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Performance optimization of a demand controlled ventilation system by long term monitoring

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ABSTRACT

The thermo-hygrometric treatment related to the air change in buildings requires a relevant quota of the total energy demand of HVAC systems, especially when the ventilation demand is significant. A correct energy saving strategy therefore should always focus on the use of suitable techniques to reduce this energy consumption. As proved by the modern theories on comfort, less strict values can be accepted for the internal humidity set points without compromising indoor comfort conditions. In addition, Demand Controlled Ventilation (DCV) gives the opportunity to reduce energy requirements. This paper investigates the opportunities offered by the installation of a DCV system and a Building Management System (BMS) able to perform long term monitoring of the HVAC system in a real case study. This refers to a historic building in Venice in the area of the harbour and recently transformed into a modern university facility. Starting from the experimental data recorded by BMS, an optimization of the control strategies and simple tuning actions of the DCV controller were possible. Results validate the use of more flexible set points of indoor relative humidity and long term on-line tuning even in absence of self-learning control systems, as well as they highlight the achievement of remarkable energy savings thanks to these actions. The research demonstrates the fundamental contribution of successive control performance assessments by long term monitoring to individuate possible weaknesses in DCV system management.

1. Introduction

In the recent past the environmental emergencies focused the efforts towards the fundamental goal to achieve NZEB condition especially in the refurbishment of existing building. But nowadays, the necessity to combine energy saving with the increasing interest for better indoor comfort and air quality is become a very relevant topic [1,2]. In Europe, people stay in indoor environments about 90% of the day [3]. Air pollution has such a concentration in indoor environments that causes adverse health effects especially in case of long exposure periods as shown in [4] and [5]. Indoor air quality (IAQ) is an important public health problem causing social and economic consequences as proved in [6,7]. This is especially true in school buildings [8]. As a consequence standards about IAQ have become increasingly strict [9], corresponding to higher ventilation flow rates. [10]. On the other hand in modern buildings the envelope is highly insulated and airtight, thus leading to the reduction of natural ventilation flow rates [11]. Therefore the use of mechanical ventilation, ensuring appropriate air change rates, is spreading. Consequently the energy demand for ventilation air handling grows and often becomes the prevailing share in the total energy required by heating, ventilation and air conditioning (HVAC) systems [12]. Therefore, especially in buildings characterized by highly variable attendance as in the case of educational buildings considered in this study, a precise information about the actual occupancy patterns permits to elaborate ventilation strategies [13] and operational tools [14] to achieve significant energy savings.

The exigency to optimize energy requirement for ventilation becomes even more strategic in the case of historical buildings subject to preservation order. Here the impossibility to modify the envelope obliges the designer to reduce energy consumption by focusing on ventilation and HVAC system management in order to achieve an energy saving retrofit . Otherwise the refurbishment of historical buildings for modern uses would be difficult to accept in terms of energy consumption and operating cost [15–17]. Therefore, a suitable building management system (BMS) becomes fundamental to achieve the lowest energy consumption without compromising indoor comfort conditions, as noted in [18] and [19], especially when operating by means of demand controlled ventilation (DCV) [20]. In particular, CO_2-based DCV [21] may enable easy real time adaption to current occupancy especially when characterized by strong variability, as proved in [22–24]. In this context, this paper focuses on the new potentialities offered by modern BMS today easily able to collect a great data flow for long periods to help energy/facility managers to redesign strategies in each appli-

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Nomenclature

Abbreviations

HVAC	Heating Ventilation Air Conditioning
DCV	Demand Controlled Ventilation
BMS	Building Management System
BIM	Building Information Modeling
IAQ	Indoor Air Quality
DSM	Demand Side Management
NZEB	Nearly Zero Energy Building
AHU	Air Handling Unit
VSD	Variable Speed Drive
PI	Proportional Integrative
PID	Proportional Integrative Derivative
CPA	Control Performance Assessment
PMV	Predicted Mean Vote
PPD	Predicted Percent of Dissatisfied
RH	Relative Humidity

Symbols

n	actual rotor speed [rpm]
n_{full}	full air flow rate rotor speed [rpm]
n_0	asynchronous speed [1500 rpm]
f	line frequency [Hz]
p	number of poles [4]
s	slip [–]
$\dot{V}$	air flow rate [m^3/s]
$\dot{V}_{full}$	full air flow rate [m^3/s]
ρ	air density [kg/m^3]
h_i	inside air enthalpy [J/kg]
h_o	outside air enthalpy [J/kg]
q	ventilation load [W]
k_p	proportional gain [–]
k_i	integrative gain [–]
k_d	derivative gain [–]
T_i	integral time [min]
T_d	derivative time [min]

cation case. Adopting a case study approach, this study investigates the ability of this method to individuate specific shortcomings in a DCV system and to resolve them by simple tuning actions usually undervalued in traditional HVAC control system. In detail, the paper treats the actual issue of the optimization of ventilation systems [25] by using the approach of the demand side management (DSM) [26–28]. In this case by CO_2-based DCV and satisfaction index evaluation with a particular care to the possibility of a performance improvement by using long term monitoring to optimize control parameters The outcomes are based on a monitoring campaign carried on in the context of the energy retrofit of an historical building in Venice. The acquired experimental data allowed the authors to optimize the use of the DCV system by: i) analysis of the operative mode, ii) control performance verification and consequent tuning intervention, iii) test of more flexible humidity control strategies by assessing the effect on energy demand of different set points, both in winter and summer. In spite of its potentiality, this technique is still poorly used in practice, because it lacks of experimental verifications in different application contexts. In this scenario a case study is here presented to provide a contribution to spread awareness of the advantages resulting from its systematic application.

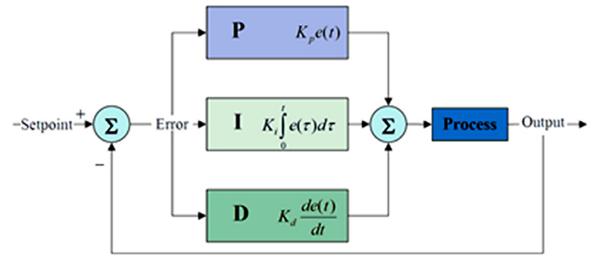


Fig. 1. Scheme of a PID controller.

