conditions are met the mechanical ventilation is switched off and the outdoor fresh is introduced to the zone through automated windows opening on the external façade and core light-wells to fulfill the indoor air quality.

Scenario C:

The active heating system follows the same schedule as scenario A and B, whereas no active cooling is foreseen in summer. During this period thermal comfort conditions are provided only by daytime and nighttime ventilation, following the logic reported in Figure 3 (Breesch, 2005). If the conditions are favorable for natural ventilation, the mechanical ventilation system is disabled and the automatic window openings are operated.

4 RESULTS

4.1 Energy

Two indicators were chosen to compare the energy performance of different scenarios: the delivered energy and the primary energy. An energy breakdown is provided for each ventilation scenario in term of delivered energy in Figure 4 – left and of primary energy in Figure 4 – right.

From the energy point of view, scenario C1 shows the best performance, whereas B2 is the best scenario among the ones including active cooling. In particular, scenario B2 shows a reduction of 68.5 % in term of delivered energy for cooling, compared to scenario A.

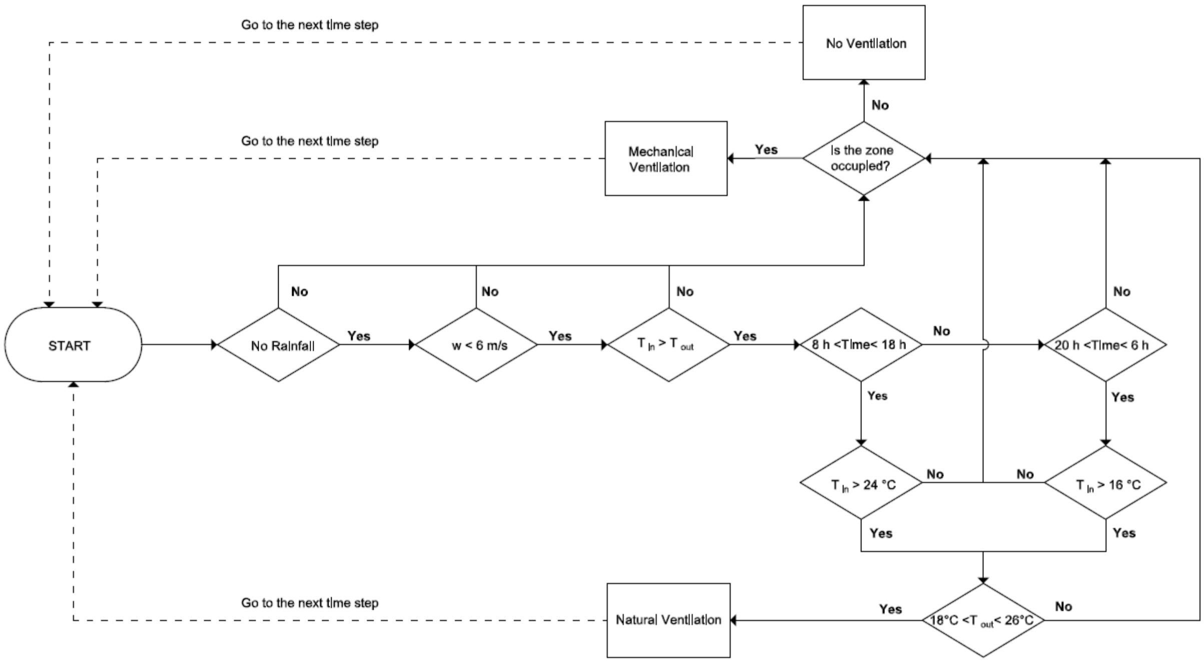

Figure 3: Logic control for Hybrid Ventilation (at each Time Step)

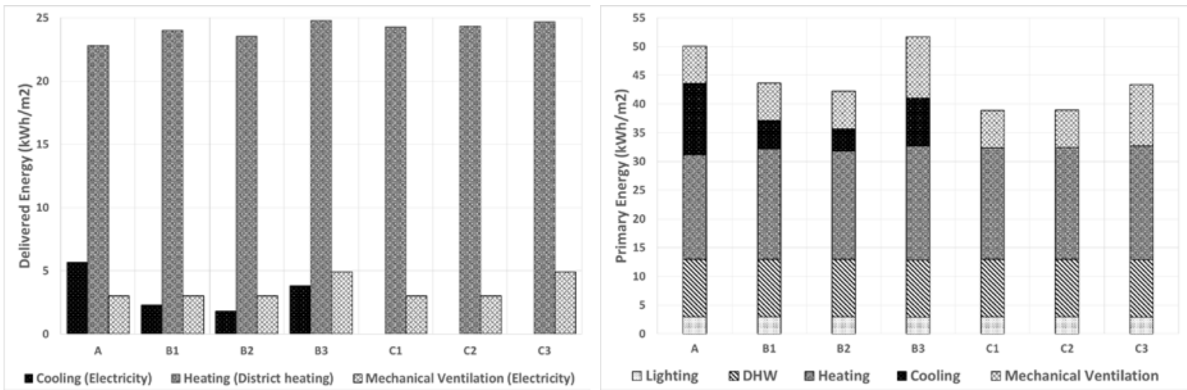

Figure 4: (left) Delivered energy for each scenario (electricity for mechanical ventilation and cooling; thermal energy from district heating for space heating); (right) Primary energy for each scenario.

