CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 10

Heiselberg, Per Kvols

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Analysis of ventilation strategies for the nearly zero energy retrofit of a day care center

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Abstract
The scientific literature often reports examples of educational buildings with extremely poor ventilation performance. An in-field investigation for the environmental and energy assessment of a day care center in Italy in Milano, confirmed that operable windows were not opened on days when the average daily outdoor temperature was below 15°C, seriously affecting indoor air quality and potentially affecting the wellbeing and learning process of the children. A numerical model for the dynamic energy simulation of the school building was developed to optimize the thermal insulation of opaque and transparent envelope, the solar control strategy, reducing energy needs and uses to implement a nearly zero-energy approach to the retrofit. Different ventilation strategies were therefore simulated, in order to evaluate the one(s) that best fit the deep energy retrofit of the building, including building envelope and systems. A control logic for hybrid ventilation was simulated and analyzed, with the aim to develop a strategy suited for replication and effective in ameliorating both energy performance and indoor environmental quality. Daytime and nighttime natural ventilation showed to be extremely effective in improving thermal comfort conditions, during the cooling season, performing better than mechanical ventilation.

Keywords - Hybrid Ventilation, Mechanical Ventilation, Energy Retrofit, Schools

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 [1]. 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 [2]. Many other countries show similar conditions [3, 4, 5]. The analysis in [1] shows that the energy retrofit of the Italian school building stock could shift from a current energy consumption rate of 9.6 TWh/y to a target value of 5.0 TWh/y. These results may be obtained improving opaque and transparent envelope performance, enhancing building systems efficiency and optimizing building management and control. A typical objective of energy efficiency retrofits is a substantial enhancement of the building's airtightness. This improvement from an energy point of view is also an opportunity to introduce effective measures to improve indoor air quality (IAQ), which is typically quite poor in existing educational buildings. The problem of insufficient ventilation in schools appears, in fact, to be quite common [3, 4, 5]. In many school buildings, the CO_2 concentration reaches high values, quite above what is suggested in relevant standards and building codes [6, 7]. 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 [8]. The present paper investigates the inclusion of a dedicated ventilation strategy in the deep energy retrofit of a day care center, owned and managed by the City of Milano, 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 optimize the final design.

2. Building Description

The building is a day care center 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. Around 58 % of the ground floor is dedicated to children activities and the rest to the staff and service areas. The building has 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).

Fig. 1 (left) Picture of the southwest façade; (right) plan view with 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 about 1.0 W/(m^2 K).

In the retrofit configuration, the façade will be entirely covered with prefabricated modules including both opaque and transparent elements. The overall U-value of the resulting stratigraphy of opaque elements 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, without any effective operable solar shading device. In addition to the low thermal performance, the low airtightness of the existing windows causes high infiltration loss. The U-value of the windows before retrofit is estimated to be about 5.9 W/(m^2 K). After retrofit, the triple glazing windows integrated in the prefabricated façade modules will have a U-value of about 0.73 W/(m^2 K). Automatic external movable shading blinds (activated when incident solar irradiance on window surface is greater than 200 W/m^2) are also integrated in the prefabricated façade modules.

Heating and cooling system: a natural gas boiler is currently installed in combination with metal radiators, whereas in the retrofit configuration decentralized reversible heat pumps will be installed to cover space heating and cooling needs, with nominal coefficient of performance (COP) for heating and nominal energy efficiency ratio (EER) for cooling equal to 3.

Ventilation system: currently the building has no mechanical ventilation system and air changes are accomplished by manual operation of the windows. A new decentralized ventilation system will be installed inside the prefabricated façade 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 December 2015. Figure 2 shows the measured operative temperature in room 5. Both Fanger's and adaptive comfort models were developed on the basis of surveys involving adult persons and mostly for office spaces, however EN 15251 [9] proposes a category I for very sensitive persons and, while waiting for a dedicated future comfort model for children, in figure 2 we have represented all three categories from the standard. Following EN 15251 we have plotted constant Fanger's boundaries from 15th October to 15th April (heating season) following the values for kindergarten suggested in Table A.3, Annex A of EN 15251 [9] (in Table 1); the adaptive model limits are applied during the free running period only, when no mechanical system is operating. During Christmas holidays there is a large drop of indoor temperature, and similar rapid temperature drops appear during winter weekends and at nighttime. This is evidence of the poor thermal behavior of the building envelope.