2. Background

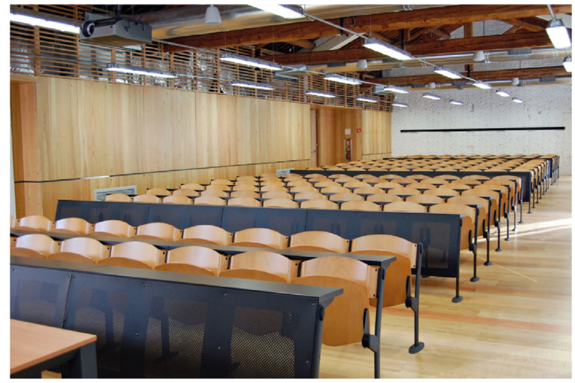
BMS is normally intended only for control and management of the operation of HVAC system. Conversely, this study evaluates the opportunities of a generalized use of a BMS also designed to measure and to record all the data necessary for a complete analysis of the indoor environment and energy performance.

Data collection by using BMS to improve the design and operation of buildings is a hot research focus. The recent developments of data science underline the increasing opportunities of its application in the area of building energy management [29]. By collecting data concerning building operation, it is possible to proceed to the elaboration and consequent validation of management strategies adapted to the particular application case [30]. For this reason, this approach concerns the active control of energy-dependent systems in the operation phase of the building. Naturally also the design stage offers the opportunity to influence deeply future energy performance. In this framework, building information modeling (BIM) can play an important role. In fact modern BIM permits to take advantage of the integrated design data in order to evaluate the expected results in term of building performance and energy consumption [31]. The use of BIM also in the post-construction phase is a research topic in rapid development, but it requires to bridge existing gaps between design and operation phase of the building. To achieve this goal, it is necessary to integrate the technological advances in BIM with a BMS specifically designed for a systematic experimental data collection [32–34]. The potential of a BMS applied to building performance visualization and optimization is therefore investigated here.

Long term monitoring by BMS is proposed as a tool to assess and optimize DCV control performance even in the case of traditional PID control systems which remain the most diffuse in HVAC applications [35], rather than other more sophisticated controllers. The aim is the experimental validation of the contribution in energy retrofit of on-line tuning actions, simple but based on long term analysis, possible in all standard PID systems. To point out their advantages in the existing building, today usually underestimated and therefore neglected in refurbishment projects.

Unlike temperature and humidity control, sudden and wide oscillations are usual around the set point value of CO_2 concentration. This is a peculiarity of CO_2-based DCV, since actual ventilation demand is often more dynamic than the DCV system operation, which is characterized by the inertia of the response of the room control and of the mechanical components involved in the air flow rate modulation. For this reason, new control algorithms were proposed based on adaptive or genetic approaches such as [36–38]. But the simpler PI and PID controls are still the most popular and widespread in usual applications for HVAC systems [39,40]. In the analysed building a PID control modulates the ventilation dampers with a negative feedback strategy. The three actions available in PID controller are calculated separately as shown in Fig. 1 and simply added algebraically [41]. As every controlled process has unique characteristics, the choice (tuning) of the parameters K_p, K_i, and K_d requires a field testing of the values previously determined

a) View of the warehouses from the outside



b) A classroom

Fig. 2. Views of the warehouses.

by manufacturers' lab tests. For this aim, heuristic methods can be used, like Zeigler-Nichols which is the first and best known, but their application is often unsatisfactory especially in HVAC applications [42,43]. In fact more than industrial processes, HVAC systems are characterized by nonlinear and varying dynamics influenced by human behavior and weather variability.

Therefore, in HVAC systems, successive control performance assessments (CPA) are necessary to verify the efficiency of PID system. BMS can provide the information about the processes being controlled necessary for this aim. Self-learning functions implemented in the PID controller are the future tools for auto-tuning [44,45]. In their absence as in this case study, manual tuning can be used as possible simple approach to test and improve PID settings [46,47].

Indoor humidity control is another important cause of energy consumption especially in buildings with relevant ventilation flow rates. The design set point of relative humidity, often strictly prescribed by technical specifications within the range 50% ± 5%, both in winter and in summer, causes an increase in energy demand sometimes avoidable. In fact, as shown by modern theories on comfort by improving Fanger's studies, reported in [48] and [49], more flexible control may be accepted for relative humidity (RH), without compromising indoor comfort as noted in [50] and [51]. On Fanger's theory and its development is based the standard EN ISO 7730 [52]. This standard describes the calculation of the comfort indices and specify acceptable conditions for thermal comfort. However EN ISO 7730 recommends to remain in the RH range 30 - 70%. These limits are associated with health exigencies. In fact too dry environments can cause excessive dryness of skin and mucous surfaces, causing irritation of dry nose, throat, eyes. RH over 70–80% favors condensation on surfaces and consequently mold growth associated with untoward health effects in humans, including allergies and infections. Indoor environments subject to the risk of extreme humidity levels, too high or low, require the installation of adequate dehumidifiers or humidifiers eventually working the whole year. But, in moderate environments, like in this case study, HVAC systems are equipped by humidifiers which normally work only in heating period when outside air is naturally drier. During air conditioning period, when outdoor air carries more moisture, only dehumidification is usually scheduled. For these HVAC systems, indoor comfort analysis individuates RH set point values which can be quite different for heating and air conditioning periods.

2. Method

2.1. Description of the experimental context

A detailed description of the building-plant system and monitoring procedure is provided to include all the information needed to replicate this analysis or use this approach. The building analysed in this paper belongs to an array of seafront historical warehouses subject to preservation order and in spite of this, recently transformed into university facilities.