The primary energy reported for scenario C1 results 22.4 % lower of scenario A and 7.8 % lower of scenario B2 (Figure 4). The delivered energy for mechanical ventilation is, nevertheless, almost constant for scenarios A, B1, B2, C1, and C2. It means that natural ventilation is not really effective during the occupied hours but mostly in the early morning before occupation or in the late evening and at nighttime. Its role is therefore not explained in terms of reductions of delivered energy for mechanical ventilation but in terms of thermal comfort. This is confirmed by the fact that the delivered energy for mechanical ventilation rises for scenarios B3 and C3, when it is also used at nighttime. In case C1, C2 and C3 it should nevertheless be noticed that no delivered energy for cooling is considered, and that only natural ventilation controls thermal comfort conditions.

4.2 Indoor climate

Minimum ventilation air change rates according to the national standard (UNI, 1995) are provided in all scenarios, though actual ventilation rates may be higher under natural ventilation conditions and thermal comfort results also different. Scenario A and B has fully active heating, cooling, and mechanical ventilation systems, which provides indoor thermal comfort during the winter and summer. In scenario C, with an active heating system for winter and no active cooling system for summer, the indoor thermal comfort in cooling season is evaluated using method A of Annex F of EN 15251 (CEN, 2007). The percentage of time (occupied hours) outside the comfort ranges has been calculated as a long term indicator of discomfort (Figure 5 – left), adopting four thresholds of operative temperature, i.e. 24, 25, 26 and 27 °C. The best scenario is C2, for all of three analysed rooms. Adopting the 24 °C threshold, that is the set-point temperature for active cooling in scenario A and B, and focusing on room 5, the percentage out of range results 29.4 % in scenario C3 whereas 15.1 % in scenario C2.

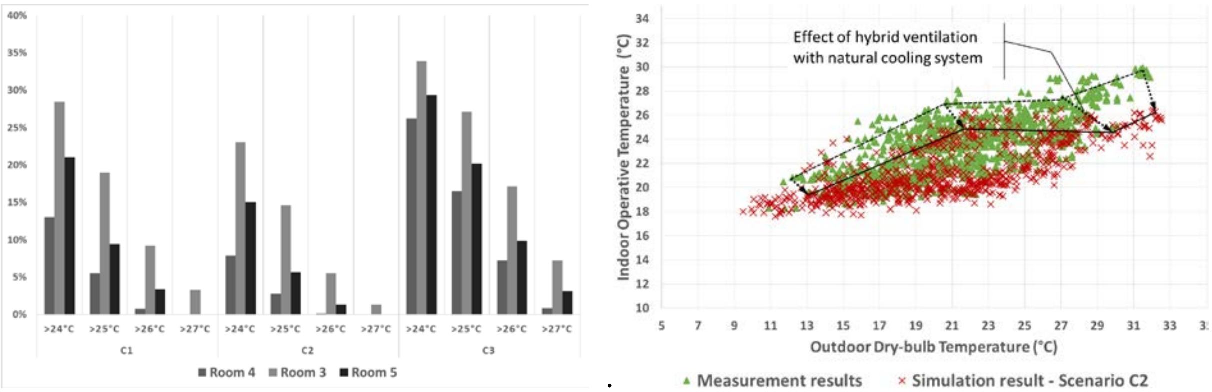

Figure 5: (left) Percentage of time out of range; (right) Indoor operative temperature as a function of outdoor dry-bulb temperature during the occupied hours from 09/07/14 to 25/05/15 (real data against C2 scenario simulations at reference room 5)

Figure 5 reports indoor operative temperature in room 5, as function of outdoor dry-bulb temperature for the existing building (based on measured data) and for the energy simulation (scenario C2). Measured data show indoor temperatures up to 30 °C when the outdoor temperature is above 30 °C. In simulated data, instead, under similar outdoor conditions the indoor temperature reaches the maximum value of 26 °C. A clear decrease of maximum indoor operative temperature is identifiable in the diagram of Figure 5.