Table 1. Comfort ranges for operative temperature in heating period for kindergartens [9].

Category I	Category II	Category III
19.0-21.0 °C	17.5-22.5 °C	16.5-23.5 °C

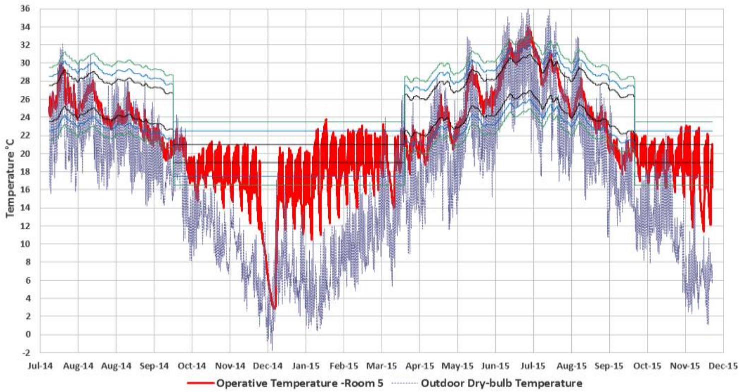

Fig. 2 Operative temperature in room 5, and outdoor dry-bulb temperature (DBT) between July 2014 and December 2015 compared to EN 15251 comfort limits (black, blue and green lines corresponding to the limits for categories I, II and III, respectively).

CO_2 concentration was monitored in room 4, 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. Figure 3 shows that after September, noticeable peaks of concentration are recorded in the room, with values that substantially exceed the reference value of 700 ppm above the background level [11]. This evaluation should be made under steady-state conditions, however, the recorded peaks go far beyond the threshold, showing that the building needs a better ventilation strategy. From mid-April to mid-September, 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 rise above the recommended threshold, showing that manual windows opening is driven by outdoor temperature and not by IAQ perception [12].

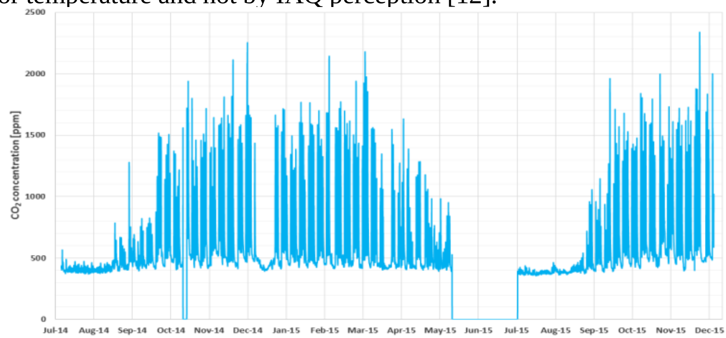

Fig. 3 CO_2 concentration in room 4, with noticeable peaks from September to May (missing data are due to a technical problem to the energy supply of the equipment).

Energy bills for year 2011 to 2013 reported an average value of 142 kWh/(m^2 y) for delivered energy in the form of natural gas for heating and domestic hot water and 35 kWh/(m^2 y) for delivered energy in the form of electricity (normalized with respect to the net floor area of the treated zones). Space heating data, normalized according to heating degree-days (HDD), amount to 202 kWh/(m^2 y) in correspondence of the weather data used for the energy simulations.

Measured data 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 2.

Table 2. 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; - 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 with a new ventilation strategy; - ensuring adequate thermal comfort condition.

3. Methodology

The objective of this analysis is to evaluate the performance of different ventilation strategies in the process of energy retrofit of the existing day care center in conjunction with high performance components for the building envelope.

In particular, we analyze various scenarios where the mechanical ventilation system is optimized and a control logic is integrated for automatic window openings to allow free cooling when necessary. For the natural ventilation, taking into account also other case studies and analysis [13, 14], we developed ventilation control rules with the following goals: (i) being comprehensive and effective, considering various conditions to reach indoor thermal comfort, adequate humidity and air velocity levels, and cooling potential, (ii) being implemented by a building management systems (BMSs). The system should therefore require only simple electronic components as a compact weather station and commercial indoor sensors; this would allow for a potential broad replicability in private and public buildings.