A view of two of them is in the picture of Fig. 2a. The building consists of three floors with a total floor area of about 3210 m^2 and an air-conditioned volume of 13,450 m^3.The whole building hosts classrooms and pertaining restrooms. Each classroom results as a composition of 57 m^2 (6.4×8.9) floor area modules. Indeed, there are classrooms with one, two or four modules (Fig. 2b). Each module has its own internal air handling unit (internal AHU). Fig. 3 shows the flow diagram of the air treatments through AHUs. Internal AHUs receive, via a primary air network, air previously handled by two identical central AHUs installed on the top of the building (rooftop AHUs) and serving the Southern and Northern branches of the building respectively.

In winter the external air is treated in the rooftop AHUs as follows: pre-heating, humidification and post-heating. A humidity probe installed in the air extraction duct, at the heat recovery inlet, controls the adiabatic humidification. In summer instead, only precooling (and dehumidification) down to a set temperature (currently 18 °C) takes place, controlled by a saturation temperature probe. Then the air is sent to the internal AHUs (Fig. 4) and there mixed with recirculated air coming from the plenum installed under each internal AHU (Fig. 4b).

Moreover, each internal AHU is equipped with two coils. The first coil is fed by cold water in summer and by hot water in winter. In summer two probes, for temperature and relative humidity respectively, located along the return air duct, control this coil. The priority is the control of indoor humidity and secondly the control of the indoor temperature within the set point range. In winter only the temperature probe drives the coil. The second coil operates only in summer in order to reheat the air if necessary after a strong cooling driven by dehumidification exigency in the first coil. The BMS enables the continuous control of each AHU operation. All the measured data are shown on the computer of the management central position. They can be visualized on the screen by maps that permit the operator to verify the operating conditions and modify the set point values.

In Fig. 5 the screenshots relative to a rooftop AHU (a) and to an internal AHU (b) are shown. The measured data are also recorded, therefore a long term monitoring was possible.

Operating hours are from 9 a.m. to 6 p.m. in the weekdays. As regards occupancy in classrooms, it is consequent to the number of the constituting modules. Each module of 57 m^2 is aimed at hosting 45 students (occupancy density is 45/57 = 0.79 people/m^2). Thus, classrooms made by 1, 2 and 4 modules may host up to 45, 90 and 180 students respectively. However the real occupancy resulted highly variable as highlighted by the results of the mon-

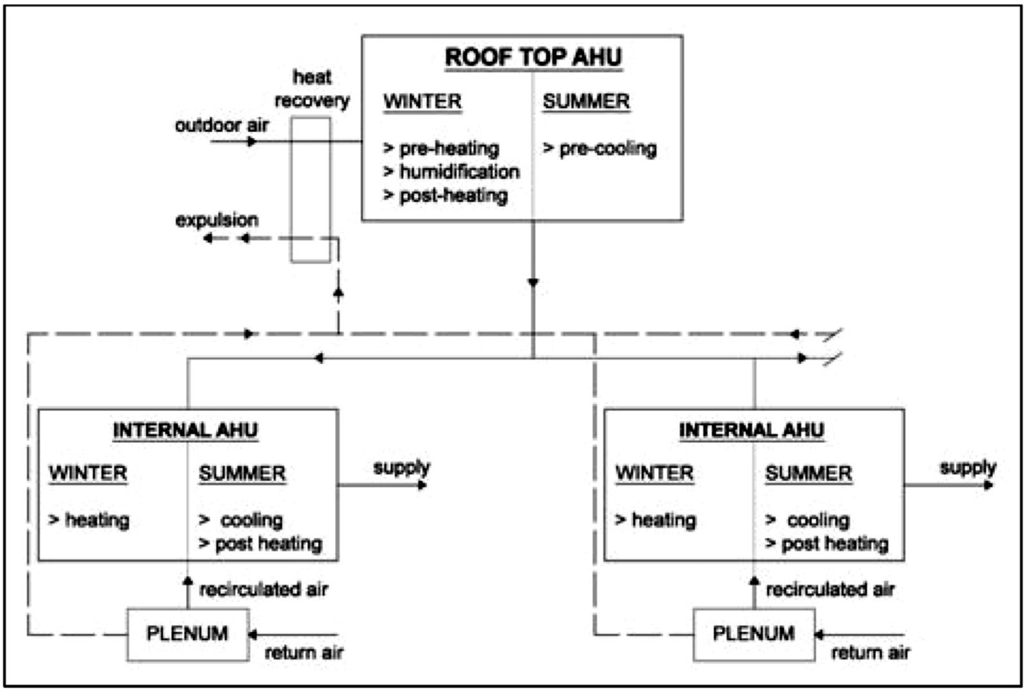
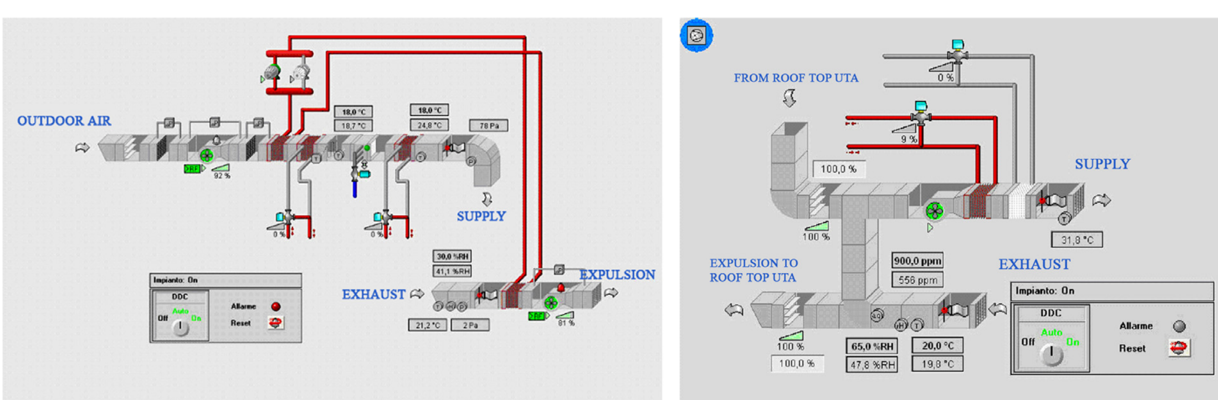


Fig. 3. Flow diagram of the air treatments through the AHUs.

a) AHU partly covered b) AHU without cover c) Modulating dampers

Fig. 4. Pictures of an internal AHU.



a) b)

Fig. 5. Screenshots of the BMS user interface for rooftop AHU (a) and internal AHU (b).

itoring here presented. These results refer to the monitoring period from October 2014 to September 2015 characterized by typical weather for Venice. In that period the students attending the courses held in the building were 1560 in total.