4.3 Pre- and post-retrofit energy performance

The energy required for space heating and the production of domestic hot water of the existing building, relying both on the same boiler, were normalized by using a regression model (R^2 = 0.87) made on the basis of the metered data and heating degree days (HDD) from 2010 to 2013. Space heating value was substantially higher than the one of domestic hot water, therefore the correlation with HDD is motivated. The energy consumption of post-retrofit are calculated and compared to the existing situation in order to evaluate the potential energy savings of the energy retrofit (Table 3).
Energy simulations shows, for scenario C1 and C2, thermal comfort conditions during all the occupied hours in summer, i.e. 100 % of occupation time. The calculations are made according method B of annex F, EN 15251, adopting category I limits of the adaptive comfort model. This value decreases to 93 % for scenario C3. In Table 3, scenario C2, the best in terms of thermal comfort and the one with the second best energy performance (after C1), is compared to existing

building performance. Energy reduction up to 86 % in terms of primary energy from pre- to post-retrofit are evaluated.

Table 3: energy consumption per net floor area of the pre and post-retrofit building

Building condition	Energy carrier	Delivered energy kWh/(m^2a)	Primary energy conversion factor	Primary energy kWh/(m^2a)
Existing building (pre-retrofit)	Fuel (Natural gas)[1]	202.07	1.00	202.07
	Electricity[2]	35.32	2.18	77.00
Post retrofit (scenario C2)	District heating[1]	36.82	0.8	29.46
	Electricity[2]	4.35	2.18	9.48

(1) Heating and production of domestic hot water
(2) Lighting, laundry, kitchen, equipment, mechanical ventilation

5 DISCUSSION

The scenario that shows the lowest energy consumption is C1, whereas the one that shows the best comfort conditions is C2. Since C2 also shows a quite considerable energy saving, it was chosen as the best scenario according to design aims. However, each scenario has pros and cons, which may be summarised as follows.

A: the envelope retrofit based on prefabricated modules including mechanical ventilation and solar shading, substantially reduces the primary energy up to 82 % compared to the existing building. Yet this scenario is not in line with the main goal of the retrofit that is to achieve indoor thermal comfort with no active cooling system.

B1: this scenario shows nighttime natural ventilation coupled with daytime active cooling. The results show 60 % reduction of delivered energy for cooling compared to the reference scenario A. This is a clear evidence of nighttime ventilation cooling effectiveness.

B2: in this scenario the hybrid mechanical logic is applied (Figure 3). The natural ventilation system is used as the primary means of ventilation and if this is not applicable, the mechanical system activates. The results show 22 % reduction of delivered energy for cooling compared to scenario B1.

B3: as a further step, in this scenario mechanical night ventilation is simulated, i.e. the mechanical system that is designed to provide minimum ventilation rates during the occupied time, works also at nighttime on full capacity. This results in 63 % higher electrical energy use compared to scenario B1. It is moreover less effectiveness then scenario B2, when only nighttime natural ventilation is simulated.

C1: the scenario includes daytime mechanical ventilation, nighttime natural ventilation and no active cooling system. This solution provides the lowest primary energy requirements and 100 % of occupied hours within category I limits according to the adaptive thermal comfort model of standard EN 15251. Adopting another indicator of thermal discomfort, in room 5 only 21 % of occupied hours show indoor temperatures higher than 24 °C, that is the set-point temperature for active cooling.

C2: this scenario adds the possibility of daytime natural ventilation to C1, and this reduces the percentage of occupied hours with indoor temperature higher than 24 °C to 15.1 %.

C3: this scenario shows that mechanical ventilation at nighttime does not provides the same thermal comfort level as natural ventilation, mostly because the airflow rate is fixed and dimensioned according to the minimum airflow requirements for daytime. Moreover, scenario C3 shows higher primary energy requirements compared to C1 and C2.

6 CONCLUSIONS

Seven different ventilation scenarios were simulated in order to evaluate which one could better fit the comprehensive deep energy retrofit of a kindergarten. The existing building showed very poor ventilation conditions during the occupied time whenever the average daily outdoor temperature dropped below 14 °C. It means that occupants (teachers) operates windows as function of outdoor temperature more than as function of perceived air quality.

All the ventilation strategies thus include mechanical ventilation during the heating season, whereas attention was made on different options for mechanical cooling and mechanical/hybrid ventilation.

Scenario C2, with no active cooling, mechanical ventilation at daytime and hybrid ventilation at nighttime (either natural or mechanical), showed to be the best scenario according to thermal comfort conditions and the second best in term of primary energy.

Natural ventilation at nighttime results extremely effective in improving daytime thermal comfort conditions during the cooling season, showing that active cooling could be avoided if the weather conditions are not too much severe, and if the building is adequately operated (ventilation, lighting, solar screen). Nighttime natural ventilation performs better than mechanical ventilation, in the simulated building, reducing furthermore the final energy use.

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