Mechanical ventilation is switched off and automatic operable windows are opened, when all the following conditions occurs: (i) the indoor air temperature is greater than 24 °C, (ii) the air temperature difference between indoor and outdoor environments is greater than 2 °C (with outdoor air temperature lower than indoor one), (iii) the outdoor relative humidity is lower than 70%, (iv) the outdoor wind velocity is lover than 10 m/s. The indoor temperature value for which automatic windows opening is activated, was chosen at 24 °C, with the aim to avoid overcooling conditions, particularly for children, in early occupation hours during morning. We are developing further analysis in order to optimize values for parameters of the natural ventilation control rule.

Scenario 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, we calculate the percentage of time (during occupied hours) outside the comfort range. In the end, the post-retrofit best scenario is selected and compared against the pre-retrofit situation. All the analyses are based on dynamic energy simulations.

4. Energy Simulation

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

In this paper we will focus on the evaluation of the ventilation strategy. The energy simulation of the building was performed using the building performance simulation tool EnergyPlus [15], version 8.1.0 and its additional programming language (Erl - EnergyPlus Runtime Language, for the Energy Management System module). 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 Italian national standard [16]. 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” [17].

Four different scenarios, including one with purely mechanical ventilation, were modeled and compared in terms of energy and thermal comfort performance.

Scenario a. (e.MV):

This scenario includes the efficiency measures on building envelope as described before, integrated with decentralized reversible heat pumps and balanced mechanical ventilation system with heat recovery, working at constant design air flow rate (8 air changes per hour (ACH) in toilets, 2 ACH in the kitchen, 4 L/s per person in other rooms) during the opening hours of the building (from 7 to 19).

Scenario b. (e.MV.dc):

It has the same features of the previous scenario a. (e.MV) with the difference that the air flow rate provided by the mechanical ventilation system is demand-controlled, i.e. proportional to the actual occupation in each rooms and hour. The demand-controlled operation is adopted in all rooms, excluding toilets and the kitchen where air flow rates remain fixed at design level during all occupation hours, as requested by the national standard.

Scenario c. (e.HV.dc):

Similar to scenario e.MV.dc, but including automatic operable windows, operated according to the control logic described in Session 3 for free cooling. In particular, only the highest part of each window is automatic operated, corresponding to 25% of the total window surface, whereas the remainder part is manually operable. This technical solution was developed to avoid drafts in the area occupied by children and teachers, and to provide higher security against burglars when natural ventilation operates during not occupied hours. When the control logic activates the windows opening, the optimized mechanical ventilation according scenario b. (e.MV.dc) switches off. If the control logic conditions are satisfied, natural ventilation can be activated during all day (24 hours).

Scenario d. (e.HV.dc.n):

It shows the same features of scenario c. (e.HV.dc), but automatic opening of windows for natural ventilation is working only during the nigh period (from 21 to 5). During the daytime ventilation is mechanical.

We simulated also a model corresponding to the building features before the retrofit interventions. This scenario is indicated below with code “0.0”.

In all scenarios, the system considers a set-point for indoor operative temperature equal to 20 °C for heating and 26 °C for cooling, with heating period lasting from October 15 to April 15, according to national regulation [18]

5. Results and Discussion

The main results are presented in terms of energy performances. The adopted primary energy factors are 1 for natural gas and 2,18 for electricity, since they are typical values for the Italy [19]. We compared primary energy demand for heating, cooling and mechanical ventilation before and after the energy retrofit. Figure 4 shows that the adopted energy efficiency measures lead to a low primary energy demand for these uses, since the value for all the retrofit scenario is lower than 25 kWh/(m^2 y), corresponding to energy savings of about 87%, compared to the pre-retrofit scenario. Moreover, the existing scenario “0.0” does not include cooling systems, so the estimated primary energy demand in that scenario includes only heating. Energy retrofit actions on building envelope and ventilation appear therefore to be extremely effective.