2.2. Description of the DCV system

For each internal AHU the design primary air rate is equal to $45 \times 25 = 1125$ m^3/h handled by the connected rooftop AHU, by considering a reference ventilation flow rate per person of 25 m^3/h (7 l/s) as prescribed by Italian standard UNI 10339 [53]. The total design ventilation flow rate of the building is 44,000 m^3/h equally divided between the two rooftop AHUs.

The high level of occupancy density and its possible wide variation suggested the introduction of a DCV system directly managed by the BMS for each internal AHU. The ventilation air flow rate sent to each internal AHU is controlled by a CO_2 probe located in the return plenum box of the internal AHU. The BMS operates the opening ratio of two motorized dampers installed in the supply duct and the in the return duct respectively, connecting the internal AHU with the primary air network. Simple and robust motorized airtight butterfly dampers were installed. The CO_2 concentration level set-point value is 850 ppm. The modulating dampers are 100% opened at 900 ppm and 10% opened at 800 ppm, keeping a 10% opening ratio in order to ensure a minimum base air change, about 0.5 ach, during the operation hours. Good air quality is usually associated to a 1000 ppm limit value. In particular ASHRAE recommends 1000 ppm as the maximum concentration ensuring a predicted percentage of people that do not express dissatisfaction greater than 80% [54]. Recently ASHRAE clearly stated that the 1000 ppm CO_2 level is a guideline for comfort acceptability rather than a maximum value for IAQ [55]. Nevertheless the 850 ppm set point is justified by the operating mode as shown below. However, all set points of each internal AHU can be easily and individually modified by BMS.

In order to follow the variation of air flow rates handled by the internal AHUs, the rooftop AHUs are provided with variable speed fans so that the values of static pressures downstream of the supply fan and upstream of the return fan are kept constant. In both of these positions a static pressure sensor is installed and connected to the fan speed controller. This variable speed drive (VSD) is integrated into the BMS and operates the inverters feeding the electric motors of the fans of the rooftop AHUs.

2.3. Monitoring mode

The data are recorded every 10 minutes. As regards measurement accuracy, NTC (Negative Temperature Coefficient) temperature sensors are used, with ±0.8 K accuracy, capacity humidity sensors with ±3% accuracy and electric power meters with 1% of full scale accuracy. In particular for this analysis the following monitoring data were used: relative humidity and air temperature upstream and downstream of each coil as well as for outside air to calculate the enthalpy variation of the air handled in each AHU component. Carbon dioxide concentration levels are measured by non dispersive infrared (NDIR) sensors (accuracy ±50 ppm + 2%). In addition BMS provides the value of all parameters describing the VSD operation: the opening ratio of each air damper, the static pressure values and the percentage signals transmitted to the inverters of the two fans of each rooftop AHU. The values of these signals enable the calculation of the actual speed rates of the two fan motors, via the knowledge of the electricity supply frequencies, and consequently the air flow rate through fans. In fact the relationship between the motor speed, the supply frequency, the number of poles and the slip of an induction motor is given by the following equations:

$$n = \frac{120 \cdot f \cdot (1 - s)}{p} \tag{1}$$

$$s = \frac{n_0 - n_{full}}{n_{full}} \tag{2}$$

Owing to the constant transmission ratio provided by a belt and pulley system, the fan speed varies with the same speed ratio as the electric motor. By applying the affinity laws of fans [56], with the impeller diameter held constant, the new operating point is characterized by a flow rate $\dot{V}$ of the fan proportional to the shaft speed as defined in Eq. (3):

$$\dot{V} = \dot{V}_{full} \cdot \left(\frac{n}{n_{full}} \right) \tag{3}$$

The fan electricity consumption of the two rooftop AHU is directly measured.

As a result of the monitoring data, the system performance of the installed DCV system can be assessed and compared with the performance in case of constant ventilation air flow rate. At each monitoring time step, the air flow rate can be calculated by formula (3), while the electricity consumption of the fans is directly measured. In the building thermal balance, the ventilation thermal load is the thermal capacity needed to bring the outside air to the required indoor thermo-hygrometric conditions. In winter, the ventilation thermal load is calculated when the outdoor air values are below indoor set points of temperature and relative humidity, in summer when they are above. Therefore, at each time step, the ventilation heating (or cooling) load q can be calculated by multiplying the air flow rate by the difference between the enthalpy of the outdoor air and the enthalpy of indoor air in the desired conditions:

$$q = \dot{V} \cdot \rho \cdot |h_i - h_o| \tag{4}$$

The absolute value is used because in winter the considered enthalpy difference is positive (heating), while in summer it is negative (cooling).

In absence of DCV, the ventilation air flow rate is constant during the occupation hours and equal to full air flow rate $\dot{V}_{full}$ and the corresponding electric consumption of the fans is constant and equal to the value measured with $\dot{V}_{full}$ In this case, the ventilation load can be calculated again by (4), but considering always the full air flow rate $\dot{V}_{full}$ instead of $\dot{V}$.

2.4. Control performance verification and tuning intervention

In this case study, the installers had no experience about DCV and operated no initial on line tuning. Thus, at the beginning of the monitoring campaign, the butterfly dampers operated only in on-off control as the differential hysteresis was very small (5 ppm) and caused a continuous and unacceptable oscillation between 100% opening and 10% opening. Therefore the first action was to choose a differential value (100 ppm) appropriate for a modulating operation. Furthermore, the PID software here installed authorized the HVAC system manager to act only on the value of proportional gain K_p in order to improve the air loop behaviour. In PID controller the integrative gain K_i is calculated as K_p/T_i where T_i is the integral time here fixed at 10 min. The derivative gain K_D is calculated as $K_p{}^*T_D$ where T_D is the derivative time here fixed at 0 min. It means that in our case the PID works as a PI. These values of integral and derivative times are typical in HVAC applications of PID controllers [57]. The initial value of K_p was equal to 1 (maximum value here admitted) and unsuitable for DCV application, as evidenced by CPA through BMS measurements. Therefore, ventilation system and indoor comfort parameters were monitored for different set values

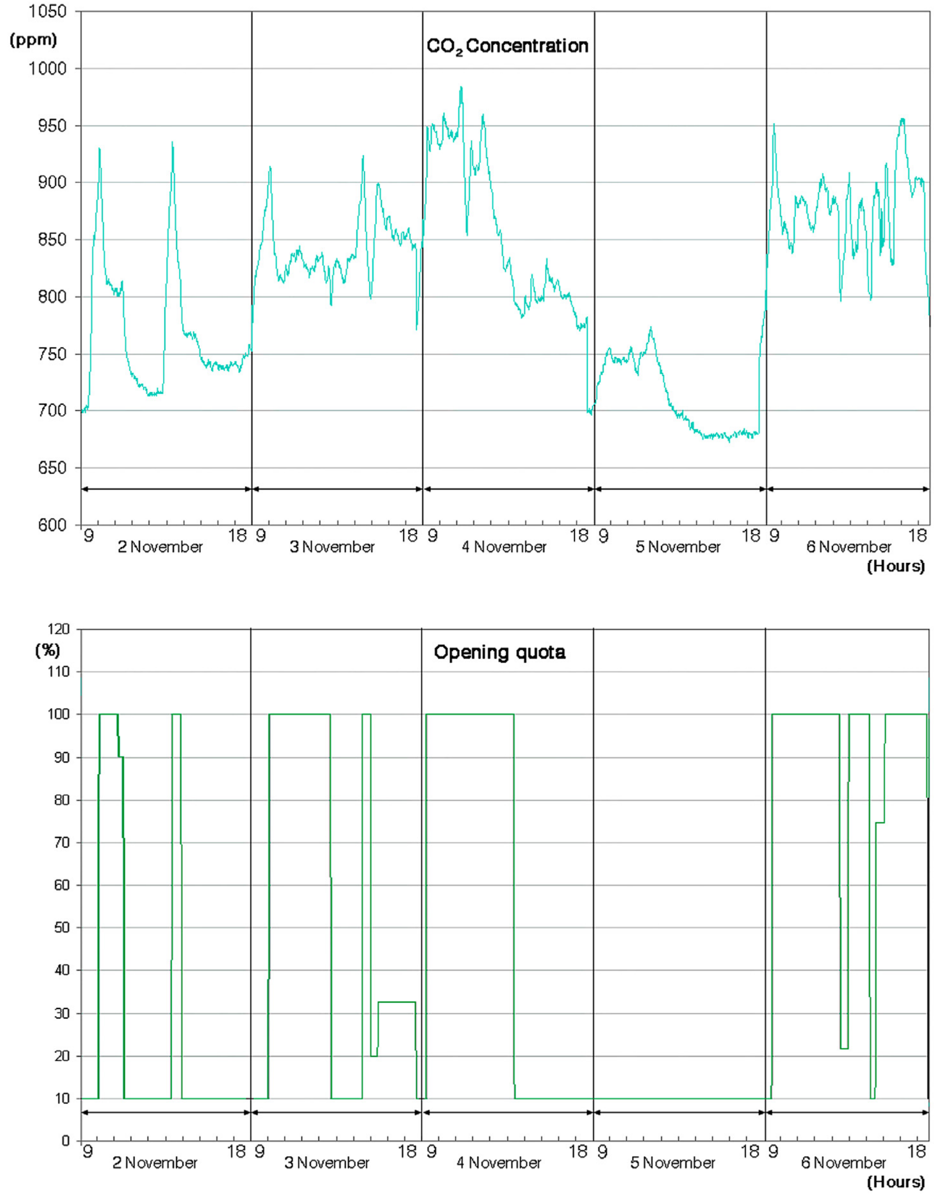


Fig. 6. CO_2 concentration levels (ppm) and corresponding opening quotas (%) of the ventilation dampers in a classroom during the operation hours of the first week of November.

for K_p, so that the most appropriate value was assessed. K_p values in the interval 0.2 to 1 were tested. High values produce high response to the error and then the system can become unstable. Low values produce a less responsive and sensitive control. In the end $K_p = 0.5$ was selected as the best value among the tested ones.