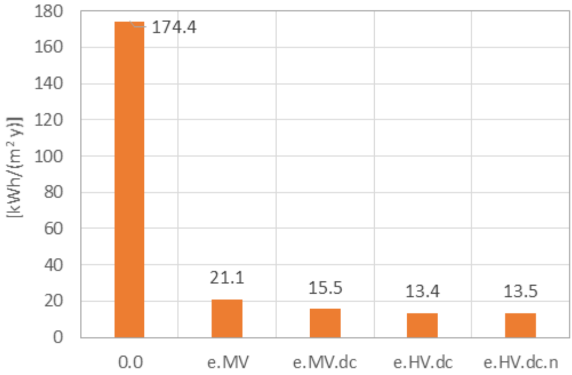

Fig. 4 Primary energy demand for space heating, cooling and mechanical ventilation per square meter of conditioned net area, in the simulated scenarios. (The scenario 0.0 has a heating system but no cooling system).

It is possible, nevertheless, to see differences between the retrofit scenarios with optimized mechanical and hybrid ventilation strategies. Figure 5 shows that, with respect to pre retrofit conditions, in the post retrofit scenario e.MV, electricity savings are about the 26% when mechanical ventilation is demand controlled (scenario e.MV.dc) and they reach values higher than 36% when hybrid ventilation is adopted (e.HV.dc and e.HV.dc.n). Differences are very low between energy use in the two scenarios adopting hybrid ventilation, respectively all day long and only during nighttime. The setting values for the ventilation control logic (e.g. upper limit for indoor temperature and temperature differences), probably, determine windows opening mostly during nighttime.

Figure 6 shows surface-weighted minimum, maximum and average values of indoor operative temperatures and active cooling operation hours, for building spaces. We can see that indoor comfort conditions are met although the active cooling system is in operation only a few times.

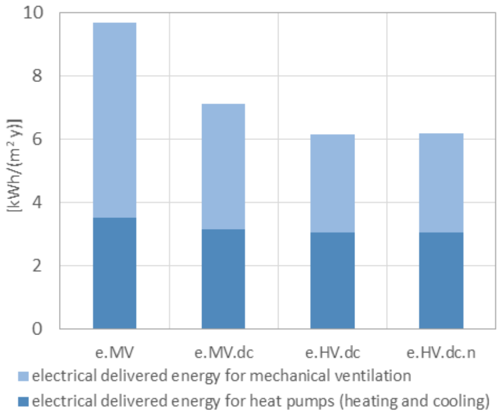

Fig. 5 Yearly electrical delivered energy for heating, cooling and mechanical ventilation per square meter of conditioned net area, in simulated post retrofit scenarios.

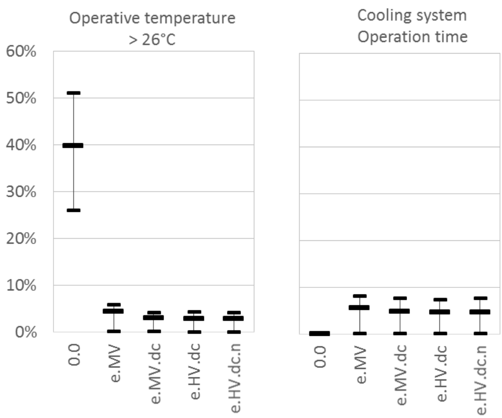

Fig. 6 Percentage of hours with indoor operative temperature out of the comfort range and of cooling system in operation, in cooling period, during occupation hours.

6. Conclusions

The proposed energy retrofit for the day care center shows a high energy saving potential combined with improved thermal comfort conditions. High performance retrofit measures on the building envelope reduce energy use, whereas hybrid ventilation with heat recovery and free cooling via automatic windows opening allows to ventilate rooms without increasing ventilation loss. The control logic is suitable to be applied by BMS, with an interesting replicability potential.

Acknowledgment

The authors would like to thank the Department of School Construction and the Office for EU Affairs of the Municipality of Milano, ROCKWOOL Italia and Askeen for the collaboration on this project. The study was developed within the EU-GUGLE project funded by Seventh Framework Programme under grant agreement n. 314632, and in the framework of the SCUOLA project funded by Regione Lombardia.

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