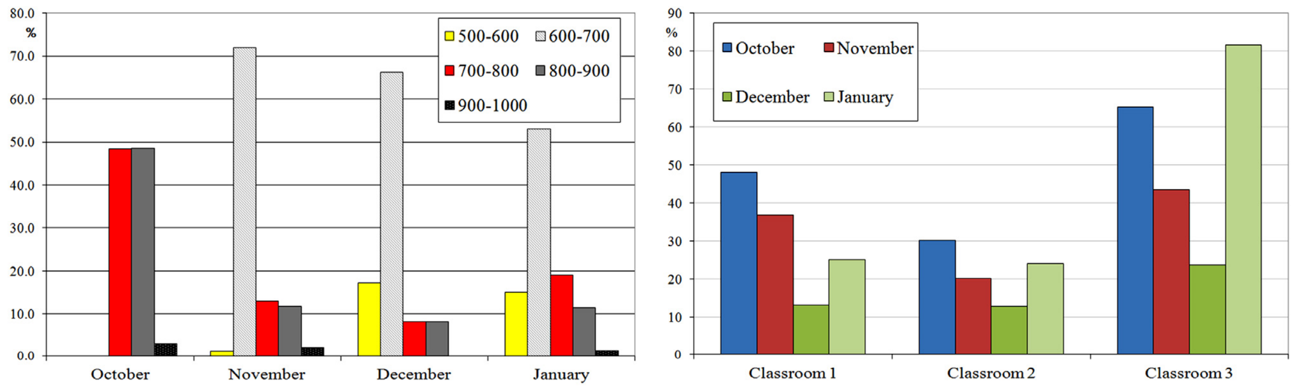
2.5. Individuation of new RH set-points

Fanger introduced the PMV (Predicted Mean Vote) index nowadays accepted by international standard [58] as the comfort index together with the PPD (Predicted Percent of Dissatisfied) index which is a function of PMV. The PMV is based on the application of heat balance equations to the human body and predicts the mean vote which would be assessed by a large group of people under specific indoor conditions in a scale between −3 (very cold) and +3 (very hot). The comfort zone is in the range between −0.5 and +0.5, corresponding to PPD values lower than 10%. The PMV is calculated by a standard procedure [52] assuming parameters typical for a school: a metabolic rate of 1.2 Met and a mean air velocity of 0.1 m/s. In winter an operative temperature of 20 °C (26 °C in summer) as mean value from measures by a globe thermometer [59]. A clothing resistance of 1.0 clo in winter and 0.5 clo in summer. In summer case we calculate an acceptable condition up to a relative humidity of 65% (PMV = 0.48, PPD = 9.8%). In winter we can go down to 35% (PMV = −0.42, PPD = 8.8%). Consequently, these two set points for relative humidity (RH) were used during the monitoring period and their effects were studied, compared with possible different RH set points.

3. Results and discussion

3.1. Analysis of the operative mode

Fig. 6 shows the DCV operating conditions measured in a classroom during the school hours in a week. The high variability of the measured CO_2 concentration confirms highly variable occupancy and the impossibility to define a ventilation schedule. Moreover, it underlines the advantage to continuously adapt the ventilation rate



a) Frequencies of occurrence (%) of the CO_2 concentration (ppm) distributed in bins

b) Average opening quotas (%) of the dampers in three classrooms

Fig. 7. Operating parameters of DCV from October 2014 to January 2015.

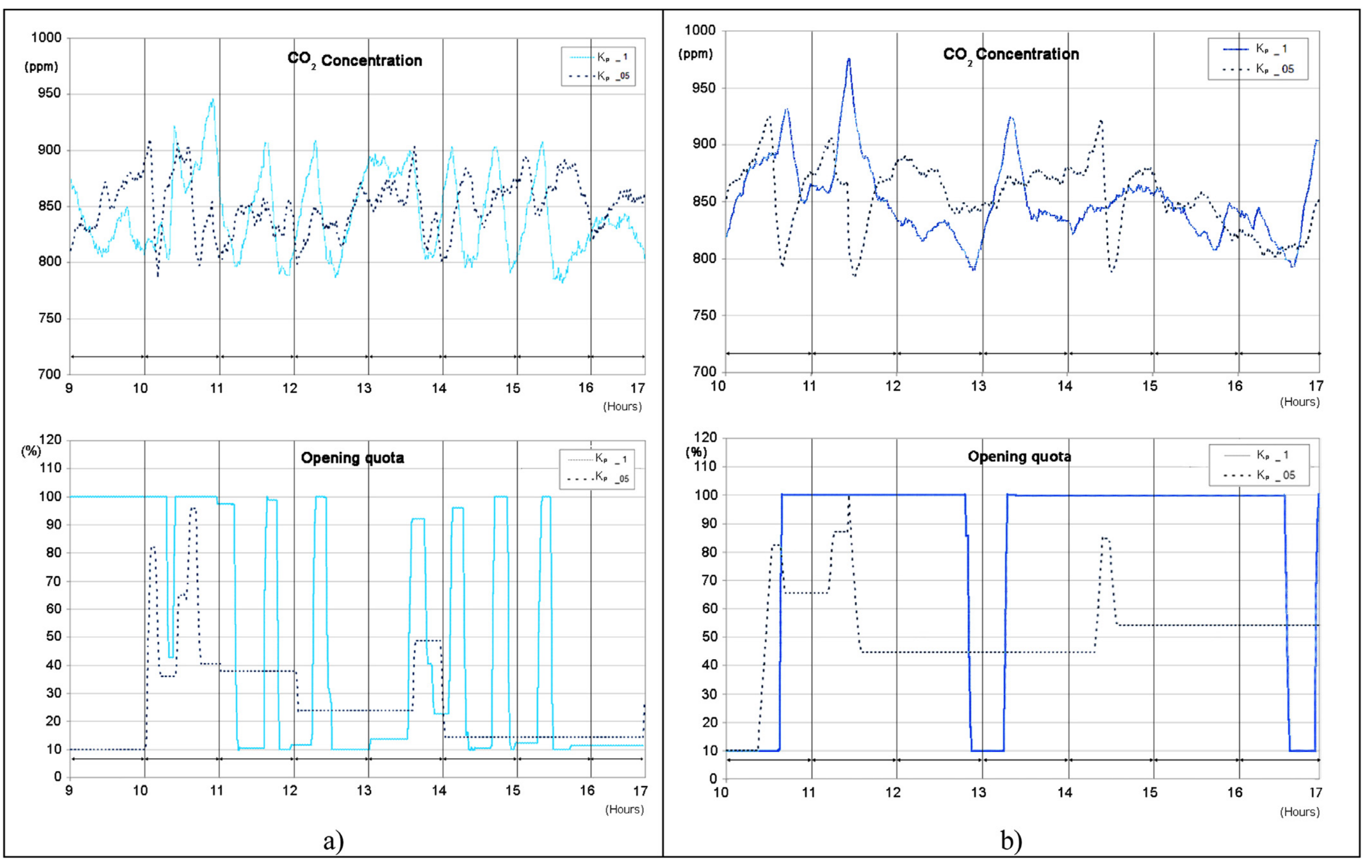


Fig. 8. Comparison of CO_2 concentration levels and corresponding opening quotas of the dampers in a classroom with $K_p = 0.5$ and $K_p = 1$. The values refer to the cases of medium occupancy (a) and high occupancy (b).

to actual requirements. In addition, it can be observed that sometimes the full ventilation rate must be used since the 900 ppm set point value is exceeded. In the bottom of Fig. 6 are reported the opening quotas of the modulating dampers in that classroom.

Wide oscillations can be observed. Sometimes the minimum opening level (10%) is sufficient to ensure CO_2 concentration levels below 900 ppm. In other conditions the total opening is not enough as noted in the upper part of the Fig. 6. Fig. 7a shows the frequencies of occurrence, in percentage of the total measurements during the operating hours, distributed in bins of CO_2 concentration levels, with reference to the ten classrooms served by the Southern branch rooftop AHU (AHU South) and refers to the period from October 2015 to January 2016 during the first teaching period. Despite of some overruns of the control limit (900 ppm), the goal to stay under 1000 ppm value is always achieved. The measurements confirm the right choice of a lower set point value (850 ppm) and the efficacy of CO_2-based DCV rather than a scheduled ventilation. However in December and January the overruns above 900 ppm are less thanks to the modification of the control parameters which is explained in the next paragraph. In detail, the frequency of these overruns are decreased from 3% in October and 2.2% in November, prior to the optimisation intervention, to 0.1% in December and 1.4% in January. Fig. 7b reports average opening quotas (%) of the ventilation dampers during the operation hours recorded for three classrooms in the same period. To increase the accuracy of the monitoring, in this case the opening quotas were recorded at every minute. Significant differences refer not only to the same classroom indifferent periods, but also to the three classrooms in the same month. For instance the high average opening quotas of classroom 3 (81.6%) in January highlights the need for high ventilation flow rate for long periods, but in the same periods the other classrooms may need low ventilation flow rates. The average for each classroom in the whole period is equal to 32%, 22% and 54% respectively.

For AHU South, during winter 2014–2015, DCV reduces the amount of ventilation air by 26%, while energy savings in thermal energy and fans electricity are equal to 31% and 40% respectively.

3.2. Effects of the tuning intervention

To highlight the improvement achieved, a comparison from monitoring is here presented between the use of $K_p = 1$, as originally set, and the new value $K_p = 0.5$. In Fig. 8, respectively for a classroom with average occupancy (Fig. 8a) and one with a high occupancy (Fig. 8b), are reported above the profiles of CO_2 concentrations levels (ppm) and below the corresponding trends of the damper opening quotas (%). In each figure are compared monitored data obtained on two similar day (i.e. with similar occupancy) in the same classroom with two different values of K_p. In case of $K_p = 1$, the sudden intervention implies frequent and high oscillations. Instead, with $K_p = 0.5$, the control follows the demand with a better approach, thus avoiding excessive opening quotas, with consequent sporadic peaks over 900 ppm. This is even clearer with reference to monthly data, shown in Fig. 7, where the clear reduction of the frequency of occurrence over 900 ppm after the adjustment with $K_p = 0.5$ in two months (December and January), if compared with the previous months ($K_p = 1$).

Overall for the classroom of Fig. 8a, the average opening of the dampers are equal to 49.6% and 25.7% with $K_p = 1$ and $K_p = 0.5$ respectively. In case of high occupancy (Fig. 8b), these values are equal to 81.7% and 51.1% with $K_p = 1$ and $K_p = 0.5$ respectively. Therefore thanks to the tuning activity there was a considerable reduction in the ventilation flow rate amount and a even better control of the CO_2 concentration levels.

3.3. Assessment of the energy saving by more flexible humidity control

Monitoring data provided the latent and total energy requirement for AHU South in case of 35% RH set point i.e. with the humidifier on when the RH measured on the return duct is below 35%. The energy requirements in the virtual case of RH set point equal to 40% and 50% were calculated with a ten minutes timestep by considering the humidifier on when RH is below 40% and 50% respectively. Fig. 9 shows the latent energy requirement share (%) in the three cases for each month and the winter season as a whole. These shares refer to the total heat demand of AHU South and confirm that high energy savings on latent energy demand can be achieved by reducing the RH set point value.

In Fig. 10 RH trends of the return air to AHU South are reported during the operation hours (9 am to 6 pm) of three typical days for each winter months. In winter official teaching periods are on and classrooms are used for ex-cathedra lessons or laboratory activities foreseen in the various degree courses. The real set point for relative humidity is at 35%. Nevertheless, the RH is often over this value because of occupancy and outdoor humidity. With RH set point equal to 35% the intervention of the humidification is therefore rare.

As regards summer operation, Fig. 11 shows the RH profiles in three classrooms during the operation hours of three days chosen within the three weeks from 29th June to 19th July 2015. In this period official teaching periods are closed, but occupancy is at the top owing to the presence of popular summer design workshops. Indoor dehumidification acts with RH set point equal to 65%, but the RH is often below this value because of the pre-dehumidification taking place in the rooftop AHUs. Consequently, RH set points greater than 50% permit a significant reduction of the cooling demand of the internal AHU, asquantified in Fig. 12 for three AHUs, each installed in one of the analysed classrooms. Fig. 12 shows the cooling demand shares for each week and the total share in this period with RH set points equal to 60% and 65% respectively, by referring to the cooling demand in case of RH set point equal to 50%. The calculation procedure was as shown

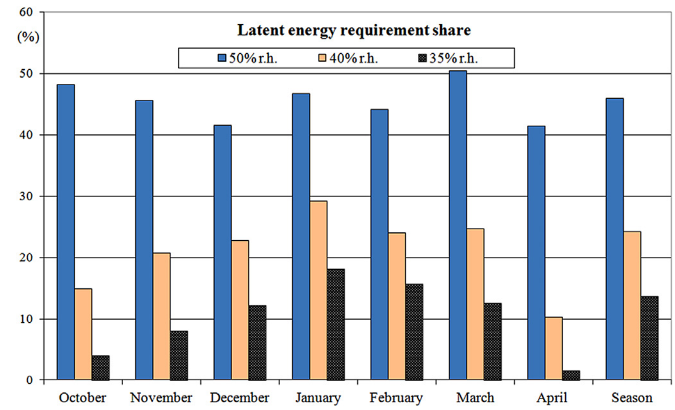


Fig. 9. Latent energy requirement shares (%) for different humidity set-points in winter. Each share refers to the corresponding AHU South total heat requirement.

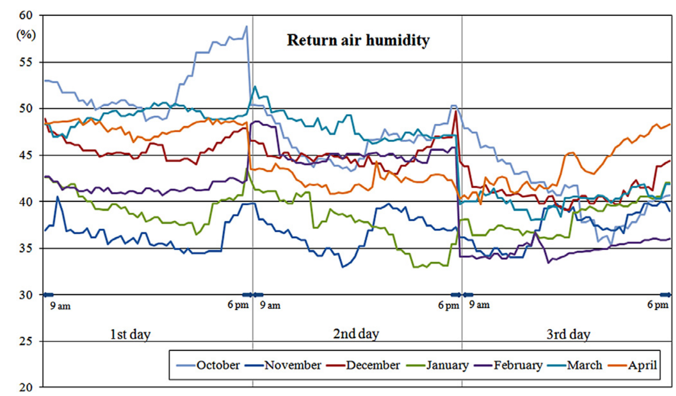


Fig. 10. RH trends (%) of the return air to AHU South during three days for winter months.

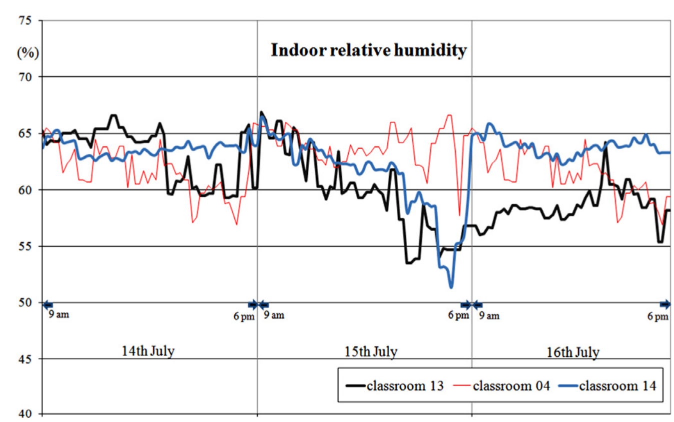


Fig. 11. RH profiles (%) for three classrooms during three summer days.

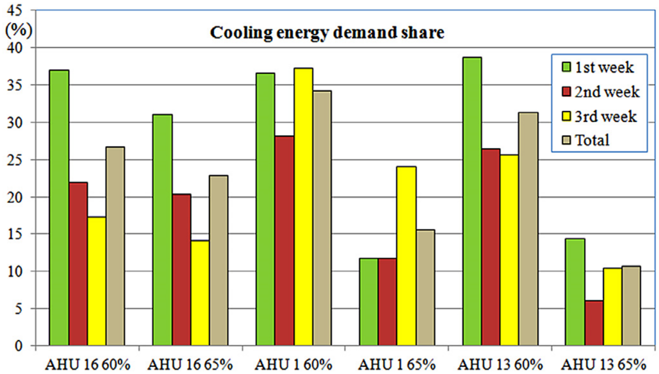


Fig. 12. Cooling energy demand shares (%) of three internal AHUs in summer with 60% or 65% RH set point. Each share refers to the corresponding requirement with 50% RH set point.

for winter operation, but considering now the effort of the cooling coil of internal AHUs. In fact performance monitoring of each internal AHU provided the cooling load with RH set points equal to 65%. From this condition the further contribution to cooling load to reach RH 60% or 50% was calculated by using Eq. (4) applied to the AHU cooling coil.

4. Conclusions

The real amount of energy savings achievable through suitable control strategies in a university facility was assessed by means of a long term monitoring. Simultaneously, the maintenance of adequate internal comfort conditions was verified. In detail, the measurements indicate as CO_2-based DCV has provided a reduction in the energy requirement equal to 31% for thermal energy demand during winter period and 40% for fan electricity consumption compared with a traditional system with constant ventilation air flow rate. The reduction of ventilation air amount was 26%. Nevertheless, the experimental data also drew attention to the peculiarity of the control of the indoor CO_2 concentration and the difficult achievement of a fine control. Maximum attention is required by an on-line specific tuning of the control system parameters to optimize DCV operation for each application case. Unlike the usual, control performance tests should be extended to the whole operation life of HVAC system. Monitoring results showed significant improvements even by simple interventions of manual tuning. The frequency of the overruns above 900 ppm limit for CO_2 concentration was reduced under 2%.

Furthermore, the experimental analysis validates the possibility to combine DCV with a flexible humidity control strategy. Additional consistent reduction in energy demand regarding air treatment was assessed as a consequence of less strict humidity set points. During winter the latent energy requirement share was reduced from 46% to 14% of the total heat demand in the roof-top AHU South thanks to 35% RH set point instead of 50%. In summer 65% RH set point versus 50% permitted a cooling load reduction between 11% and 34% for the internal AHUs Therefore greater flexibility should be promoted more effectively against the widespread use of rigid design set points.

A user-friendly BMS, if fitted for long term monitoring, can be used not only for typical management and control as usual, but it may also allow the definition of detailed energy strategies aimed at the specific case study. In particular, in the context of energy retrofitting actions, it is an essential tool especially in case of historical buildings subject to preservation orders, where other high efficiency technologies are forbidden because of their invasiveness.

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